# Sports Medicine

## The effects of mental fatigue on physical performance: a systematic review.

--Manuscript Draft--

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| **Abstract:** | Background: Mental fatigue is a psychobiological state caused by prolonged periods of demanding cognitive activity. Mental fatigue has recently been suggested to affect physical performance.<br>Objective: To evaluate the literature on the impairment in physical performance due to mental fatigue and to create an overview of the potential factors underlying this effect.<br>Data Sources: Two electronic databases, PubMed and Web of Science (until 28 April 2016) were searched.<br>Eligibility criteria for selecting studies: Studies had to be designed to test whether mental fatigue influenced performance on a physical task or influenced physiological and/or perceptual responses during the physical task. Studies using short (<30 min) self-regulatory depletion tasks were excluded from the review.<br>Results: Eleven articles were included, of which six were of strong and five of moderate quality. The general finding was a decline in endurance performance (decreased time-to-exhaustion and self-selected power output/velocity or increased completion-time) due to mental fatigue, associated with a higher than normal perceived exertion. Physiological variables traditionally associated with endurance performance (heart rate, blood lactate, oxygen uptake, cardiac output, VO2) were unaffected by mental fatigue. Maximal strength, power and anaerobic work were observed not to be affected by mental fatigue.<br>Conclusion: Duration and intensity of the physical task appear to be important factors in the decrease in physical performance due to mental fatigue. The most important factor responsible for the negative impact of mental fatigue on endurance performance is a higher perceived exertion. |
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| | I am enclosing herewith the revised version of the manuscript entitled 'The effects of mental fatigue on physical performance: a systematic review' (Ms. No. SPOA-D-16-00188-R3), written by Drs. Jeroen Van Cutsem, Prof. Dr. Samuele Marcora, Dr. Kevin De Pauw, Prof. Dr. Stephen Bailey, Prof. Dr. Romain Meeusen and Prof. Dr. Bart Roelands.<br><br>Thank you for your time and consideration, we have copy/pasted the reference list as required. We are not entirely sure what happens with the refs, as we are using the Endnote style provided. We hope everything will be fine now, and again, many thanks for the thorough review and corrections on our paper!<br><br>Yours faithfully,<br><br>Jeroen Van Cutsem, Drs. |
| **Response to Reviewers:** | |
| **Suggested Reviewers:** | Benjamin Pageaux<br>benjamin.pageaux@u-bourgogne.fr<br>Made significant contributions to the mental fatigue literature. |
| | Kristy Martin<br>kristy.martin@canberra.edu.au<br>Made significant contributions to the mental fatigue literature. |
| | Stephen Bailey<br>baileys@elon.edu<br>An authority in the field of fatigue-research and experience in EEG-measurements. |
| | Mitchell Smith<br>Mitchell.Smith@uts.edu.au<br>Made significant contributions to the mental fatigue research. |

Answers to the Editor's comments

Dear editor, we thank you for the revisions. We also revised the paper once more on grammar and vocabulary and subsequently adjusted some words, rephrased a couple of sentences and removed some redundant sentences (mainly in section 4.5 and 5). We hope you agree with these specific changes and want to emphasize that no changes were made to the content of the manuscript (in order to demonstrate this all deleted words and sentences are also indicated in the manuscript with tracked changes).

1. Section 3.4 – please number the subsections in this section 3.4.1 Behavioral, 3.4.2 Physiological and 3.4.3 Psychological.

This was adjusted.

2. Section 4.2 – please number the subsections in this section 4.2.1 Behavioral, 4.2.2 Physiological and 4.2.3 Psychological.

This was adjusted.

3. Section 4.5, sentence 1 – please change 'have already' to 'has already'.

This was adjusted.

4. Compliance with Ethical Standards section – please add 'Stephen Bailey' after 'Samuele Marcora'.

This was adjusted.

5. Conflicts of Interest section – please add 'Stephen Bailey' after 'Samuele Marcora'.

This was adjusted.

6. References list – the References list no longer has the corrected formatting that was evident in the Revision 1 version of this list. Therefore, can you please reinstate the Revision 1 version, which incorporated the requested formatting changes from the submitted version. However, please also note that the revised version of the References list in Revision 1 had 77 references, whereas the version in Revision 2 has 82 references. Therefore, the format-corrected version in Revision 1 cannot simply be transplanted into Revision 3 – it will need to be updated with the changes to the References list that increased it fron 77 to 82 references. However, please apply the same formatting guidelines to all new references that I asked you to apply to the originally submitted References list. Please let me know if that does not make sense and you require further clarification of what I am trying to say here.

This was adjusted according to the requested formatting changes from the first submitted version.

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# The effects of mental fatigue on physical performance: a systematic review.

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**Running title:** Physical performance in a mentally fatigued state

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**Fig. 1** Flowchart describing the selection process for the research articles (n=11) included in this systematic review. Adapted version of the recommendations in the PRISMA Statement [32].

**Table 1** PICOS (Participants, Interventions, Comparisons, Outcomes, Study design)

**Table 2** Number of hits on keywords and combined keywords in both search engines (Pubmed & Web of Science)

**Table 3** Quality assessment 'Qualsyst' [33]

**Table 4** Overview of the mental fatigue inducing interventions: Task characteristics and outcome measures

**Table 5** Overview of the effects of mental fatigue on endurance performance: Subjective, behavioral and physiological measures before, during and/or after the physical task

**Table 6** Overview of the effects of mental fatigue on maximal strength – power – anaerobic work: Subjective, behavioral and physiological measures before, during and/or after the physical task

## **Keypoints**

- Mental fatigue impairs endurance performance, while maximal strength, power and anaerobic work are not affected
- The impairment in endurance performance due to mental fatigue is mediated by a higher-than-normal perception of effort
- Future studies should use appropriate paradigms to induce mental fatigue and explore the role of the cognitive component and the intensity/duration of the endurance task in the effect of mental fatigue on endurance performance

## Abstract

Background: Mental fatigue is a psychobiological state caused by prolonged periods of demanding cognitive activity. Mental fatigue has recently been suggested to affect physical performance.

Objective: To evaluate the literature on the impairment in physical performance due to mental fatigue and to create an overview of the potential factors underlying this effect.

Data Sources: Two electronic databases, PubMed and Web of Science (until 28 April 2016) were searched.

Eligibility criteria for selecting studies: Studies had to be designed to test whether mental fatigue influenced performance on a physical task or influenced physiological and/or perceptual responses during the physical task. Studies using short (<30 min) self-regulatory depletion tasks were excluded from the review.

Results: Eleven articles were included, of which six were of strong and five of moderate quality. The general finding was a decline in endurance performance (decreased time-to-exhaustion and self-selected power output/velocity or increased completion-time) due to mental fatigue, associated with a higher than normal perceived exertion. Physiological variables traditionally associated with endurance performance (heart rate, blood lactate, oxygen uptake, cardiac output, $VO_2$) were unaffected by mental fatigue. Maximal strength, power and anaerobic work were observed not to be affected by mental fatigue.

Conclusion: Duration and intensity of the physical task appear to be important factors in the decrease in physical performance due to mental fatigue. The most important factor responsible for the negative impact of mental fatigue on endurance performance is a higher perceived exertion.

## 1 Introduction

Mental fatigue represents a psychobiological state caused by prolonged periods of demanding cognitive activity [1, 2] and has implications on many aspects of daily life. In the workplace, mental fatigue has been found to predict an increased risk of error [3] and in addition it is one of the most common symptoms experienced by individuals with neurological disorders [4]. Mental fatigue can be manifested subjectively, behaviorally and physiologically. Subjectively, increased feelings of tiredness, lack of energy [5] and a decrease in motivation [6] and alertness have been reported [7]. Behaviorally, mental fatigue is recognized as a decline in performance (accuracy and/or reaction time (RT)) on a cognitive task [8-10]. Finally, alterations in brain activity [11, 12, 8, 13] have been shown to be a physiologic manifestation of mental fatigue. Changes in all three of these areas (subjective, behavioral, and physiological) do not have to be present for mental fatigue to be present. For instance, cognitive performance does not necessarily decline when one is mentally fatigued, since compensatory effort (e.g. indicated by alterations in brain activity or as a result of increased motivation) may alleviate this [13, 9]. Hopstaken et al. [13] increased motivation near the end of a prolonged cognitively demanding task by providing a monetary incentive and found that cognitive performance declines were reversed, despite previous signs of mental fatigue. This suggests, as previously stated, that the effects of mental fatigue can be counteracted by increased motivation and that one can be mentally fatigued without any cognitive impairment.

In 1891 Angelo Mosso reported in his seminal book on fatigue that muscle endurance was reduced in two fellow professors of physiology after long lectures and oral examinations [14]. More than a century later Marcora et al. [10] investigated for the first time in an experimentally controlled way the effect of mental fatigue on physical performance (whole-body endurance task). Muscular endurance tasks (e.g. sit-ups, weight holding, hand-grip tasks and leg-raise tasks) mostly involve a single muscle or muscle group [15]. In contrast, whole-body endurance performance refers to the entire body's ability to sustain prolonged (>75 s), dynamic exercise using large muscle groups (>2 legs; e.g. running, cycling and rowing) [16]. The results of Marcora et al. [10] demonstrate that 90 min of a cognitively demanding task elicited mental fatigue and negatively affected subsequent whole-body endurance performance. In addition the negative effect of mental fatigue on muscle endurance reported by Mosso [14] was recently confirmed in a study by Pageaux et al. [17]. In this study it was shown that a submaximal isometric knee extensor exercise until exhaustion was impaired when mentally fatigued.

Besides endurance, another important element of physical performance is high-intensity, anaerobically-based exercise (e.g. maximal strength, power and anaerobic capacity). This kind of performance is more likely to result in peripheral fatigue (i.e. fatigue produced by changes at or distal to the neuromuscular junction [18]) and therefore distinguishes itself from endurance performance. High-intensity, anaerobically-based exercise is often characterized by an all-out strategy (i.e. the athlete working maximally from the start of the event and rapidly fatiguing as a result [19]) and can be defined as any short-duration (<75 s) local muscle (e.g. maximal voluntary contraction (MVC)) or whole-body exercise (e.g. Wingate) that is powered primarily by metabolic pathways that do not use oxygen. This indicates that high-intensity, anaerobically-based performance will mostly require fewer decision-making processes (e.g. pacing) compared to endurance performance, due to the all-out strategy (i.e. less pace regulating) and due to the inherent shorter duration of these kind of performances.

The aim of the present paper is to review the literature on the effects of mental fatigue on physical performance and, if there are any, to create an overview of the potential underlying factors. In accordance with most of the included articles in the current review, the term ‘mental fatigue’ will be used [10, 12, 20, 21]. However some haziness exists in regard to its terminology. Some authors, like Ackerman & Kanfer [22] and MacMahon et al. [23], argued that the typical task used to induce mental fatigue is more appropriately termed cognitive. Therefore instead of ‘mental fatigue’ these authors used the term ‘cognitive fatigue’. It is our opinion that ‘mental fatigue’ is more appropriate as it includes emotion and motivation rather than just cognition. Bray et al. [24-26] and Pageaux et al. [20] labeled the mental fatigue inducing intervention as a ‘self-regulatory depletion manipulation’. Self-regulation refers to the mental abilities that allow people to exert control over their behaviors, thoughts, and emotions to pursue their goals [27, 26]. This description also applies to tasks often used to induce mental fatigue and certain commonalities can be observed between both constructs. As a consequence studies using self-regulatory depletion tasks that meet the eligibility criteria (duration 30 min or more) will also be included in the present review. However, studies using shorter self-regulatory depletion tasks (often referred as “ego depletion”) will not be included. It should also be stressed that this review will not include dual-task performance studies. The focus of the current review will be the influence of a preceding mentally fatiguing task on subsequent physical performance in order to adequately assess if and how performance is affected by mental fatigue.

## 2 Methods

### 2.1 Eligibility criteria

We used Population, Intervention, Comparison, Outcome and Study design (PICOS) criteria for papers in order to be included in this review (see Table 1; [28]). Randomized controlled trials (RCTs), non-randomized controlled trials (nRCTs) and non-randomized non-controlled trials (nRnCTs) were included. These studies had to be designed to test (observe in case of nRnCTs) whether a mentally fatiguing task (= intervention) influenced performance on a physical task or influenced physiological and/or perceptual responses during the physical task. To be able to test this, the control intervention (which will potentially also induce some degree of mental fatigue) in RCTs and nRCTs logically had to induce less or no mental fatigue compared to the mentally fatiguing task. Studies using short (<30 min) cognitive "self-regulation depletion" tasks were excluded from the review. This cut-off is an important feature of this review. A recent multi-laboratory replication study of the self-regulation depletion effect did not succeed in replicating the self-regulation depletion effect [29]. The authors state that although the self-regulation depleting task used may be sufficiently arduous, as indicated by difficulty, effort, and frustration ratings, it may not have been of sufficient duration or intensity to result in fatigue, a candidate proxy measure of depletion [29]. This emphasizes the importance of the length of the task used to elicit mental fatigue. The cut-off point was set at 30 min based on the vigilance decrement that typically occurs after 20–30 min of continuous work on the tasks used to induce mental fatigue [30]. In addition subjective increases in mental fatigue have been observed to occur in a similar time range (30 min; [31]). Only original studies written in English were considered.

**INSERT Table 1 HERE**

2.2 Information Sources and Search Strategy

Two electronic databases, PubMed and Web of Science (until 28 April 2016) were searched. Medical Subject heading (MeSH) terms, if available in PubMed, were used to have a qualitative literature search. The following key-words were applied individually and combined: ‘mental fatigue (MeSH)’, ‘mental fatigue’, ‘mental exertion’, ‘cognitive fatigue’, ‘self-control strength depletion’, ‘ego depletion’ in combination with ‘athletic performance (MeSH)’, ‘physical performance’, ‘performance’, ‘muscle fatigue (MeSH)’, ‘central fatigue’, ‘peripheral fatigue’, ‘physical exercise’ (see Table 2). In addition, the reference lists of included articles were screened to make the search as complete as possible.

**INSERT Table 2 HERE**

2.3 Study Selection and Data Collection Process

In- or exclusion of articles was performed by applying the PICOS-criteria (see Table 1) on the title, abstract and/or full text of articles. First, titles and abstracts of the articles were screened. Next, full-text articles were retrieved if the citation was considered potentially eligible and relevant. The data collection process is presented in Fig. 1 [32].

**INSERT Fig. 1 HERE**

2.4 Quality Assessment

The methodological quality was assessed using the quantitative assessment tool ‘QualSyst’ of Kmet et al. [33]. QualSyst contains 14 items (see Table 3) that were scored depending on the degree to which the specific criteria were met (“yes” = 2, “partial” = 1, “no” = 0). Items not applicable to a particular study design were marked “n/a” and were excluded from the calculation of the summary score. A summary score was calculated for each article by summing the total score obtained across relevant items and dividing it by the total possible score. Two reviewers (J.V.C. and B.R.) independently performed quality assessments, and disagreements were solved by consensus or by a third reviewer (K.D.P.). An article that scored ≥75% was considered strong, a score between 55% and 75% was considered moderate and a score ≤55% was considered weak.

## 3 Results

3.1 Study Selection

Our search resulted in 281 hits, of which 16 remained after excluding duplicates and screening of the titles and abstracts (Fig. 1). Eventually five articles were included, but screening of the reference lists of these five included articles resulted in the inclusion of six additional articles, making a total of 11 selected articles. Quality assessment of these 11 selected articles determined six articles were of strong quality and five articles were of moderate quality (see Table 3).

**INSERT Table 3 HERE**

3.2 Mental fatigue inducing interventions

All but one included article could be classified as a crossover RCT, Budini et al. [34] was classified as a nRnCT. Mental fatigue was induced by a prolonged demanding cognitive task, but this task varied between studies. Pageaux et al. [35, 20] and Smith et al. [31] used a 30-min modified version of the Stroop colour-word task, in the study of Duncan et al. [36] participants had to complete concentration grids for 40 min, Budini et al. [34] employed a 100-min switch task paradigm, while the other six studies [10, 12, 37, 23, 21, 17] used a 90-min version of the AX-continuous performance test (AX-CPT). In the RCTs, the control task was always time matched with the intervention task and was chosen to differ from the intervention task in such a way that mental fatigue was only or at least significantly more induced by the intervention task. The majority, eight studies [17, 10, 12, 23, 37, 31, 36, 21], used a time-matched emotionally neutral documentary or reading magazine as a control task. Pageaux et al. [35, 20] used a less mentally fatiguing (congruent, non-response inhibition) Stroop task, as evidenced by the faster reaction time and the lower rated mental demand and effort. In order to motivate participants and increase engagement during the cognitive tasks, seven out of the eleven studies gave some sort of monetary reward for the best performance in terms of RT and accuracy. In the most recent studies however [20, 36, 31] no incentives were provided. Six [10, 12, 23, 21, 17, 34, 31] studies reported a greater subjective mental fatigue after the intervention compared to after the control task. In the studies of Marcora et al. [10], Pageaux et al. [17] and Smith et al. [21] this was assessed with the Brunel Mood Scale (BRUMS). Brownsberger et al. [12] and Smith et al. [31] used a visual analog scale ranging from ‘not at all’ to ‘completely exhausted’ to assess perceived fatigue and MacMahon et al. [23] used the Current Mood State Scale (a short version of the profile of mood states (POMS)) to assess subjective fatigue. From the five studies that observed no difference in perceived fatigue due to the cognitive task, two did not assess subjective fatigue [36, 34], two [35, 20] assessed fatigue similarly to Marcora et al. [10] with the BRUMS, and one [37] assessed fatigue similarly to MacMahon et al. [23] with the POMS. Four out of the six studies [10, 21, 23, 17, 31, 12] that observed a greater subjective fatigue after the intervention compared to the control task also observed a higher mean heart rate (HR) during the intervention [10, 17, 23, 21]. In two studies [10, 21] the greater subjective fatigue was also associated with a decline of accuracy. An increase in reaction time over time was observed by Budini et al. [34]. In the study of Brownsberger et al. [12] the increase in mental fatigue was associated with an increase in β-band activity of the prefrontal lobe. Eventually all 11 studies observed some additional measure of increased mental effort, demand or frustration in the intervention task compared to the control task. An overview of the mental fatigue inducing interventions can be found in Table 4.

**INSERT Table 4 HERE**

3.3 Endurance

3.3.1 Whole-body endurance

*Behavioral*

Homogenous subject groups were recruited in each study, allowing for comparisons between studies. The participants were healthy, young (21 – 26 y) and moderately trained (maximal aerobic capacity ($VO_2$): 48 – 56 $ml \cdot kg^{-1} \cdot min^{-1}$; performance level 2 according to De Pauw et al. [38]; see Table 5). However, the experimental protocols differed, and consequently also the outcome measures of performance (see Table 5). Marcora et al. [10] used a fixed resistance (80% of the peak power output) time-to-exhaustion cycling protocol and observed a mean decrease of 15% in time-to-exhaustion due to mental fatigue with no change in revolutions per minute (RPM). Pageaux et al. [35] and MacMahon et al. [23] on the other hand selected a distance-clamped, self-paced running protocol and both reported an increased completion time when participants were mentally fatigued. An average 5% and 2% increase due to mental fatigue was reported respectively on a 5-km [35] and a 3-km running distance [23]. Moreover, while Pageaux et al. [35] completed their study in a laboratory setting, MacMahon et al. [23] showed this negative effect of mental fatigue is also present in a more applied setting (indoor track). Smith et al. [21] used a time-clamped (45 min), self-paced running protocol to observe the effect of mental fatigue on distance covered. The protocol was designed with low- and high-intensity activities. They observed that mental fatigue decreased the overall (2%) distance and the distance covered at low-intensity (3%), but not at high intensity. Logically, running velocity was lower overall and at low-intensity. In a second study Smith et al. [31] studied the effect of mental fatigue on a Yo-Yo intermittent recovery test, level 1. This test required participants to complete 2x20m runs (up and back) at progressively increasing velocities until one failed twice to complete the 2x20 m within the time limit. Smith et al. [31] observed a decrease in the covered distance in this test (16.3%) when mentally fatigued. Martin et al. [37] used a time-clamped cycling protocol, a 3-min all-out test. Their protocol aimed to observe the effect of mental fatigue on peak and mean power output and critical power. They found no difference in any of these measures due to mental fatigue. Brownsberger et al. [12] studied the effect of mental fatigue on power output with a time- (10 min) and ratings of perceived exertion- (RPE) clamped protocol, meaning that participants had to complete two 10-min cycling bouts at self-selected intensities representative of fairly light effort (RPE 11) and hard effort (RPE 15). Both in the RPE 11- and RPE 15-trial participants chose lower self-selected power outputs in the mental fatigue condition (respectively 16% and 8% lower). In the study of Pageaux et al. [20] the only behavioral measure was RPM, as their cycling protocol was time (6 min) and resistance-clamped (80%), there was however no difference in RPM due to mental fatigue.

*Physiological*

HR and blood lactate (Bla) were measured in all whole-body endurance studies except the studies of Brownsberger et al. [12], Pageaux et al. [20] and Smith et al. [31] who did not measure Bla (see Table 5). Only the studies of Marcora et al. [10] and Brownsberger et al. [12] observed differences during exercise due to the intervention. Marcora et al. [10] reported a higher HR and Bla at exhaustion in the control condition. Brownsberger et al. [12] reported a higher mean HR (4.3%) in the control condition during the RPE 11-bout. Besides HR and Bla other physiological measures were taken that could possibly explain the decrease in endurance performance when mentally fatigued. Marcora et al. [10] showed that mental fatigue did not influence oxygen uptake, stroke volume, cardiac output and blood pressure during a subsequent whole-body endurance performance. Also brain activity (α and β-activity in the prefrontal and the parietal lobe [12]) was not differently altered during a whole-body endurance performance after a mentally fatiguing task. The time course (pre – post whole-body endurance performance) of blood glucose [21] and neuromuscular function [central (maximal voluntary activation level) and peripheral (twitch and doublet parameters and electromyography measures) parameters] of the knee extensors also did not differ due to mental fatigue [20]. Regarding electromyography (EMG) root mean square during the whole-body endurance task, also no effect of mental fatigue on the rectus femoris was found [20]. Conversely, mental fatigue was associated with increased EMG root mean square of the vastus lateralis during the whole-body endurance task [20]. In addition Smith et al. [21] reported a lower $VO_2$ (6%) during the exercise-protocol in the mental fatigue condition.

*Psychological*

The most frequently measured psychological outcomes during the whole-body endurance task were perception of effort, motivation and subjective workload related to the exercise protocol (see Table 5). Perception of effort or perceived exertion (i.e. how hard, heavy, and strenuous a physical task is [39, 40]) was always assessed through Borg's 15-point RPE scale [41], except for the study of Smith et al. [21] in which they used the CR100 RPE scale, and was found to be higher during exercise in a mentally fatigued state in the studies of Marcora et al. [10], Pageaux et al. [35, 20] and Smith et al. [21, 31]. Marcora et al. [10] used a scale developed and validated by Matthews et al. [42]. They did not find any difference in success or intrinsic motivation related to the upcoming physical tasks between conditions. The same conclusion was drawn in the studies of Pageaux et al. [35, 20] and Smith et al. [21], who used the same scale to assess motivation. In the study of Martin et al. [37] a different scale (Situational Motivation Scale; [43]) was used to assess motivation, but again no difference was detected in identified regulation, external regulation and amotivation. There was however a trend for a decrease in intrinsic motivation when mentally fatigued. Brownsberger et al. [12], MacMahon et al. [23] and Smith et al. [31] did not differentiate between different types of motivation. Brownsberger et al. [12] and Smith et al. [31] used a 10-cm visual analogue scale to assess motivation for the upcoming physical task, while MacMahon et al. [23] used a 7-point Likert scale. No effects of mental fatigue on motivation could be distinguished. The subjective workload of the exercise protocol was only assessed in the studies of Pageaux et al. [35, 20]. In Pageaux et al's 2014 article [35], the National Aeronautics and Space Administration Task Load Index found that the exercise protocol was perceived as more mentally demanding and participants also rated their performance on the time trial lower in the intervention trial. Additional psychological constructs like attentional focus [23] and mood after the exercise protocol [12] were also assessed, but no differences were observed due to mental fatigue.

**INSERT Table 5 HERE**

3.3.2 Muscle endurance

*Behavioral*

Only one study evaluating the effect of mental fatigue on muscle endurance could be included in the present review [17] (see Table 5). In this study participants had to produce a target value of 20%-MVC (a prolonged submaximal isometric contraction of the knee extensor muscles) until exhaustion. Time-to-exhaustion was observed to be 13% shorter in the mental fatigue condition [17].

*Physiological*

HR was continuously monitored during this prolonged submaximal contraction and was not observed to be affected by mental fatigue at iso-time (time elapsed from the beginning of the endurance task to the last measurement before exhaustion of the shortest performance) nor at exhaustion. Likewise EMG root mean square did not differ between conditions [17].

*Psychological*

Leg-RPE (i.e. subjects were specifically asked to rate how hard they were driving their leg during the endurance task) was measured every 20 s and was significantly higher when mentally fatigued. At exhaustion leg-RPE did not differ [17]. No difference in intrinsic and success motivation towards the endurance task was observed during this investigation [17].

## 3.4 Maximal strength, Power and Anaerobic Work

### *3.4.1 Behavioral*

Five studies examined the effect of mental fatigue on high-intensity, anaerobically-based exercise [37, 17, 20, 34, 36] (see Table 6). Four studies assessed whether an impairment in MVC of the knee extensor muscles occurred after completing a mentally fatiguing task [17, 20, 37, 34]. Both studies of Pageaux et al. [17, 20] revealed that the mentally fatiguing as well as the control task did not affect MVC torque. Martin et al. [37] confirmed these results and found no condition or time effect in any of the measures taken during the MVC (i.e. peak torque, mean torque, time to half peak torque, time to peak torque and peak torque slope). Budini et al. [34] on the contrary reported a decreased leg extension MVC (796 ± 150 N to 741 ± 137 N) after a 100-min mentally fatiguing task. Martin et al. [37] and Duncan et al. [36] examined the influence of mental fatigue on more sport specific anaerobic performance. Regarding a countermovement jump Martin et al. [37] found no difference in jump height, mean power, peak force, concentric peak velocity or eccentric displacement due to mental fatigue. Duncan et al. [36] reported that mental fatigue had no effect on mean cycling power during four consecutive 30-s Wingate anaerobic tests.

### *3.4.2 Physiological*

Martin et al. [37] did not record any specific physiological measures related to the countermovement jumps. On the other hand Duncan et al. [36] assessed HR and Bla and found no difference due to mental fatigue. In the studies of Pageaux et al. [17, 20] and Budini et al. [34] measures of peripheral and central fatigue were examined during a MVC. Pageaux et al. [17, 20] included single electrical stimulation in order to evaluate peak twitch, time to peak twitch and half-relaxation time. Double electrical stimulation was used to evaluate the peak torque of the doublet (potentiated doublet, 5 s after the MVC). In both studies [17, 20] no effects of mental fatigue on peripheral parameters of neuromuscular function (peak twitch, time to peak twitch and half-relaxation time) or on central parameters (voluntary activation level) were observed [17, 20]. Budini et al. [34] made use of two springs with a different stiffness to induce two specific tremors during a 20-s 30%-MVC. One spring induced a 9-Hz frequency oscillation (associated with the peripheral component of the stretch reflex) and another a 5-Hz (associated with the central component of the stretch reflex). The instability/tremor at 9 Hz, generated by the stretch reflex peripheral component, was decreased after the mental fatigue task [34].

### *3.4.3 Psychological*

Budini et al. [34] did not take any psychological measures and the measures (i.e. perception of effort, motivation and subjective workload) taken in the studies of Pageaux et al. [17, 20] were not related to the anaerobic maximal work. Duncan et al. [36] also employed few psychological measures, with only RPE being measured on completion of each Wingate-test, but no effect of mental fatigue was reported. Martin et al. [37] assessed RPE and motivation and did not observe any difference in RPE, identified regulation, external regulation and amotivation towards the countermovement jump or MVCs.

**INSERT Table 6 HERE**

## 4 Discussion

With the present review we sought to outline the current knowledge on the effect of mental fatigue on physical performance. Secondly, we aimed to propose possible factors mediating this effect. All investigations included in this review were of moderate to strong quality. Within the quality criteria check all studies lost points for not blinding investigators and subjects. This highlights a specific difficulty in this field of research, being the impossibility to blind a participant from which task is being done, the experimental task (the cognitive task) or the control task (a less demanding cognitive task or watching a television documentary). This could lead to different expectations regarding the performance on a subsequent physical exercise task. This is predominantly counteracted by selecting so-called 'naïve participants', meaning they were naïve to the real aims and hypotheses of the study. Instead participants were told the study examined the effects of two different cognitive activities (a computerized task and watching television) on the physiological responses to exhaustive exercise [10] or were led to believe the study was examining whether watching television or completing a mentally engaging task is a good preparation for maximal anaerobic exercise performance [37]. Despite participants being deceived, the difference in task demand between the experimental and the control task could still have created different expectations concerning the subsequent physical performance. A solution might be to measure how participants expect to perform on the physical task, however this carries the risk of emphasizing a potential difference in performance-expectations between conditions.

### 4.1 Mental fatigue inducing interventions

One of the most important questions in studying the effect of mental fatigue on physical performance is whether mental fatigue was successfully induced. To answer this question a definition of mental fatigue and its markers is needed. As already stated in section 1, mental fatigue has subjective, behavioral and physiological manifestations. Most of the included studies assessed only the subjective and behavioral manifestations and therefore the quantification of mental fatigue is often restricted. Marcora et al. [10] postulated that higher subjective fatigue and/or a decline in cognitive performance indicate the presence of mental fatigue. However, whether the presence of these two markers is sufficient to determine that mental fatigue has been successfully induced is debatable. This is shown by the fact that only six of the 11 included studies observed higher subjective fatigue [10, 12, 17, 21, 23, 31] and only two studies reported a decrease in accuracy with longer time-on-task [10, 21]. Moreover, observing an increase in subjective fatigue or not, also greatly depends on the subjective scale that is used. A visual analogue scale assessing how mentally fatigued an individual feels might be sensitive but promote response bias, while the BRUMS or POMS may be less capable of detecting small but relevant short-term changes in mental fatigue. This raises the need for well-thought paradigms that account for the relative contribution of other parameters, like motivation and/or boredom, when time-on-task effects are investigated [9, 44]. In an attempt to account for these effects (e.g. loss of motivation with subsequent task disengagement), incentives were provided for the best performances in seven of the eleven included studies. Gergelyfi et al. [44] demonstrated that alterations of the motivational state through monetary incentives failed to compensate the effects of mental fatigue and therefore this seems a legitimate way to account for task disengagement (i.e decrease in cognitive performance) through loss of motivation. Nonetheless, the interpretation of subjective and behavioral measures of mental fatigue remains challenging without (neuro)physiological measures.

Brownsberger et al. [12] is the only included study that used electroencephalography (EEG) to examine neural indices (α and β waves) of electrocortical activity in the prefrontal cortex, a brain region that is important in decision-making [5]. They reported an increased β-band activity of the prefrontal lobe in the middle of and after the mentally demanding task compared to the control task. β-waves are fast (13–30 Hz) EEG potentials associated with increased alertness, arousal and excitement [45]. Brownsberger et al. [12] subsequently interpreted this finding as an indication of successfully eliciting greater attention, information processing and cognitive engagement. This greater attention could of course indicate that compensatory mechanisms were in place to maintain performance in the presence of mental fatigue [46], however it does not automatically indicate that mental fatigue was present. The greater elicited attention and cognitive engagement rather suggests that the experimental task was more mentally demanding. EEG measures that have repeatedly been associated with the occurrence of mental fatigue are increases in frontal θ and in frontal, central and parietal α-power [47, 48, 8, 49]. Moreover, if one considers the continuous change of a measure as a criterion in order to assign it to the development of mental fatigue, the increase in frontal θ power seems to be the most valid measure of mental fatigue according to the data reported by Wascher et al. [8] and Trejo et al. [49]. Elevated θ activity shows that more effort is required to maintain the performance level, certainly when tasks have to be repeated [50-52]. Unfortunately θ activity was not measured in the study of Brownsberger et al. [12].

In order to state whether mental fatigue was induced requires subjective, behavioral and physiological measures, and the interactions between all three manifestation areas of mental fatigue should be interpreted. Moreover, adaptation, motivation and inter-individual differences in threshold to mental fatigue are important variables to account for. Participants have to be in a well-familiarized setting [9] in which subjective, behavioral and physiological effects can be most certainly attributed to mental fatigue. This could be attained by adding a different cognitive task before and after the mentally fatiguing task (i.e. the indirect method [53]), allowing researchers to evaluate the effect of fatigue on cognitive performance independently from time-on-task [44]. In addition it is likely that the occurrence of mental fatigue differs from one individual to another, and depends on the duration and/or difficulty of the mentally exerting task. Therefore, it cannot be expected that the same physiological, psychological and behavioral changes will be observed in all individuals. The importance of the duration of the task to induce mental fatigue is underlined by the recent replication study of Hagger et al. [29] and is shown again by a recent study published by Schücker et al. [54]. In this study [54] no effect of a 10-min cognitive task on subsequent whole-body endurance performance was found. The authors admit one possible explanation for these results is the ineffectiveness of the manipulation task (10-min Stroop) to induce mental fatigue. They however argue that even shorter tasks have been observed to reduce whole-body endurance performance [55] and therefore feel confident that the induced state of mental fatigue was comparable with previous studies in this line of research. However there seem to be some crucial differences between the lines of research on mental fatigue and self-regulation depletion [56]. More specifically, in the short tasks used in the self-regulation depletion research mental exertion is not sufficiently prolonged to induce subjective feelings of mental fatigue. Therefore one should be cautious about attributing the results in both lines of research to the same mechanism. In the end, all included studies in the present review but the studies of Pageaux et al. [35, 20], Martin et al. [37] and Duncan et al. [36] have arguments to state mental fatigue was induced in the experimental condition and not or to a lesser extent in the control condition. Despite not being able to substantiate mental fatigue was induced in their study, the studies of Pageaux et al. [35, 20], Martin et al. [37] and Duncan et al. [36] were included. To begin with, these studies [35, 20, 36, 37] used tasks of a similar nature and length as the tasks used in the other included studies that were successful in inducing mental fatigue. Secondly, Duncan et al. [36] did not include any subjective, behavioral or physiological measures to monitor mental fatigue, whereas Pageaux et al. [35, 20] and Martin et al. [37] used the, perhaps too insensitive, BRUMS or POMS to assess the participants' state of mental fatigue. Therefore, and because in the studies of Pageaux et al. [35, 20] and Martin et al. [37] it was reported that participants perceived the intervention task as more mentally demanding and effortful compared to the control task, these studies were also included.

### 4.2 Mental fatigue and physical performance

For the purpose of discussing the subsequent physical performance in a mentally fatigued state a distinction was made between behavioral, physiological and psychological outcomes during exercise.

#### *4.2.1 Behavioral*

Out of the nine studies that examined the effect of mental fatigue on behavioral measures, eight included an endurance performance-measure. Seven of those eight reported that endurance performance was negatively affected by mental fatigue. This was evidenced by a decrease in time-to-exhaustion [10, 17], an increase in completion time [35, 23], a decrease in self-paced velocity [21], a decrease in self-selected power outputs [12] and a decrease in distance covered [31]. Only in the 3-min all-out protocol of Martin et al. [37] no impact of mental fatigue was observed. Martin et al. [37] argued that the lack of effect of mental fatigue on performance was caused by the reduced to non-existent cognitive component of the exercise task. Indeed, an all-out strategy is characterized by the athlete working maximally from the start of the event and rapidly fatiguing as a result of that [19]. This statement seems to be supported by the null findings in the studies on the effect of mental fatigue on maximal strength, power and anaerobic work [17, 20, 36, 37]. The employed physical tasks in these studies all require a maximal all-out effort. From these results it can be pointed out that it appears to be important to differentiate between endurance and maximal power tasks to observe a negative effect of mental fatigue on behavioral measures. The shorter and more maximal the task the lower the impact of the mental fatigue. The distinction between whole-body and local muscle endurance tasks does not seem to be of great importance to find an effect of mental fatigue. In a study of Pageaux et al. [17] it was shown that besides whole-body endurance, muscle endurance was also impaired when mentally fatigued. This is however the only study examining the effect of mental fatigue on muscle endurance performance and needs to be confirmed by other studies in the future. The importance of both the cognitive component and the submaximal, endurance intensity in the physical task also points towards the need for future research to be conducted in a more applied way (e.g. in prolonged endurance tasks/events). The demands of such real life prolonged endurance events are physically but also cognitively high, as is shown by the metacognitive framework of Brick et al. [57]. Therefore such real life endurance events are possibly able to accentuate even more the decrease in endurance performance due to mental fatigue. A recent investigation by Brick et al. [58] demonstrated this by comparing an RPE-clamped time trial and an externally-controlled pace time trial. Preceding the randomized completion of these two time trials participants completed two self-controlled pace time trials. Pacing strategy for the externally-controlled and RPE-clamped time trials was the same as for the subjects' fastest self-controlled pace time trial. It was concluded that external control over pacing (e.g. drafting in a race) may facilitate performance [58], possibly mediated through reducing the cognitive load and promoting appropriate attentional strategies that optimize performance. An applied study was recently performed in soccer. Badin et al. [59] assessed the effect of mental fatigue on physical and technical performance in small-sided soccer games. Physical performance (total distance covered tracked with a global positioning system) in this setting was however not a main objective, because a player could perform better (e.g. more successful passes) without covering more distance. Therefore, because covering as much distance as possible did not translate unequivocally to a better performance in a small-sided soccer game and because the researchers also did not instruct the participants to cover as much distance as possible during the game, there was no real physical performance measure included in this study and consequently the study was not included in the review. Nonetheless studies of this kind are extremely useful and necessary in order to expand our knowledge on the effect of mental fatigue on physical performance.

*4.2.2 Physiological*

Regarding the studies on endurance performance, Marcora et al. [10], Brownsberger et al. [12] and Smith et al. [21] observed respectively a higher HR and Bla at exhaustion, a higher mean HR in the RPE 11 exercise-bout and a higher $VO_2$ in the control trial compared to the mental fatigue trial. However all these findings can be explained by behavioral changes. In the study of Marcora et al. [10] the longer time-to-exhaustion explained the physiological differences between conditions. Brownsberger et al. [12] identified the higher self-selected power-outputs as an explanation for the higher mean HR and Smith et al. [21] emphasized the higher self-selected running velocities to account for the higher $VO_2$ in the control trial. Brownsberger et al. [12] also observed elevated β activity in the prefrontal brain lobe during a 3-min warm-up due to mental fatigue. This significant difference disappeared during the subsequent exercise bout. Pageaux et al. [20] demonstrated that mental fatigue was associated with a higher EMG root mean square of the vastus lateralis during cycling. This suggests an alteration in muscle fiber recruitment for the same power output and was previously reported by a self-regulation study [24]. In contrast to the above mentioned physiological differences between conditions, it was also observed that many physiological measures did not differ. Marcora et al. [10] did not observe any effect of mental fatigue on cardiovascular measures during exercise. Pageaux et al. [20] used a time- and intensity fixed protocol in order to observe the effect of mental fatigue on exercise induced peripheral (twitch and doublet parameters and EMG measures) and central (voluntary activation level) fatigue. It could be concluded that mental fatigue did not accentuate peripheral fatigue as well as it did not increase exercise-induced central fatigue [20]. Overall, all included studies were rather unequivocal, mental fatigue does not reduce endurance performance by altering physiological, cardiorespiratory and neuromuscular responses to the subsequent exercise. These findings are confirmed by the line of research on the effect of mental fatigue on maximal strength, power and anaerobic work. Studies by Pageaux et al. [17], Martin et al. [37] and Rozand et al. [60] did not observe any effect of mental fatigue on central fatigue. In contrast, Budini et al. [34] reported a decreased MVC and a decreased tremor amplitude during a 100% MVC after a mentally fatiguing task (100 min). Weakened cortico-muscular coupling (i.e. synchronized activity of the motor cortex and the spinal motoneuron pool) induced by mental fatigue is one possible explanation for this finding [34]. Yet they did not include a control group and as a consequence muscle relaxation cannot be excluded as another potential explanation for their findings. These results demonstrate that mental fatigue is able to alter endurance performance without altering any exercise-induced physiological parameter in the periphery and without any change in the cortico-muscular coupling. A side note to this conclusion has to be that, due to the findings of Pageaux et al. [20] and Budini et al. [34], further investigations on the effect of mental fatigue on muscle fiber recruitment are warranted.

#### *4.2.3 Psychological*

Martin et al. [37] reported a trend for a decrease in intrinsic motivation towards the upcoming physical task when mentally fatigued. Moreover, Pageaux et al. [35] found that a 5-km time trial was perceived as more mentally demanding and participants also rated their performance on the time trial lower when mentally fatigued. The most consistent finding was however the higher RPE during exercise. Marcora et al. [10], Pageaux et al. [35, 20, 17] and Smith et al. [21, 31] all observed a higher RPE during exercise, Martin et al. [37] observed a trend towards a higher RPE and Brownsberger et al. [12] and MacMahon et al. [23] both showed a lower self-selected power output or running velocity for the same RPE. Therefore the current general opinion is that endurance performance is impaired by mental fatigue and this is predominantly mediated by the higher-than-normal perceived exertion during exercise. Mental fatigue appears not to alter motivation towards the upcoming endurance task. In the study of Marcora et al. [10] this could have been due to a ceiling effect, created by the artificially increased motivation by offering monetary reward for best cycling performance, that masked the possible influence of mental fatigue on motivation. However, no other studies provided monetary incentives to increase engagement in the physical task and a ceiling effect was therefore less plausible in those studies. Encouragements and visual feedback during the physical task itself are other important factors that impact on motivation. These specific aspects differed between studies, with some [21, 20] giving no feedback nor encouragement, some giving feedback but no encouragements [31, 35, 12, 34] and others giving both feedback and standardized encouragements [17, 10, 37]. However, independently from giving feedback or encouragements, all studies reported no effect of mental fatigue on motivation towards the upcoming physical task. Mental fatigue not having an effect on motivation is possibly explained by the differing natures of both tasks following upon each other. Inzlicht et al. [61] proposed a motivational shift model to explain that engaging in self-regulation at time 1 leads to declines in performance at time 2. However, while this model accounts for many relevant findings in the field, crossing over the nature of the task (e.g. a cognitive task followed by a physical task) might counteract the motivational shift (away from 'have-to' goals and towards 'want-to' goals) often observed when tasks of a similar nature follow each other (e.g. cognitive task after cognitive task) [62]. Higher perception of effort as the mediator of the negative effect of mental fatigue on physical performance also explains why mental fatigue does not impair maximal anaerobic tasks. The role of perception of effort in maximal anaerobic tasks is limited because of the all-out strategy that is employed. All-out strategies typically require no pacing and induce a faster build-up of peripheral fatigue (e.g. accumulation of metabolites).

### 4.3 How does mental fatigue increase perceived exertion during endurance performance?

Perceived exertion, also referred to as perception of effort, can be defined as the conscious sensation of how hard, heavy, and strenuous a physical task is. So far, three different theories have been suggested on which neural signal(s) are processed by the brain to generate the perception of effort [40]: (i) the afferent feedback from the working muscles and other peripheral physiological systems (i.e. the afferent feedback model [69]); (ii) the corollary discharges (neural signals from premotor/motor areas to sensory areas of the brain) associated with the central motor command (i.e. the corollary discharge model) [63-66]; (iii) a combination of afferent feedback and corollary discharges (i.e. the combined model [70]). It should be noted that recent evidence provides support in favor of the corollary discharge model (for more details please see [71, 65, 72, 73]). Yet without wishing to extend this discussion much further, it can be stated that perception of effort could possibly be increased by 1) increasing the intensity of afferent feedback from peripheral physiological systems, 2) increasing the intensity of central motor command (i.e. motor-related cortical activity) and thus its corollary discharges and 3) altering the processing of these neural signals in the brain (independently whether they originate from the periphery or from corollary discharges of the central motor command). The first option has been shown multiple times not to be influenced by mental fatigue, i.e. mental fatigue does not alter the physiological responses to exercise thought to provide afferent feedback to the brain (see section 4.2 Physiological). Regarding the second possibility, Pageaux et al. [20] demonstrated that mental fatigue was associated with a higher EMG root mean square of the vastus lateralis during cycling. This suggests that alterations in motor control may force mentally fatigued subjects to increase their central motor command and muscle recruitment (as shown by the increase in EMG amplitude) in order to produce the same power output even when central and peripheral fatigue are not exacerbated. This altered EMG amplitude due to mental fatigue has however to be confirmed by other studies. Furthermore, EEG should be used to directly test this hypothesis because central motor command can change even in the absence of changes in EMG amplitude [71]. The third option, an altered brain processing of the neural signals underlying perception of effort (independently whether they originate from peripheral receptors or premotor/motor areas of the cortex appears to be a reasonable explanation. However, we are not aware of any study who has tested this hypothesis.

### 4.4 A potential role for brain neurotransmitters

The importance of brain neurotransmitters in endurance performance has already been underlined by Roelands et al. [74]. They showed that reboxetine (a noradrenaline re-uptake inhibitor) decreased whole-body endurance performance in normal and high ambient temperature. Interestingly, despite a decreased power output during the time trial in this study there was no change in absolute RPE values, consequently increasing the RPE to power output ratio (meaning less power output is generated for a same RPE value). The intake of methylphenidate [75] [a dopamine (DA) reuptake inhibitor] in contrast allowed subjects to maintain a higher power output and improve time trial performance in the heat, again without influencing absolute RPE values. This demonstrates that altered brain neurotransmission is able to affect whole-body endurance performance and that this effect is associated with an altered RPE to power output ratio (in the case of DA, a decreased ratio). Klass et al. [76] showed that muscle endurance performance is affected in a similar way. A noradrenaline reuptake inhibitor reduced endurance time by 15.6 %. This was associated with a greater rate of supraspinal impairment and increase in RPE. Participants experienced the same intensity of intermittent contractions as harder to perform after administration of a noradrenaline reuptake inhibitor, without affecting the fatigue-related intramuscular impairments [76]. Pageaux et al. [35, 20, 17] stated that neural activity increases the extracellular concentration of adenosine (an inhibitory neurotransmitter; [77]) and that brain adenosine accumulation reduces endurance performance [78]. Subsequently they speculated that adenosine accumulation in the pre-supplementary motor area and anterior cingulate cortex (due to a mentally fatiguing task) could also explain in part the higher than normal perceived exertion during an endurance exercise in a mentally fatigued state. However, there is to date no study that demonstrates that mentally fatigued individuals have increased adenosine in specific areas. Moreover, other possible neurotransmitters that could mediate the effect of mental fatigue must not be overlooked. Hopstaken et al. [13] monitored certain psychophysiological markers of locus coeruleus activity during a mentally fatiguing task and reported that these markers (P3 and pupil diameter) were affected by the time-on-task manipulation. Consequently this indicates that the locus coeruleus (i.e. a nucleus in the brainstem responsible for the release of cortical noradrenaline) is also a possible mediator of the effects of mental fatigue [13]. Moeller et al. [79] investigated the role of DA in mental fatigue and concluded that also the dopaminergic midbrain is involved in sustaining motivation during fatigue. Research on neurological disorders and the often associated feelings of fatigue, also points towards an important role for the midbrain and other subcortical regions [80]. The above points out that most probably it will not be one particular neurotransmitter that mediates the negative effect of mental fatigue on endurance performance. Rather mental fatigue will affect neurotransmitter systems in multiple brain regions and the summation of these alterations might explain (in part) the impairment in endurance performance.

### 4.5 Future directions

Evidence from fields other than physical performance has already demonstrated that manipulation of neurotransmitter systems could reduce the negative effects of mental fatigue [79, 81]. Moeller et al. [79] used methylphenidate (i.e. a DA reuptake inhibitor) in order to manipulate the concentration of DA in the brain and assess what effect this had on the development of mental fatigue during a cognitive performance task. Similar interventions could be employed to assess the role of the above mentioned neurotransmitters in the mental fatigue/physical performance interaction. Almost 20 years ago, Caldwell et al. [81] reported that administration of dextroamphetamine (i.e. an indirect dopamine agonist) improved flight performance during the final 23 hours of a 40-hour period of continuous wakefulness. Similar studies investigating the effect of mental fatigue on physical performance could enlarge our knowledge of the role of different neurotransmitters in this interaction. Simultaneously more applied areas need further investigation as well. The cognitive tasks used to induce mental fatigue in the reviewed studies do not entirely resemble tasks (e.g. interviews, emotion control, and tactical meetings) that would regularly occur prior to competition. The mental fatigue induced by the cognitive demands of the competition itself should also be investigated. Finally, the impact of mental fatigue should be assessed on endurance performance of longer duration (e.g. marathon) and in high-level athletes, as it is likely that they may have superior ability to maintain performance [82].

## 5 Conclusion

Mental fatigue is a psychobiological state caused by prolonged periods of demanding cognitive activity and is characterized by a combination of specific subjective, behavioral and physiological manifestations. Recent research has observed the effect of mental fatigue on physical performance. The current systematic review aimed at unravelling whether mental fatigue impairs physical performance and sought to create an overview of the potential factors underlying this effect.

Eleven articles on the topic were selected and the main outcome was a decline in endurance performance (decreased time-to-exhaustion and self-selected power output/velocity or increased completion time) due to mental fatigue, associated with a higher than normal perceived exertion. Physiological variables traditionally associated with endurance performance (heart rate, blood lactate, oxygen uptake, cardiac output, $VO_2$) were not directly affected by mental fatigue during and after endurance performance. Maximal strength, power and anaerobic work were not affected by mental fatigue. This led to the conclusion that duration and intensity of the physical task appear to be important factors in the decrease in physical performance due to mental fatigue.

Practically these findings suggest that a higher-than-normal perception of effort and reduced endurance performance are respectively a psychological and behavioral marker of mental fatigue. In addition, engagement in mentally demanding tasks before competitions requiring endurance should be avoided in order to optimize performance. Moreover, the high cognitive demands of sport are most probably mentally fatiguing when prolonged over time. This opens new opportunities to improve endurance performance by minimizing as much as possible the cognitive load during competitions and/or by increasing resistance to the negative effects of mental fatigue on perception of effort and endurance performance.

**Compliance with Ethical Standards**

Jeroen Van Cutsem, Samuele Marcora, Kevin De Pauw, Stephen Bailey, Romain Meeusen and Bart Roelands declare that the systematic review complies with all ethical standards.

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**Conflicts of Interest**

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# The effects of mental fatigue on physical performance: a systematic review.

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**Running title:** Physical performance in a mentally fatigued state

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**Fig. 1** Flowchart describing the selection process for the research articles (n=11) included in this systematic review. Adapted version of the recommendations in the PRISMA Statement [32].

**Table 1** PICOS (Participants, Interventions, Comparisons, Outcomes, Study design)

**Table 2** Number of hits on keywords and combined keywords in both search engines (Pubmed & Web of Science)

**Table 3** Quality assessment 'Qualsyst' [33]

**Table 4** Overview of the mental fatigue inducing interventions: Task characteristics and outcome measures

**Table 5** Overview of the effects of mental fatigue on endurance performance: Subjective, behavioral and physiological measures before, during and/or after the physical task

**Table 6** Overview of the effects of mental fatigue on maximal strength – power – anaerobic work: Subjective, behavioral and physiological measures before, during and/or after the physical task

## Keypoints

- Mental fatigue impairs endurance performance, while maximal strength, power and anaerobic work are not affected
- The impairment in endurance performance due to mental fatigue is mediated by a higher-than-normal perception of effort
- Future studies should use appropriate paradigms to induce mental fatigue and explore the role of the cognitive component and the intensity/duration of the endurance task in the effect of mental fatigue on endurance performance

## Abstract

Background: Mental fatigue is a psychobiological state caused by prolonged periods of demanding cognitive activity. Mental fatigue has recently been suggested to affect physical performance.

Objective: To evaluate the literature on the impairment in physical performance due to mental fatigue and to create an overview of the potential factors underlying this effect.

Data Sources: Two electronic databases, PubMed and Web of Science (until 28 April 2016) were searched.

Eligibility criteria for selecting studies: Studies had to be designed to test whether mental fatigue influenced performance on a physical task or influenced physiological and/or perceptual responses during the physical task. Studies using short (<30 min) self-regulatory depletion tasks were excluded from the review.

Results: Eleven articles were included, of which six were of strong and five of moderate quality. The general finding was a decline in endurance performance (decreased time-to-exhaustion and self-selected power output/velocity or increased completion-time) due to mental fatigue, associated with a higher than normal perceived exertion. Physiological variables traditionally associated with endurance performance ~~Traditional physiological outcomes in the periphery~~ (heart rate, blood lactate, oxygen uptake, cardiac output, $VO_2$) ~~and motor function during and after endurance performance~~ were unaffected by mental fatigue. Maximal strength, power and anaerobic work were observed not to be affected by mental fatigue.

Conclusion: Duration and intensity of the physical task appear to be important factors in the decrease in physical performance due to mental fatigue. The most important factor responsible for the negative impact of mental fatigue on endurance performance is a higher perceived exertion.

## 1 Introduction

Mental fatigue represents a psychobiological state caused by prolonged periods of demanding cognitive activity [1, 2] and has implications on many aspects of daily life. In the workplace, mental fatigue has been found to predict an increased risk of error [3] and in addition it is one of the most common symptoms experienced by individuals with neurological disorders [4]. Mental fatigue can be manifested subjectively, behaviorally and physiologically. Subjectively, increased feelings of tiredness, lack of energy [5] and a decrease in motivation [6] and alertness have been reported [7]. Behaviorally, mental fatigue is recognized as a decline in performance (accuracy and/or reaction time (RT)) on a cognitive task [8-10]. Finally, alterations in brain activity [11, 12, 8, 13] have been shown to be a physiologic manifestation of mental fatigue. Changes in all three of these areas (subjective, behavioral, and physiological) do not have to be present for mental fatigue to be present. For instance, cognitive performance does not necessarily decline when one is mentally fatigued, since compensatory effort (~~physiological and/or subjective effort (~~e.g. indicated by alterations in brain activity ~~and~~ or as a result of increased ~~/or renewed~~ motivation) may alleviate this [13, 9]. Hopstaken et al. [13] increased motivation near the end of a prolonged cognitively demanding task by providing a monetary incentive and found that cognitive performance declines were reversed, despite previous signs of mental fatigue. This suggests, as previously stated, that the effects of mental fatigue can be counteracted by ~~renewed~~ increased motivation and that one can be mentally fatigued without any cognitive impairment.

In 1891 Angelo Mosso reported in his seminal book on fatigue that muscle endurance was reduced in two fellow professors of physiology after long lectures and oral examinations [14]. More than a century later Marcora et al. [10] investigated for the first time in an experimentally controlled way the effect of mental fatigue on physical performance (whole-body endurance task)~~ replicated these results in an experimentally controlled way in a whole-body endurance task~~. Muscular endurance tasks (e.g. sit-ups, weight holding, hand-grip tasks and leg-raise tasks) mostly involve a single muscle or muscle group [15]. In contrast, whole-body endurance performance refers to the entire body's ability to sustain prolonged (>75 s), dynamic exercise using large muscle groups (>2 legs; e.g. running, cycling and rowing) [16]. The results of Marcora et al. [10] demonstrate that 90 min of a cognitively demanding task elicited mental fatigue and negatively affected subsequent whole-body endurance performance. In addition the negative effect of mental fatigue on muscle endurance reported by Mosso [14] was recently confirmed in a study by Pageaux et al. [17]. In this study it was shown that a submaximal isometric knee extensor exercise until exhaustion was impaired when mentally fatigued.

Besides endurance, another important element of physical performance is high-intensity, anaerobically-based exercise (e.g. maximal strength, power and anaerobic capacity). This kind of performance is more likely to result in peripheral fatigue (i.e. fatigue produced by changes at or distal to the neuromuscular junction [18]) and therefore distinguishes itself from endurance performance. High-intensity, anaerobically-based exercise is often characterized by an all-out strategy ~~pacing~~ (i.e. the athlete working maximally from the start of the event and rapidly fatiguing as a result [19]) and can be defined as any short-duration (<75 s) local muscle (e.g. maximal voluntary contraction (MVC)) or whole-body exercise (e.g. Wingate) that is powered primarily by metabolic pathways that do not use oxygen. This indicates that high-intensity, anaerobically-based performance will mostly require fewer decision-making processes (e.g. pacing) compared to endurance performance, due to the all-out strategy ~~pacing~~ (i.e. less pace regulating) and due to the inherent shorter duration of these kind of performances.

The aim of the present paper is to review the literature on the effects of mental fatigue on physical performance and, if there are any, to create an overview of the potential underlying factors. In accordance with most of the included articles in the current review, the term ‘mental fatigue’ will be used [10, 12, 20, 21]. However some haziness exists in regard to its terminology. Some authors, like Ackerman & Kanfer [22] and MacMahon et al. [23], argued that the typical task used to induce mental fatigue is more appropriately termed cognitive. Therefore instead of ‘mental fatigue’ these authors used the term ‘cognitive fatigue’. It is our opinion that ‘mental fatigue’ is more appropriate as it includes emotion~~al~~ and motivation~~al factors~~ rather than just cognition. Bray et al. [24-26] and Pageaux et al. [20] labeled the mental fatigue inducing intervention as a ‘self-regulatory ~~strength~~ depletion manipulation’. Self-regulation refers to the mental abilities that allow people to exert control over their behaviors, thoughts, and emotions to pursue their goals [27, 26]. This description also applies to tasks often used to induce mental fatigue and certain commonalities can be observed between both constructs. As a consequence studies using self-regulatory ~~strength depleting~~ depletion ~~studies using~~ tasks ~~(e.g. due to engagement in a cognitive task requiring self-regulation)~~ that meet the eligibility criteria (duration 30 min or more) will also be included in the present review. However, studies using shorter self-regulatory depletion tasks (often referred as “ego depletion”) will not be included. It should also be stressed that this review will not include dual-task performance studies. The focus of the current review will be the influence of a preceding mentally fatiguing task on subsequent physical performance in order to adequately assess if and how performance is affected by mental fatigue.

## 2 Methods

### 2.1 Eligibility criteria

We used Population, Intervention, Comparison, Outcome and Study design (PICOS) criteria for papers in order to be included in this review (see Table 1; [28]). Randomized controlled trials (RCTs), non-randomized controlled trials (nRCTs) and non-randomized non-controlled trials (nRnCTs) were included. These studies had to be designed to test (observe in case of nRnCTs) whether a mentally fatiguing task (= intervention) influenced performance on a physical task or influenced physiological and/or perceptual responses during the physical task. To be able to test this, the control intervention (which will potentially also induce some degree of mental fatigue) in RCTs and nRCTs logically had to induce less or no mental fatigue compared to the mentally fatiguing task. Studies using short (<30 min) cognitive "self-regulation depletion" tasks were excluded from the review. This cut-off is an important feature of this review. A recent multi-laboratory replication study of the self-regulation depletion effect did not succeed in replicating the self-regulation depletion effect [29]. The authors state that although the self-regulation depleting task used may be sufficiently arduous, as indicated by difficulty, effort, and frustration ratings, it may not have been of sufficient duration or intensity to result in fatigue, a candidate proxy measure of depletion [29]. This emphasizes the importance of the length of the task used to elicit mental fatigue. The cut-off point was set at 30 min based on the vigilance decrement that typically occurs after 20–30 min of continuous work on the tasks used to induce mental fatigue [30]. In addition subjective increases in mental fatigue have been observed to occur in a similar time range (30 min; [31]). Only original studies written in English were considered.

**INSERT Table 1 HERE**

2.2 Information Sources and Search Strategy

Two electronic databases, PubMed and Web of Science (until 28 April 2016) were searched. Medical Subject heading (MeSH) terms, if available in PubMed, were used to have a qualitative literature search. The following key-words were applied individually and combined: ‘mental fatigue (MeSH)’, ‘mental fatigue’, ‘mental exertion’, ‘cognitive fatigue’, ‘self-control strength depletion’, ‘ego depletion’ in combination with ‘athletic performance (MeSH)’, ‘physical performance’, ‘performance’, ‘muscle fatigue (MeSH)’, ‘central fatigue’, ‘peripheral fatigue’, ‘physical exercise’ (see Table 2). In addition, the reference lists of included articles were screened to make the search as complete as possible.

**INSERT Table 2 HERE**

2.3 Study Selection and Data Collection Process

In- or exclusion of articles was performed by applying the PICOS-criteria (see Table 1) on the title, abstract and/or full text of articles. First, titles and abstracts of the articles were screened. Next, full-text articles were retrieved if the citation was considered potentially eligible and relevant. The data collection process is presented in Fig. 1 [32].

**INSERT Fig. 1 HERE**

2.4 Quality Assessment

The methodological quality was assessed using the quantitative assessment tool ‘QualSyst’ of Kmet et al. [33]. QualSyst contains 14 items (see Table 3) that were scored depending on the degree to which the specific criteria were met (“yes” = 2, “partial” = 1, “no” = 0). Items not applicable to a particular study design were marked “n/a” and were excluded from the calculation of the summary score. A summary score was calculated for each article by summing the total score obtained across relevant items and dividing it by the total possible score. Two reviewers (J.V.C. and B.R.) independently performed quality assessments, and disagreements were solved by consensus or by a third reviewer (K.D.P.). An article that scored ≥75% was considered strong, a score between 55% and 75% was considered moderate and a score ≤55% was considered weak.

## 3 Results

3.1 Study Selection

Our search resulted in 281 hits, of which 16 remained after excluding duplicates and screening of the titles and abstracts (Fig. 1). Eventually five articles were included, but screening of the reference lists of these five included articles resulted in the inclusion of six additional articles, making a total of 11 selected articles. Quality assessment of these 11 selected articles determined six articles were of strong quality and five articles were of moderate quality (see Table 3).

**INSERT Table 3 HERE**

3.2 Mental fatigue inducing interventions

All but one included article could be classified as a crossover RCT, Budini et al. [34] was classified as a nRnCT. Mental fatigue was induced by a prolonged demanding cognitive task, but this task varied between studies. Pageaux et al. [35, 20] and Smith et al. [31] used a 30-min modified version of the Stroop colour-word task, in the study of Duncan et al. [36] participants had to complete concentration grids for 40 min, Budini et al. [34] employed a 100-min switch task paradigm, while the other six studies [10, 12, 37, 23, 21, 17] used a 90-min version of the AX-continuous performance test (AX-CPT). In the RCTs, the control task was always time matched with the intervention task and was chosen to differ from the intervention task in such a way that mental fatigue was only or at least significantly more induced by the intervention task. The majority, eight studies [17, 10, 12, 23, 37, 31, 36, 21], used a time-matched emotionally neutral documentary or reading magazine as a control task. Pageaux et al. [35, 20] used a less mentally fatiguing (congruent, non-response inhibition) Stroop task, as evidenced by the faster reaction time and the lower rated mental demand and effort. In order to motivate participants and increase engagement during the cognitive tasks, seven out of the eleven studies gave some sort of monetary reward for the best performance in terms of RT and accuracy. In the most recent studies however [20, 36, 31] no incentives were provided. Six [10, 12, 23, 21, 17, 34, 31] studies reported a greater subjective mental fatigue after the intervention compared to after the control task. In the studies of Marcora et al. [10], Pageaux et al. [17] and Smith et al. [21] this was assessed with the Brunel Mood Scale (BRUMS). Brownsberger et al. [12] and Smith et al. [31] used a visual analog scale ranging from ‘not at all’ to ‘completely exhausted’ to assess perceived fatigue and MacMahon et al. [23] used the Current Mood State Scale (a short version of the profile of mood states (POMS)) to assess subjective fatigue. From the five studies that observed no difference in perceived fatigue due to the cognitive task, two did not assess subjective fatigue [36, 34], two [35, 20] assessed fatigue similarly to Marcora et al. [10] with the BRUMS, and one [37] assessed fatigue similarly to MacMahon et al. [23] with the POMS. Four out of the six studies [10, 21, 23, 17, 31, 12] that observed a greater subjective fatigue after the intervention compared to the control task also observed a higher mean heart rate (HR) during the intervention [10, 17, 23, 21]. In two studies [10, 21] the greater subjective fatigue was also associated with a decline of accuracy. An increase in reaction time over time was observed by Budini et al. [34]. In the study of Brownsberger et al. [12] the increase in mental fatigue was associated with an increase in β-band activity of the prefrontal lobe. Eventually all 11 studies observed some additional measure of increased mental effort, demand or frustration in the intervention task compared to the control task. An overview of the mental fatigue inducing interventions can be found in Table 4.

**INSERT Table 4 HERE**

3.3 Endurance

3.3.1 Whole-body endurance

*Behavioral*

Homogenous subject groups were recruited in each study, allowing for comparisons between studies. The participants were healthy, young (21 – 26 y) and moderately trained (maximal aerobic capacity ($VO_2$): 48 – 56 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$; performance level 2 according to De Pauw et al. [38]; see Table 5). However, the experimental protocols differed, and consequently also the outcome measures of performance (see Table 5). Marcora et al. [10] used a fixed resistance (80% of the peak power output) time-to-exhaustion cycling protocol and observed a mean decrease of 15% in time-to-exhaustion due to mental fatigue with no change in revolutions per minute (RPM). Pageaux et al. [35] and MacMahon et al. [23] on the other hand selected a distance-clamped, self-paced running protocol and both reported an increased completion time when participants were mentally fatigued. An average 5% and 2% increase due to mental fatigue was reported respectively on a 5-km [35] and a 3-km running distance [23]. Moreover, while Pageaux et al. [35] completed their study in a laboratory setting, MacMahon et al. [23] showed this negative effect of mental fatigue is also present in a more applied setting (indoor track). Smith et al. [21] used a time-clamped (45 min), self-paced running protocol to observe the effect of mental fatigue on distance covered. The protocol was designed with low- and high-intensity activities. They observed that mental fatigue decreased the overall (2%) distance and the distance covered at low-intensity (3%), but not at high intensity. Logically, running velocity was lower overall and at low-intensity. In a second study Smith et al. [31] studied the effect of mental fatigue on a Yo-Yo intermittent recovery test, level 1. This test required participants to complete 2x20m runs (up and back) at progressively increasing velocities until one failed twice to complete the 2x20 m within the time limit. Smith et al. [31] observed a decrease in the covered distance in this test (16.3%) when mentally fatigued. Martin et al. [37] used a time-clamped cycling protocol, a 3-min all-out test. Their protocol aimed to observe the effect of mental fatigue on peak and mean power output and critical power. They found no difference in any of these measures due to mental fatigue. Brownsberger et al. [12] studied the effect of mental fatigue on power output with a time- (10 min) and ratings of perceived exertion- (RPE) clamped protocol, meaning that participants had to complete two 10-min cycling bouts at self-selected intensities representative of fairly light effort (RPE 11) and hard effort (RPE 15). Both in the RPE 11- and RPE 15-trial participants chose lower self-selected power outputs in the mental fatigue condition (respectively 16% and 8% lower). In the study of Pageaux et al. [20] the only behavioral measure was RPM, as their cycling protocol was time (6 min) and resistance-clamped (80%), there was however no difference in RPM due to mental fatigue.

*Physiological*

HR and blood lactate (Bla) were measured in all whole-body endurance studies except the studies of Brownsberger et al. [12], Pageaux et al. [20] and Smith et al. [31] who did not measure Bla (see Table 5). Only the studies of Marcora et al. [10] and Brownsberger et al. [12] observed differences during exercise due to the intervention. Marcora et al. [10] reported a higher HR and Bla at exhaustion in the control condition. Brownsberger et al. [12] reported a higher mean HR (4.3%) in the control condition during the RPE 11-bout. Besides HR and Bla other physiological measures were taken that could possibly explain the decrease in endurance performance when mentally fatigued. Marcora et al. [10] showed that mental fatigue did not influence oxygen uptake, stroke volume, cardiac output and blood pressure during a subsequent whole-body endurance performance. Also brain activity (α and β-activity in the prefrontal and the parietal lobe [12]) was not differently altered during a whole-body endurance performance after a mentally fatiguing task. The time course (pre – post whole-body endurance performance) of blood glucose [21] and neuromuscular function [central (maximal voluntary activation level) and peripheral (twitch and doublet parameters and electromyography measures) parameters] of the knee extensors also did not differ due to mental fatigue [20]. Regarding electromyography (EMG) root mean square during the whole-body endurance task, also no effect of mental fatigue on the rectus femoris was found [20]. Conversely, mental fatigue was associated with increased EMG root mean square of the vastus lateralis during the whole-body endurance task [20]. In addition Smith et al. [21] reported a lower $VO_2$ (6%) during the exercise-protocol in the mental fatigue condition.

*Psychological*

The most frequently measured psychological outcomes during the whole-body endurance task were perception of effort, motivation and subjective workload related to the exercise protocol (see Table 5). Perception of effort or perceived exertion (i.e. how hard, heavy, and strenuous a physical task is [39, 40]) was always assessed through Borg's 15-point RPE scale [41], except for the study of Smith et al. [21] in which they used the CR100 RPE scale, and was found to be higher during exercise in a mentally fatigued state in the studies of Marcora et al. [10], Pageaux et al. [35, 20] and Smith et al. [21, 31]. Marcora et al. [10] ~~already pointed out that it is important to assess motivation in different dimensions and therefore they~~ used a scale developed and validated by Matthews et al. [42]. They did not find any difference in success or intrinsic motivation related to the upcoming physical tasks between conditions. The same conclusion was drawn in the studies of Pageaux et al. [35, 20] and Smith et al. [21], who used the same scale to assess motivation. In the study of Martin et al. [37] a different scale (Situational Motivation Scale; [43]) was used to assess motivation, but again no difference was detected in identified regulation, external regulation and amotivation. There was however a trend for a decrease in intrinsic motivation when mentally fatigued. Brownsberger et al. [12], MacMahon et al. [23] and Smith et al. [31] did not differentiate between different types of motivation. Brownsberger et al. [12] and Smith et al. [31] used a 10-cm visual analogue scale to assess motivation for the upcoming physical task, while MacMahon et al. [23] used a 7-point Likert scale. No effects of mental fatigue on motivation could be distinguished. The subjective workload of the exercise protocol was only assessed in the studies of Pageaux et al. [35, 20]. In Pageaux et al's 2014 article [35], the National Aeronautics and Space Administration Task Load Index found that the exercise protocol was perceived as more mentally demanding and participants also rated their performance on the time trial lower in the intervention trial. Additional psychological constructs like attentional focus [23] and mood after the exercise protocol [12] were also assessed, but no differences were observed due to mental fatigue.

**INSERT Table 5 HERE**

3.3.2 Muscle endurance

*Behavioral*

Only one study evaluating the effect of mental fatigue on muscle endurance could be included in the present review [17] (see Table 5). In this study participants had to produce a target value of 20%-MVC (a prolonged submaximal isometric contraction of the knee extensor muscles) until exhaustion. Time-to-exhaustion was observed to be 13% shorter in the mental fatigue condition [17].

*Physiological*

HR was continuously monitored during this prolonged submaximal contraction and was not observed to be affected by mental fatigue at iso-time (time elapsed from the beginning of the endurance task to the last measurement before exhaustion of the shortest performance) nor at exhaustion. Likewise EMG root mean square did not differ between conditions [17].

*Psychological*

Leg-RPE (i.e. subjects were specifically asked to rate how hard they were driving their leg during the endurance task) was measured every 20 s and was significantly higher when mentally fatigued. At exhaustion leg-RPE did not differ [17]. No difference in intrinsic and success motivation towards the endurance task was observed during this investigation [17].

3.4 Maximal strength, Power and Anaerobic Work

*3.4.1 Behavioral*

Five studies examined the effect of mental fatigue on high-intensity, anaerobically-based exercise [37, 17, 20, 34, 36] (see Table 6). Four studies assessed whether an impairment in MVC of the knee extensor muscles occurred after completing a mentally fatiguing task [17, 20, 37, 34]. Both studies of Pageaux et al. [17, 20] revealed that the mentally fatiguing as well as the control task did not affect MVC torque. Martin et al. [37] confirmed these results and found no condition or time effect in any of the measures taken during the MVC (i.e. peak torque, mean torque, time to half peak torque, time to peak torque and peak torque slope). Budini et al. [34] on the contrary reported a decreased leg extension MVC (796 ± 150 N to 741 ± 137 N) after a 100-min mentally fatiguing task. Martin et al. [37] and Duncan et al. [36] examined the influence of mental fatigue on more sport specific anaerobic performance. Regarding a countermovement jump Martin et al. [37] found no difference in jump height, mean power, peak force, concentric peak velocity or eccentric displacement due to mental fatigue. Duncan et al. [36] reported that mental fatigue had no effect on mean cycling power during four consecutive 30-s Wingate anaerobic tests.

*3.4.2 Physiological*

Martin et al. [37] did not record any specific physiological measures related to the countermovement jumps. On the other hand Duncan et al. [36] assessed HR and Bla and found no difference due to mental fatigue. In the studies of Pageaux et al. [17, 20] and Budini et al. [34] measures of peripheral and central fatigue were examined during a MVC. Pageaux et al. [17, 20] included single electrical stimulation in order to evaluate peak twitch, time to peak twitch and half-relaxation time. Double electrical stimulation was used to evaluate the peak torque of the doublet (potentiated doublet, 5 s after the MVC). In both studies [17, 20] no effects of mental fatigue on peripheral parameters of neuromuscular function (peak twitch, time to peak twitch and half-relaxation time) or on central parameters (voluntary activation level) were observed [17, 20]. Budini et al. [34] made use of two springs with a different stiffness to induce two specific tremors during a 20-s 30%-MVC. One spring induced a 9-Hz frequency oscillation (associated with the peripheral component of the stretch reflex) and another a 5-Hz (associated with the central component of the stretch reflex). The instability/tremor at 9 Hz, generated by the stretch reflex peripheral component, was decreased after the mental fatigue task [34].

*3.4.3 Psychological*

Budini et al. [34] did not take any psychological measures and the measures (i.e. perception of effort, motivation and subjective workload) taken in the studies of Pageaux et al. [17, 20] were not related to the anaerobic maximal work. Duncan et al. [36] also employed few psychological measures, with only RPE being measured on completion of each Wingate-test, but no effect of mental fatigue was reported. Martin et al. [37] assessed RPE and motivation and did not observe any difference in RPE, identified regulation, external regulation and amotivation towards the countermovement jump or MVCs.

**INSERT Table 6 HERE**

## **4 Discussion**

With the present review we sought to outline the current knowledge on the effect of mental fatigue on physical performance. Secondly, we aimed to propose possible factors mediating this effect. All investigations included in this review were of moderate to strong quality. Within the quality criteria check all studies lost points for not blinding investigators and subjects. This highlights a specific difficulty in this field of research, being the impossibility to blind a participant from which task is being done, the experimental task (the cognitive task) or the control task (a less demanding cognitive task or watching a television documentary). This could lead to different expectations regarding the performance on a subsequent physical exercise task. This is predominantly counteracted by selecting so-called 'naïve participants', meaning they were naïve to the real aims and hypotheses of the study. Instead participants were told the study examined the effects of two different cognitive activities (a computerized task and watching television) on the physiological responses to exhaustive exercise [10] or were led to believe the study was examining whether watching television or completing a mentally engaging task is a good preparation for maximal anaerobic exercise performance [37]. Despite participants being deceived, the difference in task demand between the experimental and the control task could still have created different expectations concerning the subsequent physical performance. A solution might be to measure how participants expect to perform on the physical task, however this carries the risk of emphasizing a potential difference in performance-expectations between conditions.

### 4.1 Mental fatigue inducing interventions

One of the most important questions in studying the effect of mental fatigue on physical performance is whether mental fatigue was successfully induced. To answer this question a definition of mental fatigue and its markers is needed. As already stated in section 1, mental fatigue has subjective, behavioral and physiological manifestations. Most of the included studies assessed only the subjective and behavioral manifestations and therefore the quantification of mental fatigue is often restricted. Marcora et al. [10] postulated that higher ~~increased~~ subjective fatigue and/or a decline in cognitive performance indicate the presence of mental fatigue. However, whether the presence of these two markers is sufficient to determine that mental fatigue has been successfully induced is debatable. This is shown by the fact that only six of the 11 included studies observed higher ~~an increased~~ subjective fatigue [10, 12, 17, 21, 23, 31] and only two studies reported a decrease in accuracy with longer time-on-task [10, 21]. Moreover, observing an increase in subjective fatigue or not, also greatly depends on the subjective scale that is used. A visual analogue scale assessing how mentally fatigued an individual feels might be ~~too~~ sensitive but ~~and~~ promote response bias, while the BRUMS or POMS may be ~~are~~ less ~~rather insensitive and might be in~~capable of detecting small but relevant short-term changes in mental fatigue. ~~Automatically t~~ This raises the need for well-thought paradigms that account for the relative contribution of other parameters, like motivation and/or boredom, when time-on-task effects are investigated [9, 44]. In an attempt to account for these effects (e.g. loss of motivation with subsequent task disengagement), incentives were provided for the best performances in seven of the eleven included studies. Gergelyfi et al. [44] demonstrated that alterations of the motivational state through monetary incentives failed to compensate the effects of mental fatigue and therefore this seems a legitimate way to account for task disengagement (i.e decrease in cognitive performance) through loss of motivation. Nonetheless, the interpretation of subjective and behavioral measures of mental fatigue remains challenging without (neuro)physiological measures.

Brownsberger et al. [12] is the only included study that used electroencephalography (EEG) to examine neural indices (α and β waves) of electrocortical activity in the prefrontal cortex, a brain region that is important in decision-making [5]. They reported an increased β-band activity of the prefrontal lobe in the middle of and after the mentally demanding task compared to the control task. β-waves are fast (13–30 Hz) EEG potentials associated with increased alertness, arousal and excitement [45]. Brownsberger et al. [12] subsequently interpreted this finding as an indication of successfully eliciting greater attention, information processing and cognitive engagement. This greater attention could of course indicate that compensatory mechanisms were in place to maintain performance in the presence of mental fatigue [46], however it does not automatically indicate that mental fatigue was present. The greater elicited attention and cognitive engagement rather suggests that the experimental task was more mentally demanding. EEG measures that have repeatedly been associated with the occurrence of mental fatigue are increases in frontal θ and in frontal, central and parietal α-power [47, 48, 8, 49]. Moreover, if one considers the continuous change of a measure as a criterion in order to assign it to the development of mental fatigue, the increase in frontal θ power seems to be the most valid measure of mental fatigue according to the data reported by Wascher et al. [8] and Trejo et al. [49]. Elevated θ activity shows that more ~~increased~~ effort is required to maintain the performance level, certainly when tasks have to be repeated [50-52]. Unfortunately θ activity was not measured in the study of Brownsberger et al. [12].

In order to state whether mental fatigue was induced requires subjective, behavioral and physiological measures, and the interactions between all three manifestation areas of mental fatigue should be interpreted. Moreover, adaptation, motivation and inter-individual differences in threshold to mental fatigue are important variables to account for. Participants have to be in a well-familiarized setting [9] in which subjective, behavioral and physiological effects can be most certainly attributed to mental fatigue. This could be attained by adding a different cognitive task before and after the mentally fatiguing task (i.e. the indirect method [53]), allowing researchers to evaluate the effect of fatigue on cognitive performance independently from time-on-task [44]. In addition it is likely that the occurrence of mental fatigue differs from one individual to another, and depends on the duration and/or difficulty of the mentally exerting task. Therefore, it cannot be expected that the same physiological, psychological and behavioral changes will be observed in all individuals. The importance of the duration of the task to induce mental fatigue is underlined by the recent replication study of Hagger et al. [29] and is shown again by a recent study published by Schücker et al. [54]. In this study [54] no effect of a 10-min cognitive task on subsequent whole-body endurance performance was found. The authors admit one possible explanation for these results is the ineffectiveness of the manipulation task (10-min Stroop) to induce mental fatigue. They however argue that even shorter tasks have been observed to reduce whole-body endurance performance [55] and therefore feel confident that the induced state of mental fatigue was comparable with previous studies in this line of research. However there seem to be some crucial differences between the lines of research on mental fatigue and self-regulation depletion [56]. More specifically, in the short tasks used in the self-regulation depletion research mental exertion is not sufficiently prolonged to induce subjective feelings of mental fatigue. Therefore one should be cautious about attributing the results in both lines of research to the same mechanism. In the end, all included studies in the present review but the studies of Pageaux et al. [35, 20], Martin et al. [37] and Duncan et al. [36] have arguments to state mental fatigue was induced in the experimental condition and not or to a lesser extent in the control condition. Despite not being able to substantiate mental fatigue was induced in their study, the studies of Pageaux et al. [35, 20], Martin et al. [37] and Duncan et al. [36] were included. To begin with, these studies [35, 20, 36, 37] used tasks of a similar nature and length as the tasks used in the other included studies that were successful in inducing mental fatigue. Secondly, Duncan et al. [36] did not include any subjective, behavioral or physiological measures to monitor mental fatigue, whereas Pageaux et al. [35, 20] and Martin et al. [37] used the, perhaps too insensitive, BRUMS or POMS to assess the participants' state of mental fatigue. Therefore, and because in the studies of Pageaux et al. [35, 20] and Martin et al. [37] it was reported that participants perceived the intervention task as more mentally demanding and effortful compared to the control task, these studies were also included.

### 4.2 Mental fatigue and physical performance

For the purpose of discussing the subsequent physical performance in a mentally fatigued state a distinction was made between behavioral, physiological and psychological outcomes during exercise.

#### *4.2.1 Behavioral*

Out of the nine studies that examined the effect of mental fatigue on behavioral measures, eight ~~that~~ included an endurance performance-measure. Seven of those eight reported that endurance performance was negatively affected by mental fatigue. This was evidenced by a decrease in time-to-exhaustion [10, 17], an increase in completion time [35, 23], a decrease in self-paced velocity [21], a decrease in self-selected power outputs [12] and a decrease in distance covered [31]. Only in the 3-min all-out protocol of Martin et al. [37] ~~and in the 6-min at 80% protocol of Pageaux et al. [20]~~ no impact of mental fatigue was observed. ~~In the study of Pageaux et al. [20] no behavioral measure but RPM could be influenced and this was observed not to be altered by mental fatigue.~~ Martin et al. [37] argued that the lack of effect of mental fatigue on performance was caused by the reduced to non-existent cognitive component of the exercise task. Indeed, an all-out strategy ~~pacing~~ is characterized by the athlete working maximally from the start of the event and rapidly fatiguing as a result of that [19]. This statement seems to be supported by the null findings in the studies on the effect of mental fatigue on maximal strength, power and anaerobic work [17, 20, 36, 37]. The employed physical tasks in these studies all require a maximal all-out ~~pacing~~ effort. From these results it can be pointed out that it appears to be important to differentiate between endurance and maximal power tasks to observe a negative effect of mental fatigue on behavioral measures. The shorter and more maximal the task the lower the impact of the mental fatigue. The distinction between whole-body and local muscle endurance tasks does not seem to be of great importance to find an effect of mental fatigue. In a study of Pageaux et al. [17] it was shown that besides whole-body endurance, muscle endurance was also impaired when mentally fatigued. This is however the only study examining the effect of mental fatigue on muscle endurance performance and needs to be confirmed by other studies in the future. The importance of both the cognitive component and the submaximal, endurance intensity in the physical task also points towards the need for future research to be conducted in a more applied way (e.g. in prolonged endurance tasks/events). The demands of such real life prolonged endurance events are physically but also cognitively high, as is shown by the metacognitive framework of Brick et al. [57]. Therefore such real life endurance events are possibly able to accentuate even more the decrease in endurance performance due to mental fatigue. A recent investigation by Brick et al. [58] demonstrated this by comparing an RPE-clamped time trial and an externally-controlled pace time trial. Preceding the randomized completion of these two time trials participants completed two self-controlled pace time trials. Pacing strategy for the externally-controlled and RPE-clamped time trials was the same as for the subjects' fastest self-controlled pace time trial. It was concluded that external control over pacing (e.g. drafting in a race) may facilitate performance [58], possibly mediated through reducing the cognitive load and promoting appropriate attentional strategies that optimize performance. An applied study was recently performed in soccer. Badin et al. [59] assessed the effect of mental fatigue on physical and technical performance in small-sided soccer games. Physical performance (total distance covered tracked with a global positioning system) in this setting was however not a main objective, because a player could perform better (e.g. more successful passes) without covering more distance. Therefore, because covering as much distance as possible did not translate unequivocally to a better performance in a small-sided soccer game and because the researchers also did not instruct the participants to cover as much distance as possible during the game, there was no real physical performance measure included in this study and consequently the study was not included in the review. Nonetheless studies of this kind are extremely useful and necessary in order to expand our knowledge on the effect of mental fatigue on physical performance.

#### *4.2.2 Physiological*

Regarding the studies on endurance performance, Marcora et al. [10], Brownsberger et al. [12] and Smith et al. [21] observed respectively a higher HR and Bla at exhaustion, a higher mean HR in the RPE 11 exercise-bout and a higher $VO_2$ in the control trial compared to the mental fatigue trial. However all these findings can be explained by behavioral changes. In the study of Marcora et al. [10] the longer time-to-exhaustion explained the physiological differences between conditions. Brownsberger et al. [12] identified the higher self-selected power-outputs as an explanation for the higher mean HR and Smith et al. [21] emphasized the higher self-selected running velocities to account for the higher $VO_2$ in the control trial. Brownsberger et al. [12] also observed elevated β activity in the prefrontal brain lobe during a 3-min warm-up due to mental fatigue. This significant difference disappeared during the subsequent exercise bout. Pageaux et al. [20] demonstrated that mental fatigue was associated with a higher EMG root mean square of the vastus lateralis during cycling. This suggests an alteration in muscle fiber recruitment for the same power output and was previously reported by a self-regulation study [24]. In contrast to the above mentioned physiological differences between conditions, it was also observed that many physiological measures did not differ. Marcora et al. [10] did not observe any effect of mental fatigue on cardiovascular measures during exercise. Pageaux et al. [20] used a time- and intensity fixed protocol in order to observe the effect of mental fatigue on exercise induced  peripheral (twitch and doublet parameters and EMG measures) and central (voluntary activation level) fatigue. It could be concluded that mental fatigue did not accentuate peripheral fatigue as well as it did not increase exercise-induced central fatigue [20]. Overall, all included studies were rather unequivocal, mental fatigue does not reduce endurance performance by altering physiological, cardiorespiratory and neuromuscular responses to the subsequent exercise. These findings are confirmed by the line of research on the effect of mental fatigue on  maximal strength, power and anaerobic work. Studies by Pageaux et al. [17], Martin et al. [37] and Rozand et al. [60] did not observe any effect of mental fatigue on central fatigue. In contrast, Budini et al. [34] reported a decreased MVC and a decreased tremor amplitude during a 100% MVC after a mentally fatiguing task (100 min). Weakened cortico-muscular coupling (i.e. synchronized activity of the motor cortex and the spinal motoneuron pool) induced by mental fatigue is one possible explanation for this finding [34]. Yet they did not include a control group and as a consequence muscle relaxation cannot be excluded as another potential explanation for their findings. These results demonstrate that mental fatigue is able to alter endurance performance without altering any exercise-induced physiological parameter in the periphery and without any change in the cortico-muscular coupling. A side note to this conclusion has to be that, due to the findings of Pageaux et al. [20] and Budini et al. [34], further investigations on the effect of mental fatigue on muscle fiber recruitment are warranted.

### *4.2.3 Psychological*

Martin et al. [37] reported a trend for a decrease in intrinsic motivation towards the upcoming physical task when mentally fatigued. Moreover, Pageaux et al. [35] found that a 5-km time trial was perceived as more mentally demanding and participants also rated their performance on the time trial lower when mentally fatigued. The most consistent finding was however the higher ~~increased~~ RPE during exercise. Marcora et al. [10], Pageaux et al. [35, 20, 17] and Smith et al. [21, 31] all observed a higher RPE during exercise, Martin et al. [37] observed a trend towards a higher RPE and Brownsberger et al. [12] and MacMahon et al. [23] both showed a lower self-selected power output or running velocity for the same RPE. Therefore the current general opinion is that endurance performance is impaired by mental fatigue and this is predominantly mediated ~~through~~ by the higher-than-normal perceived exertion during exercise. Mental fatigue appears not to alter motivation towards the upcoming endurance task. In the study of Marcora et al. [10] this could have been due to a ceiling effect, created by the artificially increased motivation by offering monetary reward for best cycling performance, that masked the possible influence of mental fatigue on motivation. However, no other studies provided monetary incentives to increase engagement in the physical task and a ceiling effect was therefore less plausible in those studies. Encouragements and visual feedback during the physical task itself are other important factors that impact on motivation. These specific aspects differed between studies, with some [21, 20] giving no feedback nor encouragement, some giving feedback but no encouragements [31, 35, 12, 34] and others giving both feedback and standardized encouragements [17, 10, 37]. However, independently from giving feedback or encouragements, all studies reported no effect of mental fatigue on motivation towards the upcoming physical task. Mental fatigue not having an effect on motivation is possibly explained by the differing natures of both tasks following upon each other. Inzlicht et al. [61] proposed a motivational shift model to explain that engaging in self-regulation at time 1 leads to declines in performance at time 2. However, while this model accounts for many relevant findings in the field, crossing over the nature of the task (e.g. a cognitive task followed by a physical task) might counteract the motivational shift (away from 'have-to' goals and towards 'want-to' goals) often observed when tasks of a similar nature follow each other (e.g. cognitive task after cognitive task) [62]. Higher ~~Increased~~ perception of effort as the mediator of the negative effect of mental fatigue on physical performance also explains why mental fatigue does not impair maximal anaerobic tasks. The role of perception of effort in maximal anaerobic tasks is limited because of the all-out ~~pacing~~ strategy that is employed. All-out strategies typically require no pacing ~~less to no decision-making processes~~ and induce a faster build-up of peripheral fatigue (e.g. accumulation of metabolites).

4.3 How does mental fatigue increase perceived exertion during endurance performance?

Perceived exertion, also ~~understood~~ referred to as perception of effort, ~~is a major feature of fatigue and~~ can be defined as the conscious sensation of how hard, heavy, and strenuous a physical task is. ~~To date the discussion whether this feeling originates from afferent and/or efferent feedback is still ongoing. Marcora [63, 40] suggested that the sense of effort is centrally generated by forwarding neural signals (i.e. the corollary discharge model), termed corollary discharges or efference copies, from motor to sensory areas of the cerebral cortex (from structures located upstream to primary motor cortex [64], e.g. supplementary motor area [65] that has direct projections to the somatosensory cortex [66]). In contrast Nybo [67] referred to a study of Scott et al. [68] to state that perception of effort is also dependent on peripheral factors (e.g. delayed onset muscle soreness).~~ So far, three different theories have been suggested on which ~~sensory~~ neural signal(s) are processed by the brain to generate the perception of effort [40]: (i) the afferent feedback from the working muscles ~~(including the respiratory muscles)~~ and other peripheral physiological systems ~~interoceptors~~ (i.e. the afferent feedback model [69]); (ii) the corollary discharges (neural signals from premotor/motor areas to sensory areas of the brain) associated with the central motor command (i.e. the corollary discharge model) [63-66]; (iii) a combination of ~~both~~ afferent feedback and ~~the~~ corollary discharges ~~associated with the central motor command~~ (i.e. the combined model [70]). It should be noted that recent evidence provides support in favor of the corollary discharge model (for more details please see [71, 65, 72, 73]). Yet without wishing to extend this discussion ~~too~~ much further, it can be stated that perception of effort could possibly be increased by 1) increasing the intensity of afferent feedback from peripheral physiological systems ~~sensory signals~~, 2) increasing the intensity of central motor command (i.e. motor-related cortical activity) and thus its corollary discharges and 3) altering the processing of these neural signals in the brain (independently whether they originate from the periphery or from corollary discharges of the central motor command). The first option has been shown multiple times not to be influenced by mental fatigue, i.e. mental fatigue does not alter the physiological responses to exercise thought to provide afferent feedback to the brain ~~changes in the periphery related to endurance performance are not altered due to mental fatigue~~ (see section 4.2 Physiological). Regarding the second possibility, Pageaux et al. [20] demonstrated that mental fatigue was associated with a higher EMG root mean square of the vastus lateralis during cycling. This suggests that alterations in motor control may force mentally fatigued subjects to increase their central motor command and muscle recruitment ~~subsequently~~ (as shown by the increase in EMG ~~signal~~ amplitude) in order to produce the same power output even when central and peripheral fatigue are not exacerbated. This altered EMG amplitude ~~signal~~ due to mental fatigue has however to be confirmed by other studies. Furthermore, EEG should be used to directly test this hypothesis because central motor command can change even in the absence of changes in EMG amplitude [71]. The third option, an altered brain processing of the ~~feedback~~ neural signals underlying perception of effort (independently whether they originate from peripheral receptors or premotor/motor areas of the cortex ~~the periphery or the central motor command~~) ~~in the brain~~ appears to be a reasonable ~~the most reasonable~~ explanation. However, we are not aware of any study who has tested this hypothesis.~~. Obviously more research is required.~~

4.4 A potential role for brain neurotransmitters

The importance of brain neurotransmitters in endurance performance has already been underlined by Roelands et al. [74]. They showed that reboxetine (a noradrenaline re-uptake inhibitor) decreased whole-body endurance performance in normal and high ambient temperature. Interestingly, despite a decreased power output during the time trial in this study there was no change in absolute RPE values, consequently increasing the RPE to power output ratio (meaning less power output is generated for a same RPE value). The intake of methylphenidate [75] [a dopamine (DA) reuptake inhibitor] in contrast allowed subjects to maintain a higher power output and improve time trial performance in the heat, again without influencing absolute RPE values. This demonstrates that altered brain neurotransmission is able to affect whole-body endurance performance and that this effect is associated with an altered RPE to power output ratio (in the case of DA, a decreased ratio). Klass et al. [76] showed that muscle endurance performance is affected in a similar way. A noradrenaline reuptake inhibitor reduced endurance time by 15.6 %. This was associated with a greater rate of supraspinal impairment and increase in RPE. Participants experienced the same intensity of intermittent contractions as harder to perform after administration of a noradrenaline reuptake inhibitor, without affecting the fatigue-related intramuscular impairments [76]. Pageaux et al. [35, 20, 17] stated that neural activity increases the extracellular concentration of adenosine (an inhibitory neurotransmitter; [77]) and that brain adenosine accumulation reduces endurance performance [78]. Subsequently they speculated that adenosine accumulation in the pre-supplementary motor area and anterior cingulate cortex (due to a mentally fatiguing task) could also explain in part the higher than normal perceived exertion during an endurance exercise in a mentally fatigued state. However, there is to date no study that demonstrates that mentally fatigued individuals have increased adenosine in specific areas. Moreover, other possible neurotransmitters that could mediate the effect of mental fatigue must not be overlooked. Hopstaken et al. [13] monitored certain psychophysiological markers of locus coeruleus activity during a mentally fatiguing task and reported that these markers (P3 and pupil diameter) were affected by the time-on-task manipulation. Consequently this indicates that the locus coeruleus (i.e. a nucleus in the brainstem responsible for the release of cortical noradrenaline) is also a possible mediator of the effects of mental fatigue [13]. Moeller et al. [79] investigated the role of DA in mental fatigue and concluded that also the dopaminergic midbrain is involved in sustaining motivation during fatigue. Research on neurological disorders and the often associated feelings of fatigue, also points towards an important role for the midbrain and other subcortical regions [80]. The above points out that most probably it will not be one particular neurotransmitter that mediates the negative effect of mental fatigue on endurance performance. Rather mental fatigue will affect neurotransmitter systems in multiple brain regions and the summation of these alterations might explain (in part) the impairment in endurance performance.

### 4.5 Future directions

Evidence from fields other than physical performance has already demonstrated that manipulation of neurotransmitter systems could reduce the negative effects of mental fatigue [79, 81]. Moeller et al. [79] used methylphenidate (i.e. a DA reuptake inhibitor) in order to manipulate the concentration of DA in the brain and assess what effect this had on the development of mental fatigue during a cognitive performance task. Similar interventions could be employed to assess the role of the above mentioned neurotransmitters in the mental fatigue/physical performance interaction. Almost 20 years ago, Caldwell et al. [81] reported that administration of dextroamphetamine (i.e. an indirect dopamine agonist) improved flight performance during the final 23 hours of a 40-hour period of continuous wakefulness. Similar studies investigating the effect of mental fatigue on physical performance could enlarge our knowledge of the role of different neurotransmitters in this interaction. Simultaneously more applied areas need further investigation as well. The cognitive tasks used to induce mental fatigue in the reviewed studies do not entirely resemble tasks (e.g. interviews, emotion control, and tactical meetings) that would regularly occur prior to competition. The mental fatigue induced by the cognitive demands of the competition itself should also be investigated. ~~Therefore future research should assess whether commonly occurring cognitive tasks have a similar impact to those used in the reviewed studies. Additionally~~ Finally, the impact of mental fatigue ~~cognitively demanding activity on physical performance~~ should be assessed on endurance performance of longer duration (e.g. marathon) and in high-level athletes, as it is likely that they may have superior ability to maintain performance [82].

## 5 Conclusion

Mental fatigue is a psychobiological state caused by prolonged periods of demanding cognitive activity and is characterized by a combination of specific subjective, behavioral and physiological manifestations. Recent research has observed the effect of mental fatigue on physical performance. The current systematic review aimed at unravelling whether mental fatigue impairs physical performance and sought to create an overview of the potential factors underlying this effect.

Eleven ~~11~~ articles on the topic were selected and the main outcome was a decline in endurance performance (decreased time-to-exhaustion and self-selected power output/velocity or increased completion time) due to mental fatigue, associated with a higher than normal perceived exertion. Physiological variables traditionally associated with endurance performance ~~Traditional physiological outcomes in the periphery~~ (heart rate, blood lactate, oxygen uptake, cardiac output, $VO_2$) ~~and motor function during and after endurance performance~~ were not directly affected by mental fatigue during and after endurance performance. Maximal strength, power and anaerobic work were ~~also observed~~ not ~~to be~~ affected by mental fatigue. This led to the conclusion that duration and intensity of the physical task appear to be important factors in the decrease in physical performance due to mental fatigue. ~~Mental fatigue does negatively affect endurance performance but not maximal anaerobic work. Most plausibly mental fatigue affects central processing of the sensory inputs generating perception of effort during exercise.~~

Practically these findings suggest that a higher-than-normal perception of effort ~~during (endurance) exercise~~ and reduced endurance performance are respectively a psychological and behavioral marker~~s~~ of mental fatigue. In addition, ~~preceding a physical endurance performance,~~ engagement in mentally demanding tasks before competitions requiring endurance ~~(e.g. interviews)~~ should be avoided in order to optimize performance. Moreover ~~during endurance events~~, the high cognitive demands of sport ~~prolonged performance in itself is~~ are most probably mentally fatiguing when prolonged over time. This opens new opportunities to improve endurance performance by ~~develop new or optimize already existing (e.g. drafting) techniques in order to~~ minimizing as much as possible the cognitive load during competitions and/or by increasing resistance to the negative ~~negative~~ effects of mental fatigue on perception of effort and endurance performance.

~~Future studies should use appropriate paradigms (e.g. indirect method) to induce mental fatigue and take into account the relative contributions of adaptation and motivation parameters on time-on-task effects. A worthwhile focus for future research would be to explore the role of the cognitive component and the intensity/duration of the endurance task in the effect of mental fatigue on endurance performance. Also if and how mental fatigue alters central processing of sensory inputs is a question that should be addressed in future studies.~~

## Compliance with Ethical Standards

Jeroen Van Cutsem, Samuele Marcora, Kevin De Pauw, Stephen Bailey, Romain Meeusen and Bart Roelands declare that the systematic review complies with all ethical standards.

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## Conflicts of Interest

Jeroen Van Cutsem, Samuele Marcora, Kevin De Pauw, Stephen Bailey, Romain Meeusen and Bart Roelands declare that they have no conflicts of interest relevant to the content of this review.

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**Table 1** PICOS (Participants, Interventions, Comparisons, Outcomes, Study design)

| PICOS component | Detail |
|---|---|
| *Participants (P)* | Humans, healthy |
| *Interventions (I)* | Inducing mental fatigue with a cognitive task of 30min or longer |
| *Comparisons (C)* | Non or less mentally fatigued individuals |
| *Outcomes (O)* | Physical performance, physiological and perceptual strain |
| *Study designs (S)* | RCTs, nRCTs and nRnCTs |

*Randomized Controlled Trial (RCT), non-Randomized Controlled Trial (nRCT), non-Randomized non-Controlled Trial (nRnCT)*

Table 2



**Table 2** Number of hits on keywords and combined key words in both search engines (PubMed & Web of Science)

| | PubMed | | Web of Science | |
|---|---|---|---|---|
| **Key words** | **Hits (28/04/16)** | **Selected articles** | **Hits (28/04/16)** | **Selected articles** |
| (1) Mental fatigue (MeSH) OR mental fatigue OR mental exertion OR cognitive fatigue OR self-control strength depletion OR ego depletion | 10 409 | / | 29 013 | / |
| (2) Athletic performance (MeSH) OR physical performance OR performance | 741 110 | / | 4 132 391 | / |
| (3) Muscle fatigue (MeSH) OR central fatigue OR peripheral fatigue | 13 036 | / | 68 089 | / |
| (4) Physical exercise | 317 864 | / | 401 479 | / |
| **Combined key words** | **Hits (28/04/16)** | **Selected articles** | **Hits (28/04/16)** | **Selected articles** |
| (1) AND (2) | 2 159 | / | 6 095 | / |
| (1) AND (3) | 978 | / | 5 235 | / |
| (1) AND (4) | 1 378 | / | 1 781 | / |
| * (1) AND (2) AND (3) AND (4) | 91 | 3 | 190 | 2 |

* Combined keywords were included in the screening process.

**Table 3** Quality assessment 'Qualsyst' [33]

| Study | A | B | C | D | E | F | G | H | I | J | K | L | M | N | **Rating** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Marcora et al. [10] | 2 | 2 | 2 | 2 | N/A | 0 | 1 | 2 | 2 | 2 | 2 | 0 | 2 | 2 | **Strong** |
| Pageaux et al. [17] | 2 | 2 | 2 | 2 | N/A | 2 | 1 | 2 | 1 | 2 | 2 | 0 | 2 | 1 | **Strong** |
| Brownsberger et al. [12] | 2 | 2 | 2 | 2 | N/A | 0 | 1 | 2 | 1 | 2 | 2 | 0 | 2 | 1 | **Moderate** |
| Pageaux et al. [35] | 2 | 2 | 2 | 2 | N/A | 0 | 1 | 2 | 1 | 2 | 2 | 0 | 2 | 2 | **Strong** |
| MacMahon et al. [23] | 1 | 2 | 2 | 1 | N/A | 0 | 1 | 2 | 2 | 1 | 2 | 0 | 2 | 2 | **Moderate** |
| Budini et al. [34] | 2 | 1 | 1 | 1 | N/A | N/A | N/A | 2 | 1 | 1 | 1 | 0 | 2 | 1 | **Moderate** |
| Martin et al. [37] | 2 | 2 | 2 | 2 | N/A | 0 | 1 | 2 | 1 | 2 | 2 | 0 | 2 | 2 | **Strong** |
| Smith et al. [21] | 2 | 2 | 2 | 2 | N/A | 0 | 1 | 2 | 1 | 1 | 2 | 0 | 2 | 2 | **Moderate** |
| Duncan et al. [36] | 2 | 2 | 2 | 2 | N/A | 0 | 0 | 2 | 1 | 2 | 2 | 0 | 2 | 2 | **Moderate** |
| Pageaux et al. [20] | 2 | 2 | 2 | 2 | N/A | 0 | 1 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | **Strong** |
| Smith et al. [31] | 2 | 2 | 2 | 2 | N/A | 2 | 1 | 2 | 1 | 2 | 2 | 0 | 2 | 2 | **Strong** |

A=Question described?, B=Appropriate study design?, C=Appropriate subject selection?, D=Characteristics described?, E=Random allocation?, F=Researchers blinded?, G=Subjects blinded?, H=Outcome measures well defined and robust to bias?, I=Sample size appropriate?, J=Analytic methods well described?, K=Estimate of variance reported?, L=controlled for confounding?, M=Results reported in detail?, N=Conclusion supported by results?

2 = yes, 1 = partial, 0 = no, N/A = Not Applicable

Strong = ≥75%, Moderate = 55% ≥ 75%, Weak = ≤55%

**Table 4** Overview of mental fatigue inducing interventions: Task characteristics and outcome measures

| Study | Sample | Intervention (I) | Control (C) | Duration | Monetary incentive | Methodological characteristics | Outcome | Remarks |
|---|---|---|---|---|---|---|---|---|
| Marcora et al. [10] | 10 M 6 F | AX-CPT | Watching a documentary | 90 min | £50 best performance on AX-CPT<br><br>£50 best cycling performance | RCT, crossover | MF ↑ after I compared to C (assessed using BRUMS), associated with a decline in cognitive performance (less correct responses to AX trials)<br><br>HR ↑ during I compared to C | |
| Pageaux et al. [17] | 10 M | AX-CPT | Watching a documentary | 90 min | Ticket for a professional sporting event | RCT, crossover | MF ↑ after I compared to C (assessed using BRUMS)<br><br>HR ↑ during I compared to C | No decline over time in ACC or RT on AX-CPT |
| Brownsberger et al. [12] | 8 M 4 F | AX-CPT | Watching a documentary | 90 min | $100 for the most vigilant participant during AX-CPT | RCT, crossover | MF ↑ after I compared to C (assessed using VAS)<br><br>Increased β-band activity of the prefrontal lobe in the middle and after I, compared to C (assessed using EEG) | |
| Budini et al. [34] | 12 M | Switch task paradigm | - | 100 min | - | nRnCT | RT ↑ in time | |
| Pageaux et al. [35] | 8 M 4 F | 100% incongruent modified Stroop colour-word task | 100% congruent Stroop colour-word task | 30 min | A £10 Amazon voucher for overall highest score on Stroop | RCT, crossover | MF = after I compared to C (assessed using BRUMS)<br><br>Higher mental demand and effort in I compared to C (assessed using NASA-TLX)<br><br>HR ↑ during I compared to C | Despite no overt mental fatigue, the I was perceived as more mentally demanding<br><br>Modified Stroop = words presented in red ink react on the real meaning of the word, all other words react on the colour of the word |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| MacMahon et al. [23] | 18 M 2 F | AX-CPT | Watching a documentary + 3min AX-CPT before and after | 90 min | 50€ for best performance on AX-CPT | RCT, crossover | MF ↑ after I compared to C (assessed using CMSS)<br><br>Lower positive mood after I compared to C (assessed using CMSS)<br><br>HR ↑ during I compared to C | |
| Martin et al. [37] | 7 M 5 F | AX-CPT | Watching a documentary | 90 min | $50 for best five performances on AX-CPT | RCT, crossover | MF = after I compared to C (assessed using POMS)<br><br>A greater cognitive effort during I compared to C (assessed using RSME) | |
| Smith et al. [21] | 10 M | AX-CPT | Watching a documentary | 90 min | $50 for the best performance on AX-CPT | RCT, crossover | MF ↑ after I compared to C (assessed using BRUMS)<br><br>Increased incorrect responses on the AX-CPT in time (assessed using AX-CPT)<br><br>HR ↑ during I compared to C | |
| Duncan et al. [36] | 7 M 1 F | Completing concentration grids | Watching a documentary | 40 min | - | RCT, crossover | - | |
| Pageaux et al. [20] | 12 M | 100% incongruent modified Stroop colour-word task | 100% congruent Stroop colour-word task | 30 min | - | RCT, crossover | MF = after I compared to C (assessed using BRUMS)<br><br>Higher mental and temporal demand and effort in I compared to C (assessed using NASA-TLX)<br><br>HR ↑ during I compared to C | Results suggest presence of mental fatigue after both CT |
| Smith et al. [31] | 12 M | 100% incongruent modified Stroop colour-word task | Reading magazines | 30 min | - | RCT, crossover | MF ↑ after I compared to C (assessed using VAS) | |

- Not applicable, *AX-CPT* AX-continuous performance test, *ACC* accuracy, *BRUMS* The Brunel Mood Scale, *C* control, *CMSS* Current Mood State Scale, *CT* cognitive task, *EEG* electroencephalography, *F* female, *HR* heart rate, *I* intervention, *M* male, *MF* mental fatigue or self-reported fatigue or fatigue or general fatigue or subjective fatigue, *NASA-TLX* National

Aeronautics and Space Administration Task Load Index, *nRnCT* non-randomized non-controlled trial, *POMS* Profile Of Mood States, *RCT* randomized controlled trial, *RPE* rating of perceived exertion, *RSME* rating scale of mental effort, *RT* reaction time, *VAS* visual analog scale (perceived level of fatigue)

Table 5 

**Table 5** Overview of the effects of mental fatigue on endurance performance: Subjective, behavioral and physiological measures before, during and/or after the physical task

| Study | Sample | Characteristics | MF ↑ compared to C | Motivation to exercise | Physical task | Time of physical task | Outcome | Remarks |
|---|---|---|---|---|---|---|---|---|
| ***Whole-body endurance*** | | | | | | | | |
| Marcora et al. [10] | 10 M 6 F | Trained, healthy<br><br>A = 26 ± 3 y<br><br>Mass = 69 ± 10 kg<br><br>Wmax = 288 ± 70 W<br><br>$VO_2$max = 52 ± 8 ml/kg.min | Yes | No difference in intrinsic and success motivation between conditions (assessed using scale by Matthews et al. [42]) | Cycling time to exhaustion at 80% of Wmax | Post CT | Time-to-exhaustion ↓ in I compared to C<br><br>RPE ↑ during exercise in I compared to C<br><br>HR and Bla ↑ at exhaustion in C compared to I | Time-to-exhaustion in C = 754 ± 339 s |
| Brownsberger et al. [12] | 8 M 4 F | Trained, healthy<br><br>A = 24 ± 5 y<br><br>Mass = 71 ± 15 kg<br><br>$VO_2$max = 56 ± 6 ml/kg.min | Yes | No difference in motivation between conditions (assessed using VAS) | 2 consecutive self-paced 10 min bouts of cycling exercise. One representative for RPE 11 (fairly light) and one for RPE 15 (hard) | Post CT | Self-selected power outputs ↓ in I compared to C for both RPE 11 and RPE 15 exercise bouts<br><br>HR ↑ in C compared to I for the RPE 11 bout (4.3%)<br><br>β-band activity ↑ during warm-up in I compared to C | |
| Pageaux et al. [35] | 8 M 4 F | Trained, healthy<br><br>A = 21 ± 1 y<br><br>Mass = 69 ± 11 kg<br><br>Aerobic activities 2x/week in the previous 6 months | No<br><br>(more mentally exerted after I compared to C) | No difference in intrinsic and success motivation between conditions (assessed using motivation scale by Matthews et al. [42]) | Run 5 km in the quickest time possible | Post CT | Performance ↓ in I compared to C<br><br>No difference in pacing strategy between conditions<br><br>RPE ↑ during exercise in I compared to C<br><br>TT-performance was perceived lower and more mentally demanding in I compared to C | TT performed on a treadmill in a lab setting |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| MacMahon et al. [23] | 18 M 2 F | Trained (familiarized with a 3 km run)<br><br>A = 25 ± 3 y<br>Running on average 2.84 ± 1.79 hr/week | Yes | No difference in motivation between conditions (assessed using a 7 point Likert scale)<br><br>Greater decrease in positive mood when mentally fatigued compared to control (assessed using CMSS) | Run 3 km in the quickest time possible | Post CT | Performance ↓ in I compared to C<br><br>RPE = during exercise in I compared to C<br><br>No difference in attentional focus before and during exercise between conditions | TT performed on an indoor track<br><br>Focus of attention was assessed using a 10 point bipolar scale |
| Smith et al. [21] | 10 M | Healthy, competitive intermittent team sporters (for a minimum of 3 y)<br><br>A = 22 ± 2 y<br><br>Mass = 75 ± 6 kg<br><br>$VO_2max$ = 48 ± 6 ml/kg.min | Yes | No difference in intrinsic and success motivation between conditions (assessed using motivation scale by Matthews et al. [42]) | 45 min self-paced intermittent high-intensity running protocol, with LIA and HIA | Post CT | Overall and LIA velocity ↓ and total and LIA distance ↓ in I compared to C<br><br>HIA and peak velocity = and HIA distance = between conditions<br><br>Work performed at any intensity did not differ between conditions<br><br>RPE = between conditions during running protocol<br><br>RPE ↑ 30 min after running protocol | Running protocol was based on time motion analysis data from multiple team sports, six activities were included:<br>LIA (stand, walk, jog and run)<br>HIA (fast run and sprint) |
| Martin et al. [37] | 7 M 5 F | Trained, healthy<br><br>A = 23 ± 3 y<br><br>$VO_2max$ = 53 ± 13 l/min | No | Intrinsic motivation tended to be reduced postCT in MF-condition compared to C (assessed using SIMS) | 3MT | Pre and post CT<br><br>3MT, only post CT | No difference in anaerobic work capacity or power (3MT) between conditions<br><br>No difference in CMJ (explosive power) or MVC between conditions<br><br>RPE tended to ↑ during 3MT in I compared to C | |
| Pageaux et al. [20] | 12 M | Healthy active<br><br>A = 25 ± 4 y | No | Motivation was not assessed | 6 min cycling at 80% of Wmax | Cycling task post CT | No difference in MVC between both conditions | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Mass = 77 ± 11 kg<br><br>Moderate/high intensity exercise 2x/week in the previous 6 months | | | | MVC pre and post CT and post cycling task | RPE ↑ during cycling in I compared to C<br><br>No effect of mental fatigue on central or peripheral fatigue | |
| Smith et al. [31] | 12 M | Moderately-trained soccer players | Yes | No difference in motivation between conditions (assessed using VAS) | Yo-Yo IR1 | Post CT | Distance covered ↓ in I compared to C<br><br>RPE ↑ during exercise in I compared to C<br><br>No difference in HR between conditions | Distance covered in C = 1410 ± 354 m |
| ***Muscle endurance*** | | | | | | | | |
| Pageaux et al. [17] | 10 M | Active<br><br>A = 22 ± 2 y<br><br>Mass = 70 ± 8 kg | Yes | No difference in intrinsic and success motivation (assessed using scale by Matthews et al. [42]) | To maintain 20% MVC of the knee extensor muscles until exhaustion | Post CT | Time-to-exhaustion ↓ in I compared to C<br><br>Leg RPE ↑ during the exhaustion-task in I compared to C<br><br>No difference in EMG activity between conditions | Time-to-exhaustion in C = 266 ± 26 s |

*3MT* 3min all-out cycling test, *A* age, *BRUMS* The Brunel Mood Scale, *Bla* blood lactate, *C* control, *CMSS* Current Mood State Scale, *CT* cognitive task, *EMG* electromyography, *F* female, *HIA* high-intensity activity, *HR* heart rate, *I* intervention, *kg* kilogram, *km* kilometers, *LIA* low-intensity activity, *M* male, *m* meter, *MF* mental fatigue, *min* minutes, *ml* millimeter, *MVC* maximal voluntary contraction, *RPE* ratings of perceived exertion, *s* seconds, *SIMS* Situational Itrinsic Motivation Scale, *TT* time trial, *VAS* Visual Analog Scale, *$VO_2max$* maximal aerobic capacity, *W* watt, *Wmax* maximal wattage, *Y* years, *Yo-Yo IR1* Yo-Yo intermittent recovery test, level 1

Table 6 

**Table 6** Overview of the effects of mental fatigue on maximal strength - power - anaerobic work: Subjective, behavioral and physiological measures before, during and/or after the physical task

| Study | Sample | Characteristics | MF ↑ compared to C? | Motivation to exercise | Physical task | Time of physical task | Outcome | Remarks |
|---|---|---|---|---|---|---|---|---|
| Pageaux et al. [17] | 10 M | Active<br><br>A = 22 ± 2 y<br><br>Mass = 70 ± 8 kg | Yes | Motivation was not assessed | MVC (duration of ~5 s) with superimposed supramaximal paired stimuli (doublet) at 100 Hz and followed (4 s intervals) by paired stimuli at 100 Hz, (ii) 60 s rest and (iii) three single supramaximal stimulations at rest (interspaced by 3 s). | Pre and post CT and post cycling task | MF no effect on MVC<br><br>MF no effect on neuromuscular function | |
| Budini et al. [34] | 12 M | Healthy<br><br>A = 29 ± 4 y | - | Motivation was not assessed | Two submaximal 20 s contractions of the knee extensor muscles at 30% MVC using a long and short spring<br><br>Three 3 s MVCs of the knee extensor muscles | Pre and post CT | MVC ↓ when mentally fatigued (-6.9%)<br><br>EMG activity ↓ within the 8-12 Hz frequency band when mentally fatigued | Short spring induces 8-12 Hz = stretch reflex peripheral component<br><br>Long spring induces 3-6 Hz = stretch reflex central component |
| Martin et al. [37] | 7 M 5 F | Trained, healthy<br><br>A = 23 ± 3 y<br><br>$VO_2max$ = 53 ± 13 l/min | No | Intrinsic motivation tended to be reduced postCT in MF-condition compared to C (assessed using SIMS) | Three CMJ<br><br>Three MVCs of the knee extensor muscles | Pre and post CT | No difference in CMJ (explosive power) or MVC between conditions | |
| Duncan et al. [36] | 7 M 1 F | Trained, healthy (University level, team games) | ? | Motivation was not assessed | Four 30 s Wingates (separated by 4 min rest) | Post CT | No difference in mean cycling power between conditions | No manipulation checks included |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | No difference in RPE between conditions<br><br>No difference in HR or Bla between conditions |
| Pageaux et al. [20] | 12 M | Healthy active<br><br>A = 25 ± 4 y<br><br>Mass = 77 ± 11 kg | No | Motivation was not assessed | MVC (duration of ~4 s) with superimposed supramaximal paired stimuli (doublet) at 100 Hz and followed (4 s intervals) by paired stimuli at 100 Hz, (ii) 60 s rest and (iii) three single supramaximal stimulations at rest (interspaced by 3 s). | Pre and post CT and post cycling task | No difference in MVC between both conditions<br><br>RPE ↑ during cycling in I compared to C<br><br>No effect of mental fatigue on central or peripheral fatigue |

- not applicable, *A* age, *Bla* Blood lactate, C control, *CMJ* countermovement jump, *CT* cognitive task, *F* female, *EMG* Electromyography, *min* minutes, *HR* heart rate, *Hz* hertz, *I* intervention, *kg* kilogram, *M* male, *MF* mental fatigue or self-reported fatigue or fatigue or general fatigue or subjective fatigue, *MVC* maximal voluntary contraction, *PT* physical task, *RPE* rating of perceived exertion, *s* seconds, *SIMS* Situational Intrinsic Motivation Scale, *Y* years

Figure 1

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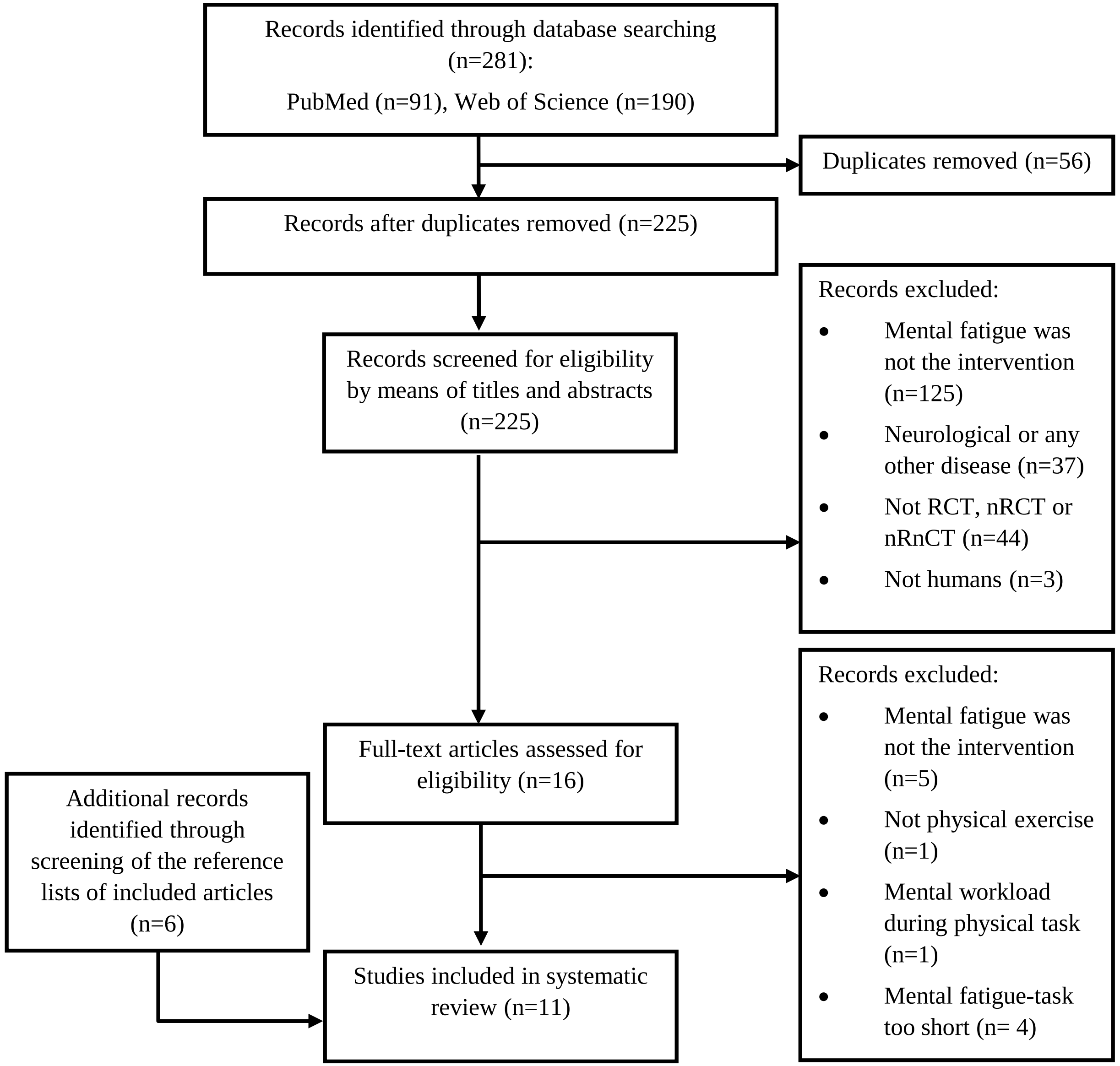
**Fig. 1** PRISMA flowchart describing the process of obtaining the research articles (n=11) included in this systematic review [32]



14 December 2016 Journal and article name - Sports Medicine

"The effects of mental fatigue on physical performance: a systematic review."

We the undersigned authors confirm that we agree to the addition of Stephen Bailey (to be listed as author 4) to the list of author names on the above-mentioned article.

Signed

Author 1 – Jeroen Van Cutsem

Author 2 – Samuele Marcora

Author 3 – Kevin De Pauw

Stephen Bailey

Author 4 – Stephen Bailey

Author 5 – Romain Meeusen

Author 6 – Bart Roelands

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