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SYSTEMATIC REVIEW

The Effects of Mental Fatigue on Physical Performance: A Systematic Review

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Abstract

Background Mental fatigue is a psychobiological state caused by prolonged periods of demanding cognitive activity. It has recently been suggested that mental fatigue can affect physical performance.

Objective Our objective was to evaluate the literature on impairment of physical performance due to mental fatigue and to create an overview of the potential factors underlying this effect.

Methods Two electronic databases, PubMed and Web of Science (until 28 April 2016), were searched for studies designed to test whether mental fatigue influenced performance of 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 A total of 11 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) associated with a higher than normal perceived exertion. Physiological variables traditionally associated with endurance performance (heart rate, blood lactate, oxygen uptake, cardiac output, maximal aerobic capacity) were unaffected by mental fatigue. Maximal strength, power, and anaerobic work were not affected by mental fatigue.

Conclusion The 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.

Key Points

Mental fatigue impairs endurance performance, whereas 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.

1 Introduction

Mental fatigue represents a psychobiological state caused by prolonged periods of demanding cognitive activity [1, 2] and has implications for many aspects of daily life. In the

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workplace, mental fatigue has been found to predict an increased risk of error [3]; it is also one of the most common symptoms experienced by individuals with neurological disorders [4]. Mental fatigue can manifest subjectively, behaviorally, and physiologically. Subjectively, increased feelings of tiredness, lack of energy [5], and decreased 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 [8, 11–13] 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 [9, 13]. 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 verbal 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 (more than two legs; e.g., running, cycling, and rowing) [16]. Their results [10] demonstrated 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], who showed that a submaximal isometric knee extensor exercise until exhaustion was impaired by mental fatigue.

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 is distinguished from endurance performance. High-intensity anaerobically based exercise is often characterized by an all-out strategy (i.e., the athlete works maximally from the start of the event and rapidly fatigues 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) 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) than endurance performance because of the all-out strategy (i.e., less pace regulating) and the inherent shorter duration of these kinds of performances.

The aim of the present paper was 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' is used [10, 12, 20, 21]. However, some haziness exists in regard to its terminology. Some authors, such as Ackerman and Kanfer [22] and MacMahon et al. [23], have 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 and colleagues [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 [26, 27]. This description also applies to tasks often used to induce mental fatigue, and certain commonalities can be observed between both constructs. Consequently, studies using self-regulatory depletion tasks that meet the eligibility criteria (duration ≥30 min) are also included in the present review. However, studies using shorter self-regulatory depletion tasks (often referred as 'ego depletion') are not included. We also stress that this review does not include dual-task performance studies. The focus of the current review is the influence of a preceding mentally fatiguing task on subsequent physical performance to adequately assess whether and how performance is affected by mental fatigue.

2 Methods

2.1 Eligibility Criteria

We used PICOS (Population, Intervention, Comparison, Outcome, and Study design) criteria as the inclusion criteria for this review (see Table 1 [28]). Randomized

Table 1 PICOS (participants, interventions, comparisons, outcomes, study design)

PICOS component	Detail
Participants	Humans, healthy
Interventions	Inducing mental fatigue with a cognitive task of ≥30 min
Comparisons	Non-fatigued or less mentally fatigued individuals
Outcomes	Physical performance, physiological and perceptual strain
Study designs	RCTs, nRCTs, and nRnCTs

nRCT non-randomized controlled trial, *nRnCT* non-randomized non-controlled trial, *RCT* randomized controlled trial

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 (or observe, in 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 than 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 stated 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.

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 for a qualitative literature search. The following keywords 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.

2.3 Study Selection and Data-Collection Process

Inclusion or exclusion of articles was decided with application of the PICOS criteria (see Table 1) to the title, abstract, and/or full text of articles. Titles and abstracts were screened first, then full-text articles were retrieved if the citation was considered potentially eligible and relevant. The data-collection process is presented in Fig. 1 [32].

2.4 Quality Assessment

The methodological quality was assessed using the quantitative assessment tool 'QualSyst' by Kmet et al. [33]. QualSyst contains 14 items (see Table 3) that are 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 'NA' and 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 (JVC and BR) independently performed quality assessments, and disagreements were solved by consensus or by a third reviewer (KDP). A score of ≥75% indicated strong quality, a score of 55–75% indicated moderate quality, and a score ≤55% indicated weak quality.

3 Results

3.1 Study Selection

Our search resulted in 281 hits, of which 16 remained after duplicates were excluded and titles and abstracts were screened (Fig. 1). Five articles were eventually included; screening of their reference lists resulted in the inclusion of six additional articles for a total of 11 selected articles. Quality assessment of these 11 selected articles determined that six articles were of strong quality and five articles were of moderate quality (see Table 3).

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 an nRnCT. Mental fatigue was induced by a prolonged

Table 2 Number of hits on keywords and combined keywords in PubMed and Web of Science

Keywords	PubMed		Web of Science	
	Hits (28 April 2016)	Selected articles	Hits (28 April 2016)	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	NA	29,013	NA
(2) Athletic performance (MeSH) OR physical performance OR performance	741,110	NA	4,132,391	NA
(3) Muscle fatigue (MeSH) OR central fatigue OR peripheral fatigue	13,036	NA	68,089	NA
(4) Physical exercise	317,864	NA	401,479	NA
Combined keywords				
(1) AND (2)	2159	NA	6095	NA
(1) AND (3)	978	NA	5235	NA
(1) AND (4)	1378	NA	1781	NA
(1) AND (2) AND (3) AND (4)[a]	91	3	190	2

[a] Combined keywords were included in the screening process

demanding cognitive task, but this task varied between studies: Pageaux and colleagues [20, 35] and Smith et al. [31] used a 30-min modified version of the Stroop color–word task; Duncan et al. [36] required participants to complete concentration grids for 40 min; Budini et al. [34] employed a 100-min switch task paradigm; and the other six studies [10, 12, 17, 21, 23, 37] 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 [10, 12, 17, 21, 23, 31, 36, 37], used a time-matched emotionally neutral documentary or reading a magazine as a control task. Pageaux and colleagues [20, 35] used a less mentally fatiguing (congruent, non-response inhibition) Stroop task, as evidenced by the faster RT and the lower rated mental demand and effort. To motivate participants and increase engagement during the cognitive tasks, seven of the 11 studies gave some sort of monetary reward for the best performance in terms of RT and accuracy. However, the most recent studies did not provide any incentives [20, 31, 36]. Six [10, 12, 17, 21, 23, 31] studies reported greater subjective mental fatigue after the intervention than after the control task. In the studies by 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 (VAS) 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. Of the five studies that observed no difference in perceived fatigue due to the cognitive task, two did not assess subjective fatigue [34, 36], two [20, 35] 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 of the six studies [10, 12, 17, 21, 23, 31] that observed greater subjective fatigue after the intervention than after the control task also observed a higher mean heart rate (HR) during the intervention [10, 17, 21, 23]. In two studies [10, 21], the greater subjective fatigue was also associated with a decline in accuracy. An increase in RT 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 with the control task. An overview of the mental fatigue-inducing interventions can be found in Table 4.

3.3 Endurance

3.3.1 *Whole-Body Endurance*

3.3.1.1 Behavioral Homogenous subject groups were recruited in each study, allowing for comparisons between studies. The participants were healthy, young (aged 21–26 years), and moderately trained (maximal aerobic capacity [VO_2]: 48–56 ml/kg^{-1}/min^{-1}; performance level 2 according to De Pauw et al. [38]; see Table 5). However, the experimental protocols differed, and consequently so did 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). On the other hand, Pageaux et al. [35] and

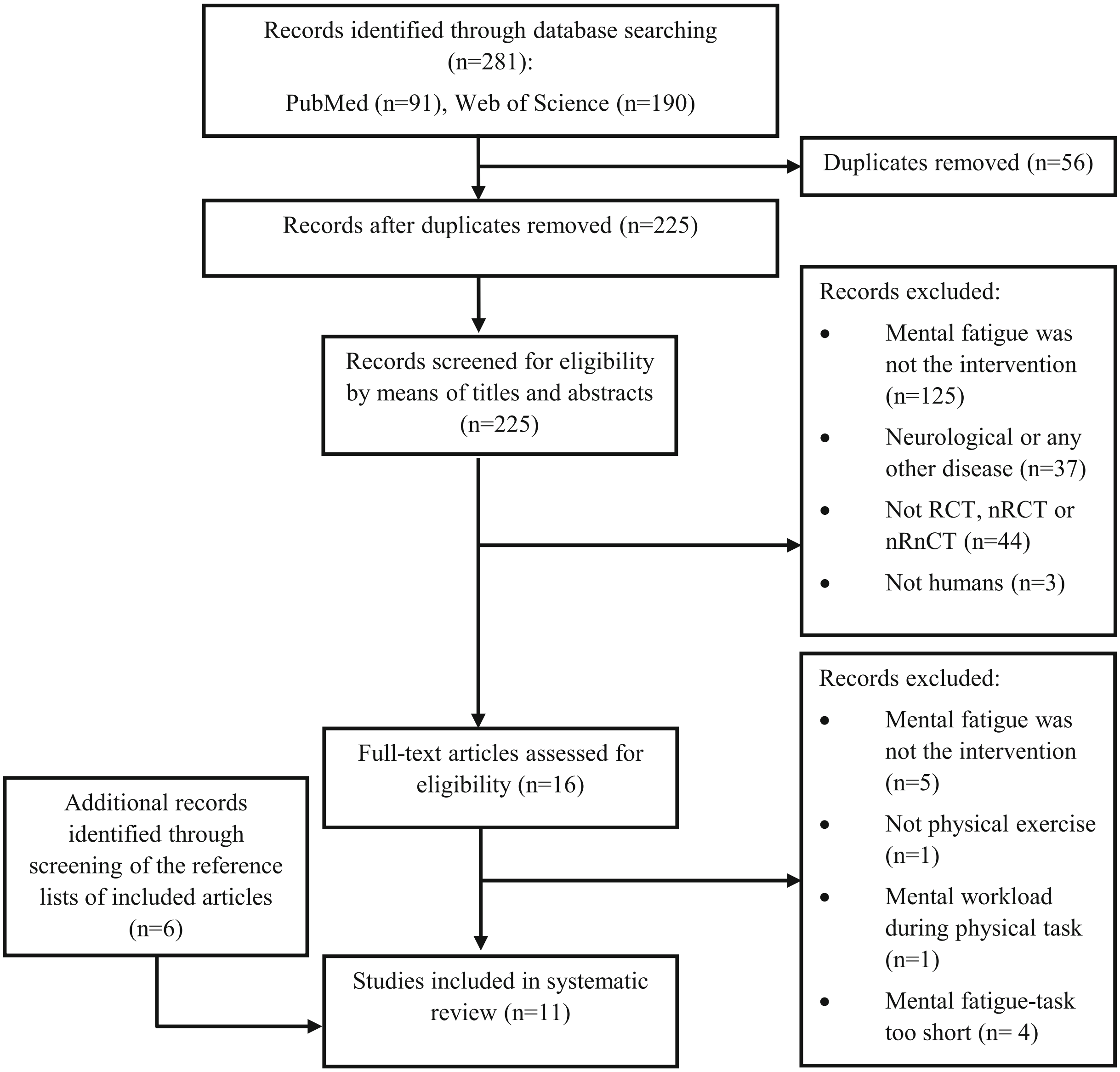

Fig. 1 Selection process for research articles ($n = 11$) included in this systematic review. Adapted version of the recommendations in the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement [32]. *nRCT* non-randomized controlled trial, *nRnCT* non-randomized non-controlled trial, *RCT* randomized controlled trial

MacMahon et al. [23] 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 [23] running distance. Moreover, whereas Pageaux et al. [35] completed their study in a laboratory setting, MacMahon et al. [23] showed that this negative effect of mental fatigue was 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 two 20-m runs (up and back) at progressively increasing velocities until one twice failed to complete the two distances of 20 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

Table 3 Quality assessment 'Qualsyst' [33]

Study	Question described	Appropriate study design	Appropriate subject selection	Characteristics described	Random allocation	Researchers blinded	Subjects blinded	Outcome measures well defined and robust to bias	Sample size appropriate	Analytic methods well described	Estimate of variance reported	Controlled for confounding	Results reported in detail	Conclusion supported by results?	Rating
Marcora et al. [10]	2	2	2	2	NA	0	1	2	2	2	2	0	2	2	Strong
Pageaux et al. [17]	2	2	2	2	NA	2	1	2	1	2	2	0	2	1	Strong
Brownsberger et al. [12]	2	2	2	2	NA	0	1	2	1	2	2	0	2	1	Moderate
Pageaux et al. [35]	2	2	2	2	NA	0	1	2	1	2	2	0	2	2	Strong
MacMahon et al. [23]	1	2	2	1	NA	0	1	2	2	1	2	0	2	2	Moderate
Budini et al. [34]	2	1	1	1	NA	NA	NA	2	1	1	1	0	2	1	Moderate
Martin et al. [37]	2	2	2	2	NA	0	1	2	1	2	2	0	2	2	Strong
Smith et al. [21]	2	2	2	2	NA	0	1	2	1	1	2	0	2	2	Moderate
Duncan et al. [36]	2	2	2	2	NA	0	0	2	1	2	2	0	2	2	Moderate
Pageaux et al. [20]	2	2	2	2	NA	0	1	2	1	2	2	2	2	2	Strong
Smith et al. [31]	2	2	2	2	NA	2	1	2	1	2	2	0	2	2	Strong

NA not applicable, *2* indicates yes, *1* indicates partial, *0* indicates no

Quality scores: $\geq$75% strong, 55 $\geq$ 75% moderate, $\leq$55% weak

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; £50 best cycling performance	RCT, crossover	MF ↑ after I vs. C (assessed using BRUMS), associated with a decline in cognitive performance (fewer correct responses to AX trials). HR ↑ during I vs. 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 vs. C (assessed using BRUMS). HR ↑ during I vs. 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 vs. C (assessed with VAS). Increased β-band activity of the prefrontal lobe in the middle and after I vs. C (assessed using EEG)	
Budini et al. [34]	12 M	Switch task paradigm	NA	100 min	NA	nRnCT	RT ↑ in time	
Pageaux et al. [35]	8 M, 4 F	100% incongruent modified Stroop color–word task	100% congruent Stroop color–word task	30 min	£10 Amazon voucher for overall highest score on Stroop	RCT, crossover	MF = after I vs. C (assessed using BRUMS). Higher mental demand and effort in I vs. C (assessed using NASA-TLX). HR ↑ during I vs. C	Despite no overt mental fatigue, the I was perceived as more mentally demanding. Modified Stroop = words presented in red ink: react on the real meaning of the word; all other words: react on the color of the word
MacMahon et al. [23]	18 M, 2 F	AX-CPT	Watching a documentary + 3 min AX-CPT before and after	90 min	€50 for best performance on AX-CPT	RCT, crossover	MF ↑ after I vs. C (assessed using CMSS). Lower positive mood after I vs. C (assessed using CMSS). HR ↑ during I vs. 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 vs. C (assessed using POMS). A greater cognitive effort during I vs. 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 vs. C (assessed using BRUMS). Increased incorrect responses on the AX-CPT in time (assessed using AX-CPT). HR ↑ during I vs. C	
Duncan et al. [36]	7 M, 1 F	Completing concentration grids	Watching a documentary	40 min	NA	RCT, crossover	NA	

peak and mean power output and critical power. They found no difference due to mental fatigue in any of these measures. Brownsberger et al. [12] studied the effect of mental fatigue on power output with a time-clamped (10 min) and rating-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). In both the RPE 11 and the RPE 15 trial, participants chose lower self-selected power outputs in the mental fatigue condition (respectively, 16% and 8% lower). In the study by Pageaux et al. [20], the only behavioral measure was RPM, as their cycling protocol was time (6 min) and resistance clamped (80%); however, there was no difference in RPM due to mental fatigue.

3.3.1.2 Physiological HR and blood lactate (Bla) were measured in all whole-body endurance studies except those by Brownsberger et al. [12], Pageaux et al. [20], and Smith et al. [31], who did not measure Bla (see Table 5). Only the studies by Marcora et al. [10] and Brownsberger et al. [12] observed intervention-related differences during exercise. 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, or blood pressure during subsequent whole-body endurance performance. Brain activity (α and β activity in the prefrontal and the parietal lobe [12]) was also 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 showed no mental fatigue-related differences [20]. Furthermore, no effect on the rectus femoris from mental fatigue was found in terms of electromyography (EMG) root mean square during the whole-body endurance task [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 mentally fatigued condition.

3.3.1.3 Psychological The most frequently measured psychological outcomes during the whole-body endurance

Table 4 continued

Study	Sample	Intervention (I)	Control (C)	Duration	Monetary incentive	Methodological characteristics	Outcome	Remarks
Pageaux et al. [20]	12 M	100% incongruent modified Stroop color-word task	100% congruent Stroop color–word task	30 min	NA	RCT, crossover	MF = after I vs. C (assessed using BRUMS). Higher mental and temporal demand and effort in I vs. C (assessed using NASA-TLX). HR ↑ during I vs. C	Results suggest presence of mental fatigue after both CT
Smith et al. [31]	12 M	100% incongruent modified Stroop color–word task	Reading magazines	30 min	NA	RCT, crossover	MF ↑ after I vs. C (assessed using VAS)	

ACC accuracy, *AX-CPT* AX-continuous performance test, *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, *NA* not applicable, *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, *RSME* rating scale of mental effort, *RT* reaction time, *VAS* visual analog scale (perceived level of fatigue)

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 ↑ vs. 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 $A = 26 \pm 3$ y Mass = 69 ± 10 kg $W_{max} = 288 \pm 70$ W $VO_{2max} = 52 \pm 8$ 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 W_{max}	Post CT	Time-to-exhaustion ↓ in I vs. C; RPE ↑ during exercise in I vs. C; HR and Bla ↑ at exhaustion in C vs. I	Time to exhaustion in $C = 754 \pm 339$ s
Brownsberger et al. [12]	8 M, 4 F	Trained, healthy $A = 24 \pm 5$ y Mass = 71 ± 15 kg $VO_{2max} = 56 \pm 6$ ml/kg/min	Yes	No difference in motivation between conditions (assessed using VAS)	Two 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 vs. C for both RPE 11 and RPE 15 exercise bouts; HR ↑ in C vs. I for the RPE 11 bout (4.3%); β-band activity ↑ during warm-up in I vs. C	
Pageaux et al. [35]	8 M, 4 F	Trained, healthy $A = 21 \pm 1$ y Mass = 69 ± 11 kg Aerobic activities 2×/week in the previous 6 months	No (more mentally exerted after I vs. 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 vs. C; no difference in pacing strategy between conditions; RPE ↑ during exercise in I vs. C; TT-performance was perceived lower and more mentally demanding in I vs. C	TT performed on a treadmill in a lab setting
MacMahon et al. [23]	18 M, 2 F	Trained (familiar with a 3-km run) $A = 25 \pm 3$ y Running on average 2.84 ± 1.79 h/week	Yes	No difference in motivation between conditions (assessed using 7-point Likert scale). Greater decrease in positive mood when mentally fatigued vs. control (assessed using CMSS)	Run 3 km in the quickest time possible	Post CT	Performance ↓ in I vs. C; RPE = during exercise in I vs. C; no difference in attentional focus before and during exercise between conditions	TT performed on an indoor track; focus of attention was assessed using a 10-point bipolar scale

Table 5 continued

Study	Sample	Characteristics	MF ↑ vs. C	Motivation to exercise	Physical task	Time of physical task	Outcome	Remarks
Smith et al. [21]	10 M	Healthy, competitive intermittent team sportsmen (for a minimum of 3 y) $A = 22 \pm 2$ y Mass $= 75 \pm 6$ kg $VO_{2\max} = 48 \pm 6$ 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 vs. C; HIA and peak velocity = and HIA distance = between conditions; work performed at any intensity did not differ between conditions; RPE = between conditions during running protocol; RPE ↑ 30 min after running protocol	Running protocol was based on time motion analysis data from multiple team sports, six activities were included: LIA (stand, walk, jog and run); HIA (fast run and sprint)
Martin et al. [37]	7 M, 5 F	Trained, healthy $A = 23 \pm 3$ y $VO_{2\max} = 53 \pm 13$ l/min	No	Intrinsic motivation tended to be reduced post-CT in MF-condition vs. C (assessed using SIMS)	3MT	Pre and post CT. 3MT, only post CT	No difference in anaerobic work capacity or power (3MT) between conditions; no difference in CMJ (explosive power) or MVC between conditions; RPE tended to ↑ during 3MT in I vs. C	
Pageaux et al. [20]	12 M	Healthy active $A = 25 \pm 4$ y Mass $= 77 \pm 11$ kg Moderate-/high-intensity exercise 2×/week in the previous 6 months	No	Motivation was not assessed	6 min cycling at 80% of $W_{\max}$	Cycling task post CT. MVC pre and post CT and post cycling task	No difference in MVC between both conditions; RPE ↑ during cycling in I vs. C; 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 vs. C; RPE ↑ during exercise in I vs. C; no difference in HR between conditions	Distance covered in $C = 1410 \pm 354$ m

Table 5 continued

Study	Sample	Characteristics	MF ↑ vs. C	Motivation to exercise	Physical task	Time of physical task	Outcome	Remarks
Muscle endurance								
Pageaux et al. [17]	10 M	Active $A = 22 \pm 2$ y $\text{Mass} = 70 \pm 8$ 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 vs. C; leg RPE ↑ during the exhaustion-task in I vs. C; no difference in EMG activity between conditions	Time-to-exhaustion in $C = 266 \pm 26$ s

3MT 3 min all-out cycling test, *A* age, *Bla* blood lactate, *C* control, *CMJ* countermovement jump, *CMSS* Current Mood State Scale, *CT* cognitive task, *EMG* electromyography, *F* female, *HIA* high-intensity activity, *HR* heart rate, *I* intervention, *LIA* low-intensity activity, *M* male, *MF* mental fatigue, *MVC* maximal voluntary contraction, *RPE* ratings of perceived exertion, *SIMS* Situational Itrinsic Motivation Scale, *TT* time trial, *VAS* visual analog scale, *VO_2max* maximal aerobic capacity, *W* watt, *Wmax* maximal wattage, *Yo-Yo IR1* Yo-Yo intermittent recovery test—level 1

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 assessed with Borg's 15-point RPE scale [41] in all studies except for that by Smith et al. [21], who used the CR100 RPE scale. Marcora et al. [10], Pageaux and colleagues [20, 35], and Smith and colleagues [21, 31] found perceived exertion to be higher during exercise in a mentally fatigued state. Marcora et al. [10] used a scale developed and validated by Matthews et al. [42] and found no difference in success or intrinsic motivation related to the upcoming physical tasks between conditions. Pageaux and colleagues [20, 35] and Smith et al. [21] used the same scale to assess motivation and came to the same conclusion. Martin et al. [37] used a different scale (Situational Motivation Scale [43]) to assess motivation but again detected no difference in identified regulation, external regulation, and amotivation. However, there was 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 VAS to assess motivation for the upcoming physical task, whereas MacMahon et al. [23] used a 7-point Likert scale. No effects of mental fatigue on motivation could be distinguished. Only Pageaux and colleagues [20, 35] assessed the subjective workload of the exercise protocol. In 2014, Pageaux et al. [35] used the National Aeronautics and Space Administration Task Load Index and found that the exercise protocol was perceived as more mentally demanding, and participants also rated their performance in the time trial lower after the intervention. Additional psychological constructs such as attentional focus [23] and mood after the exercise protocol [12] were also assessed, but no differences due to mental fatigue were observed.

3.3.2 Muscle Endurance

3.3.2.1 Behavioral Only one study evaluating the effect of mental fatigue on muscle endurance was 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 13% shorter in the mental fatigue condition [17].

3.3.2.2 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) or at exhaustion. Likewise, EMG root mean square did not differ between conditions [17].

3.3.2.3 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 [17, 20, 34, 36, 37] (see Table 6). Four assessed whether an impairment in MVC of the knee extensor muscles occurred after completing a mentally fatiguing task [17, 20, 34, 37]. Both studies by Pageaux and colleagues [17, 20] revealed that neither the mentally fatiguing nor the control task affected 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). Conversely, Budini et al. [34] 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. Pageaux and colleagues [17, 20] and Budini et al. [34] examined measures of peripheral and central fatigue during an MVC. Pageaux and colleagues [17, 20] included single electrical stimulation 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). Neither study [17, 20] found an effect from 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). Budini et al. [34] used two springs with differing 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); the other induced a 5-Hz frequency oscillation (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 taken by Pageaux and colleagues [17, 20] (i.e. perception of effort, motivation and subjective workload) were not related to the anaerobic maximal work. Duncan et al. [36] also employed few psychological measures, only measuring RPE on completion of each Wingate test, but reported no effect of mental fatigue. Martin et al. [37] assessed RPE and motivation and did not observe any difference in RPE, identified regulation, external regulation, or amotivation towards the countermovement jump or MVCs.

4 Discussion

In this review, we sought to outline the current knowledge on the effect of mental fatigue on physical performance. We also 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: the impossibility of blinding a participant to the task being conducted, 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 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 good preparation for maximal anaerobic exercise performance [37]. Despite participants being deceived, the difference in task demand between the experimental and the control tasks could still have created different

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 ↑ vs. C?	Motivation to exercise	Physical task	Time of physical task	Outcome	Remarks
Pageaux et al. [17]	10 M	Active $A = 22 \pm 2$ y Mass $= 70 \pm 8$ kg	Yes	Motivation not assessed	MVC (duration of ~5 s) with superimposed supramaximal paired stimuli (doublet) at (1) 100 Hz and followed (4 s intervals) by paired stimuli at 100 Hz, (2) 60 s rest and (3) three single supramaximal stimulations at rest (interspaced by 3 s)	Pre and post CT and post cycling task	MF no effect on MVC or neuromuscular function	
Budini et al. [34]	12 M	Healthy $A = 29 \pm 4$ y	NA	Motivation not assessed	Two submaximal 20-s contractions of the knee extensor muscles at 30% MVC using a long and short spring. Three 3-s MVCs of the knee extensor muscles	Pre and post CT	MVC ↓ when mentally fatigued (–6.9%); EMG activity ↓ within the 8- to 12-Hz frequency band when mentally fatigued	Short spring induced 8- to 12-Hz = stretch reflex peripheral component; long spring induced 3- to 6-Hz = stretch reflex central component
Martin et al. [37]	7 M, 5 F	Trained, healthy $A = 23 \pm 3$ y $VO_{2max} = 53 \pm 13$ l/min	No	Intrinsic motivation tended to be reduced post CT in MF-condition vs. C (assessed using SIMS)	Three CMJ. 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 not assessed	Four 30-s Wingates (separated by 4-min rest)	Post CT	No difference in mean cycling power between conditions; no difference in RPE between conditions; no difference in HR or Bla between conditions	No manipulation checks included
Pageaux et al. [20]	12 M	Healthy active $A = 25 \pm 4$ y Mass $= 77 \pm 11$ kg	No	Motivation not assessed	MVC (duration of ~4 s) with superimposed supramaximal paired stimuli (doublet) at 100 Hz and followed (4 s intervals) by (1) paired stimuli at 100 Hz, (2) 60 s rest and (3) 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; RPE ↑ during cycling in I vs. C; no effect of mental fatigue on central or peripheral fatigue	

A age, *Bla* Blood lactate, C control, *CMJ* countermovement jump, *CT* cognitive task, *EMG* electromyography, *F* female, *HR* heart rate, *I* intervention, *M* male, *MF* mental fatigue or self-reported fatigue or fatigue or general fatigue or subjective fatigue, *MVC* maximal voluntary contraction, *NA* not applicable, *RPE* rating of perceived exertion, *SIMS* Situational Intrinsic Motivation Scale, VO_2max maximal aerobic capacity 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 Sect. 1, mental fatigue has subjective, behavioral, and physiological manifestations. Most of the included studies assessed only the subjective and behavioral manifestations; 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 used. A VAS assessing how mentally fatigued an individual feels might be sensitive but promote response bias, whereas 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-considered paradigms that account for the relative contribution of other parameters, such as 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 11 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] conducted 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 with 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], but 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 mental fatigue are increases in frontal θ and in frontal, central, and parietal α power [8, 47–49]. Moreover, if one considers the continuous change of a measure as a criterion 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, Brownsberger et al. [12] did not measure θ activity.

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 must 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 independent of time on task [44]. It is also 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 highlighted by the recent replication study by Hagger et al. [29] and is shown again by a recent study by Schücker and MacMahon [54] that found no effect of a 10-min cognitive task on subsequent whole-body endurance performance. The authors admit one possible explanation for these results is the ineffectiveness of the manipulation task (10-min Stroop) to induce mental fatigue. However, they argued that even shorter tasks have been observed to reduce whole-body endurance performance [55] and therefore felt 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, caution is required when attributing the results in both lines of research to the same mechanism. In the end, all studies in the present review aside from those by Pageaux and colleagues [20, 35], 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 that mental fatigue was induced in their study, we did include the studies by Pageaux and colleagues [20, 35], Martin et al. [37], and Duncan et al. [36]. To begin with, these studies [20, 35–37] used tasks that were of a similar nature and length as those used in the other included studies that were successful in inducing mental fatigue. Second, Duncan et al. [36] did not include any subjective, behavioral, or physiological measures to monitor mental fatigue, whereas Pageaux and colleagues [20, 35] and Martin et al. [37] used the—perhaps too insensitive—BRUMS or POMS to assess the mental fatigue state of participants. Therefore, and because Pageaux and colleagues [20, 35] and Martin et al. [37] reported that participants perceived the intervention task as more mentally demanding and effortful than the control task, we also included these studies.

4.2 Mental Fatigue and Physical Performance

To discuss 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

Eight of the nine studies that examined the effect of mental fatigue on behavioral measures 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 [23, 35], 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] was no impact of mental fatigue 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 physical tasks employed in these studies all required maximal all-out effort. On the basis of these results, it appears 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 hugely important in terms of finding an effect of mental fatigue. Pageaux et al. [17] showed that, besides whole-body endurance, mental fatigue also impaired muscle endurance. However, this is the only study to examine the effect of mental fatigue on muscle endurance performance, and the results need to be confirmed by future studies. The importance of both the cognitive component and the submaximal endurance intensity in the physical task also indicates a need for future research conducted in a more applied manner (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. However, physical performance (total distance covered tracked with a global positioning system) in this setting was not a primary 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, the study did not include any real physical performance measure.

Consequently, we did not include this study in the review. Nonetheless, studies of this kind are extremely useful and necessary 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], respectively, observed 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 with the mental fatigue trial. However, all these findings can be explained by behavioral changes. In the study by 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 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, because mental fatigue did not increase exercise-induced central fatigue, it also did not accentuate peripheral 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 100-min mentally fatiguing task. 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]. However, they did not include a control group, so 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 must be that, given 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. However, the most consistent finding was the higher RPE during exercise. Marcora et al. [10], Pageaux and colleagues [17, 20, 35], 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 by Marcora et al. [10], this could have been due to a ceiling effect created by the artificially increased motivation when offering monetary reward for best cycling performance, masking 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. Encouragement and visual feedback during the physical task itself are other important factors that impact on motivation. These specific aspects differed between studies, with some [20, 21] giving no feedback or encouragement, some giving feedback but no encouragement [12, 31, 34, 35], and others giving both feedback and standardized encouragement [10, 17, 37]. However, independent from giving feedback or encouragement, all studies reported no effect of mental fatigue on motivation towards the upcoming physical task. A lack of effect of mental fatigue 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, although 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 by which neural signal(s) are processed by the brain to generate the perception of effort [40]: (1) the afferent feedback from the working muscles and other peripheral physiological systems (i.e., the afferent feedback model [67]); (2) 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]; (3) a combination of afferent feedback and corollary discharges (i.e., the combined model [68]). It should be noted that recent evidence provides support for the corollary discharge model (for more details, please see Zenon et al. [65], de Morree et al. [69], Pageaux and Gaveau [70], and Sharples et al. [71]). 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 (independent of 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 Sect. 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) to produce the same power output even when central and peripheral fatigue are not exacerbated. However, this altered EMG amplitude due to mental fatigue is yet 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 [69]. The third option, an altered brain processing of the neural signals underlying perception of effort (independent of whether they originate from peripheral receptors or premotor/motor areas of the cortex) appears to be a reasonable explanation. However, we are unaware of any study that 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. [72], who 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 ratio of RPE to power output (meaning less power output is generated for the same RPE value). In contrast, intake of methylphenidate [73] (a dopamine [DA] reuptake inhibitor) 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 ratio of RPE to power output (in the case of DA, a decreased ratio). Klass et al. [74] 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 [74]. Pageaux and colleagues [17, 20, 35] stated that neural activity increases the extracellular concentration of adenosine (an inhibitory neurotransmitter [75]) and that brain adenosine accumulation reduces endurance performance [76]. Subsequently, they speculated that adenosine accumulation in the pre-supplementary motor area and anterior cingulate cortex (due to a mentally fatiguing task) could also partly explain the higher than normal perceived exertion during an endurance exercise in a mentally fatigued state. However, to date, no study has demonstrated 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 (P3 and pupil diameter) during a mentally fatiguing task and reported that these markers 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. [77] investigated the role of DA in mental fatigue and concluded that the dopaminergic midbrain is also 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 [78]. The above indicates that it will most likely 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 (partly) explain 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 [77, 79]. Moeller et al. [77] used methylphenidate (i.e., a DA reuptake inhibitor) to manipulate the concentration of DA in the brain and assess the effect of this 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 and Caldwell [79] reported that administration of dextroamphetamine (i.e., an indirect dopamine agonist) improved flight performance during the final 23 h of a 40-h period of continuous wakefulness. Similar studies investigating the effect of mental fatigue on physical performance could increase our knowledge of the role of different neurotransmitters in this interaction. More applied areas also need further investigation. 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 they may have superior ability to maintain performance [80].

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 to unravel whether mental fatigue impairs physical performance and sought to create an overview of the potential factors underlying this effect.

A total of 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 (HR, Bla, 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.

In practical terms, 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, to optimize performance, mentally demanding tasks should be avoided before competitions requiring endurance. 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.

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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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