The effects of mental fatigue on sport-related performance

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Abstract

Mental fatigue is known to increase subjective feelings of fatigue and to decrease cognitive performance, but its impact on physical performance remains poorly understood. The aim of this chapter was to review the results of 29 studies published between 2009 and April 2018 and focusing on the impact of mental fatigue on sport-related performance. Taken all studies together, it appears that mental fatigue impairs endurance performance, motor skills performance and decision-making performance. However, maximal force production is not reduced in the presence of mental fatigue. These observations suggest that mental fatigue impairs sport-related performance during exercises performed at a submaximal intensity and not during exercises performed at maximal and supramaximal intensity. The negative impact of mental fatigue on submaximal exercises seems to be mediated by an increase in perception of effort. Future studies should now identify the physiological alterations induced by mental fatigue and responsible of the increased perceived effort.

Keywords

Cognitive fatigue, Perception of effort, Perceived exertion, Endurance performance, Force production capacity, Motor skills, Decision-making, Psychophysiology

1 INTRODUCTION

The Oxford Dictionary defines fatigue as an "extreme tiredness resulting from mental or physical exertion or illness" and/or "a reduction in the efficiency of a muscle or organ after prolonged activity." When fatigue results from the prolonged engagement in physical exertion, the function of different physiological systems (e.g., respiratory, cardiovascular or neuromuscular systems) can be altered. The exercise

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science literature traditionally classifies an exercise-induced decrease in maximal force production as neuromuscular or muscle fatigue (Gandevia, 2001). A reduction in force production capacity of a muscle group (i.e., muscle fatigue) has been shown to impair endurance performance and motor skills both in the lab and on the field (Apriantono et al., 2006; De Morree and Marcora, 2013; Enoka, 1995; Enoka and Duchateau, 2008; Marcora et al., 2008; Missenard et al., 2009). These alterations in physical performance have been attributed to both central (i.e., a progressive reduction in voluntary activation of muscle during exercise; Gandevia, 2001) and peripheral (i.e., changes at or distal to the neuromuscular junction; Allen et al., 2008) alterations of neuromuscular function.

When fatigue is induced by prolonged engagement in mental exertion, fatigue is traditionally defined as cognitive fatigue or mental fatigue (e.g., Boksem and Tops, 2008; MacMahon et al., 2014; Marcora et al., 2009; Wang et al., 2016). In this chapter, no difference will be made between the two terminologies, and "mental fatigue" will be used consistently. Mental fatigue is a psychobiological state caused by prolonged demanding cognitive activities. It can be characterized by an increase in feelings of tiredness or even exhaustion, an aversion to continue the ongoing task, and a decrease in cognitive performance (Boksem and Tops, 2008; Boksem et al., 2006). While the effects of mental fatigue on cognitive performance have been widely investigated (Boksem et al., 2006; Lorist, 2008; Lorist et al., 2005; van Der Linden and Eling, 2006; van Der Linden et al., 2003, 2006), the interest for researchers in investigating a potential impact of mental fatigue on physical performance remains relatively new. Since the pioneer work of Mosso (1906) reporting a decreased muscle endurance performance in two colleague professors after several lectures and oral examinations, we had to wait more than one century to confirm a negative impact of mental fatigue on physical performance in humans (Marcora et al., 2009). Since the study of Marcora et al. (2009), several studies from different research groups investigating the effects of mental fatigue on physical performance have been published (Fig. 1).

In sports, physical performance is directly linked to the ability of an athlete (i) to produce a given force, power or speed for as long as possible (i.e., endurance performance), (ii) to produce a maximal force, power or speed for a short duration (i.e., maximal force production), (iii) to accurately perform goal-directed movements (i.e., motor skills performance), and (iv) to take accurate sport-related decisions during sporting events (i.e., decision-making performance). The aim of this narrative review is to present the impact of mental fatigue on sport-related performance, defined as any athlete's performance having a potential impact on the outcome of a sporting event (see descriptions above). First, we will provide a brief presentation of how mental fatigue is induced and monitored in a laboratory setting. Second, we will present the results of all studies that have investigated the effects of mental fatigue on sport-related performance: endurance performance, maximal force production, motor skills performance, and decision-making performance. As this chapter focuses on sport-related performance, studies including non-healthy volunteers were excluded. Finally, we will provide some perspectives for future research interested in this topic.

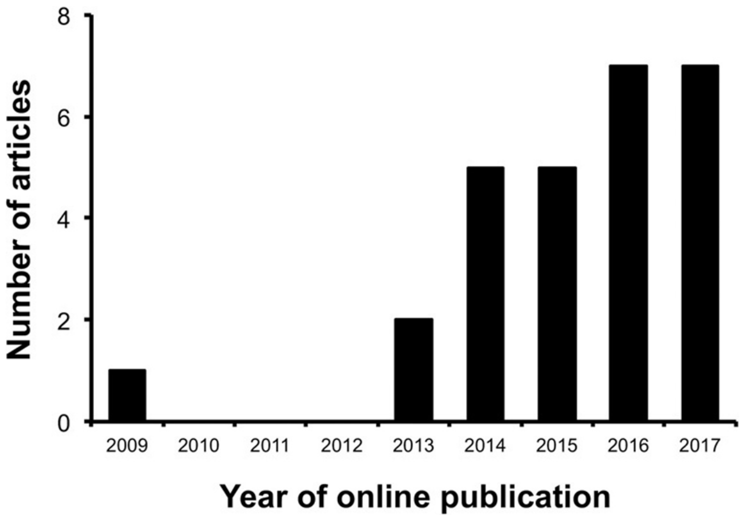

FIG. 1

Number of articles investigating the impact of mental fatigue on physical performance per year of online publication. The studies included in this figure are those presented in this chapter. The year 2009 corresponds to the first published article on the effect of mental fatigue on physical performance. The year 2018 was excluded since the current book chapter includes studies published until April 2018, and the full year could not be included.

The presence of mental fatigue being consistently observed following 30 min of engagement in demanding cognitive tasks, only studies involving cognitive tasks performed for a minimum duration of 30 min have been included (Van Cutsem et al., 2017b). All theses studies involved a cognitive task as an experimental manipulation to induce mental fatigue and investigate its effect on sport-related performance. The literature search consisted of the inclusion of the 11 studies included in the systematic review of Van Cutsem et al. (2017b). Additional studies included ($n = 18$) were found via "the Cited by" tool in Google Scholar used for each study included in Van Cutsem et al. (2017b). In total, this chapter reviews the results of 29 studies published from 2009 to April 2018.

2 STUDYING MENTAL FATIGUE IN THE LABORATORY

2.1 HOW TO INDUCE MENTAL FATIGUE?

As previously presented, mental fatigue is induced in laboratory settings by prolonged engagement in demanding cognitive tasks. A significant number of publications used the Stroop Task (Stroop, 1992) or the AX Continuous Performance test (AXCPT) (Carter et al., 1998) as an experimental tool to induce mental fatigue (e.g., Marcora et al., 2009; Pageaux et al., 2013; Smith et al., 2016a,b). However, the literature suggests that other cognitive tasks also involving sustained attention, working memory, and response inhibition are effective in inducing mental fatigue (e.g., Head et al., 2017; Lorist et al., 2005). While we agree that the cognitive tasks used in the studies included in this chapter are laboratory-controlled tasks, it is important to note that they involve specific executive functions that are also involved on the field during training sessions, long day at work or sport competitions. Therefore, we believe that the approach used is accurate and has strong potential to have direct impact on the field.

While it seems to exist a link between the duration of the cognitive task and the magnitude of mental fatigue induced by the completion of this task, this relation remains unclear and under-investigated (Brown and Bray, 2017). The psychology literature investigating "the ego-depletion effect" using similar cognitive tasks during short duration seems to find non-reproducible effects of short mental exertion on subsequent cognitive and/or physical performance (Carter and McCullough, 2013; Hagger et al., 2010; Inzlicht and Berkman, 2015). On the contrary, when the cognitive task is prolonged ($\geq$30 min), the presence of mental fatigue is consistently observed (Van Cutsem et al., 2017b). Consequently, we suggest that studies willing to explore the negative impact of mental fatigue on physical performance should use cognitive tasks involving sustained attention, working memory, and response inhibition for a minimum duration of 30 min.

2.2 HOW TO QUANTIFY MENTAL FATIGUE?

By using electroencephalography (EEG), magnetoencephalography (MEG) or functional magnetic resonance imagery (fMRI), several studies demonstrated possible alterations in prefrontal brain areas activity. Notably, presence of mental fatigue has been associated with alterations in cingulate and frontal regions activity (Cook et al., 2007; Tanaka et al., 2012, 2014). While measuring changes in brain activity with EEG, MEG or fMRI has the potential to identify the presence of mental fatigue; it has to be acknowledged that both techniques are expensive and time consuming. Therefore, it seems important to propose cost-free and easy to use methods to quantify mental fatigue.

As mental fatigue is characterized by an increase in feelings of tiredness and lack of energy and/or a decrease in cognitive performance, self-related changes in subjective mood or feelings of fatigue and/or cognitive performance overtime can identify the presence of mental fatigue. To monitor changes in subjective feelings of fatigue, most studies used a visual analog scale and/or specific questionnaires such as the Brunel Mood Scale developed by Terry et al. (2003) (e.g., Le Mansec et al., 2018; Marcora et al., 2009; Pageaux et al., 2013; Smith et al., 2016a). With both methodologies, feelings of fatigue are monitored before and after engagement in a demanding cognitive task, and the presence of mental fatigue is highlighted by an increase in the self-reported values following the cognitive task.

As mental fatigue is also characterized by a decrease in cognitive performance, monitoring performance throughout the completion of the cognitive task used to induce mental fatigue is of interest for coaches and researchers. Of particular importance are the reaction time, response accuracy and lapses of attention. Reaction time corresponds to the interval between the appearance of the stimulus and the answer provided by the participants, response accuracy corresponds to the proportion of correct answers in a given time window, and lapses of attention correspond to the appearance of stimuli with no answer given by the participants. Overtime, an increase in reaction time or lapses of attention, and/or a decrease in response accuracy are markers of the presence of mental fatigue (e.g., Head et al., 2016, 2017; Marcora et al., 2009; Wang et al., 2016).

3 MENTAL FATIGUE IMPAIRS ENDURANCE PERFORMANCE

In this section, endurance performance refers to a submaximal whole-body or single-joint exercise soliciting mainly the aerobic energy system. Therefore, only studies involving exercise lasting at least 75 s were included (Gastin, 2001). In these studies (see Table 1), endurance performance was investigated as constant-load exercise (e.g., time to exhaustion test), incremental exercise, or self-paced exercise (e.g., time trial).

3.1 CONSTANT-LOAD EXERCISE

In 2009, Marcora and colleagues performed the first experiment on the interaction between mental fatigue and physical performance since the work of the Italian scientist Mosso (1906). In this study, 16 subjects completed a cycling time to exhaustion test at 80% of their peak power output after completion of either 90 min of the AXCPT (mental fatigue condition) or 90 min of watching an emotionally neutral documentary (control condition). The increase in subjective feelings of fatigue induced by 90 min of the AXCPT, as well as the decrease in response accuracy during the cognitive task confirmed the presence of mental fatigue. In the mental fatigue condition, cycling time to exhaustion was ~15% shorter compared to the control condition. This impaired endurance performance was not caused by any mental fatigue-induced alterations in cardiorespiratory and musculoenergetic responses during exercise. The only significant change observed during exercise was a higher perception of effort in the mental fatigue condition.

In 2013, Pageaux and colleagues confirmed the negative impact of mental fatigue on submaximal isometric exercise of the knee extensors performed until exhaustion. The authors observed a ~13% decrement in time to exhaustion of a knee extensors submaximal isometric contraction in the mental fatigue condition compared to the control condition. In line with the results of Marcora et al. (2009), no difference in physiological responses to the time to exhaustion test was apparent between the mental fatigue and control condition. As mental fatigue has been proposed in the literature to negatively impact the voluntary activation level and consequently maximal muscle activation (i.e., index of the brain ability to maximally drive

Table 1 Comprehensive List of Studies Investigating the Impact of Mental Fatigue on Endurance Performance

References	Subjects	Mental Fatigue Protocol	Markers of Mental Fatigue	Endurance Performance Test	Impact of Mental Fatigue on Endurance Performance	Perception of Effort During the Endurance Performance Test
Azevedo et al. (2016)	8 recreationally active ♂	90 min of AX-continuous performance test	↑ in self-reported fatigue	Cycling time to exhaustion at 80% PPO with and without caffeine ingestion	↓ in time to exhaustion without caffeine ingestion, no change in performance with caffeine ingestion	↑
Brownsberger et al. (2013)	8 active ♂ and 4 active ♀ cyclists	90 min of a computerized decision-making task	↑ in self-reported fatigue	2 × 10 min cycling at a fixed RPE (11 and 15)	↓ in cycling power output at RPE 11 and 15	↑
MacMahon et al. (2014)	18 trained ♂ and 2 trained ♀ runners	90 min of AX-continuous performance test	↑ in self-reported fatigue	3 km running time trial	↑ in time to complete the time trial	↑
Marcora et al. (2009)	10 active ♂ and 6 active ♀	90 min of AX-continuous performance test	↑ in self-reported fatigue ↓ in cognitive performance	Cycling time to exhaustion at 80% PPO	↓ in time to exhaustion	↑
Martin et al. (2016)	11 professional ♂ road cyclists and 9 recreational ♂ cyclists	30 min of incongruent Stroop task	↑ in self-reported fatigue for both groups	20 min cycling time trial	Reduction in power output in the recreational cyclists group only, no change in performance in the professional cyclist group	↑ in the recreational cyclists group
Otani et al. (2017)	8 active ♂	90 min of different computer-based cognitive tests	↑ in self-reported fatigue	Cycling time to exhaustion at 80% VO_{2max}	↓ in time to exhaustion	No change
Pageaux et al. (2013)	10 active ♂	90 min of AX-continuous performance test	↑ in self-reported fatigue	20% knee extensors MVC time to exhaustion	↓ in time to exhaustion	↑
Pageaux et al. (2014)	10 recreationally active ♂	30 min of incongruent Stroop task	No overt mental fatigue	5 km running time trial	↑ in time to complete the time trial	↑

Pageaux et al. (2015)	12 active ♂	30 min of incongruent Stroop task	↑ in self-reported fatigue	6 min cycling at 80% PPO	No measure of performance as all subjects cycles for the same duration	↑
Penna et al. (2018)	11 young ♂ and 5 young ♀ (~16 yo) experienced (~7 y) swimmers	30 min of incongruent Stroop task	↑ in self-reported fatigue	1500 m swimming time trial	↑ in time to complete the time trial	↑
Pires et al. (2018)	8 recreational cyclists ♂	30 min of Rapid Visual Information Processing test	↓ in cognitive performance	20 km cycling time trial	↑ in time to complete the time trial	↑
Salam et al. (2018)	11 well-trained ♂ cyclists	30 min of incongruent Stroop task	↑ in self-reported fatigue	3 cycling time to exhaustion test at 3 different intensities	↓ in time to exhaustion for all intensities	↑
Smith et al. (2015)	10 recreationally active ♂	90 min of AX-continuous performance test	↑ in self-reported fatigue	45 min self-paced intermittent running protocol replicating team sports physical demand	↓ in running velocity at low intensity	↑
Smith et al. (2016a)	12 moderately trained soccer ♂ (study 1)	30 min of incongruent Stroop task	↑ in self-reported fatigue	Yo-Yo intermittent recovery test, Level 1	↓ in running distance	↑
Van Cutsem et al. (2017a)	10 trained ♂ cyclists	45 min of incongruent Stroop task	↑ in self-reported fatigue	In a hot environment: 45 min cycling at 60% PPO followed by a cycling time trial	No change in cycling time trial performance	No change
Veness et al. (2017)	12 elite cricket ♂	30 min of incongruent Stroop task	↑ in self-reported fatigue	Yo-Yo intermittent recovery test, Level 1	↓ in running distance	↑
Vrijkotte et al. (2018)	10 trained ♂ cyclists	90 min of incongruent Stroop task	↑ in self-reported fatigue	Two incremental cycling tests interspaced by the mental fatigue protocol	No difference in peak power output between the two incremental cycling tests	No change

All studies presented in this table are discussed within this chapter. MVC = maximal voluntary contraction; PPO = peak power output; RPE = rating of perceived exertion. Please note that perception of effort was measured with psychophysical scales. An increase in perception of effort is highlighted in two possible ways: (i) increase in the rating (RPE) at a fixed workload, or (ii) same rating associated with a reduction in workload in the context of self-paced exercise.

the working muscles) (e.g., Bray et al., 2012; Di Giulio et al., 2006), Pageaux and colleagues measured this parameter before and after completion of 90 min of the AXCPT. Interestingly, while the prolonged engagement in the cognitive task increased the feelings of fatigue, the presence of mental fatigue was not associated with a reduction in the voluntary activation level, commonly named central fatigue in the neurophysiology of exercise literature (Gandevia, 2001). The reduction in endurance performance could only be explained by an increased perceived effort induced by mental fatigue, without any apparent physiological alterations or reduction in voluntary activation level (for more information see the next section on the impact of mental fatigue on maximal force production).

The reduced time to exhaustion in the presence of mental fatigue has also been observed by other research groups where time to exhaustion tests were performed at 80% of maximum oxygen uptake (Otani et al., 2017) or 80% of peak power output until exhaustion (Azevedo et al., 2016). Importantly, it has to be noted that this observed decrement in time to exhaustion occurred at different submaximal intensities (Salam et al., 2018). Even so it is unlikely that time to exhaustion at a constant-load only decreases for cycling exercise and not in other locomotion modes, it would be of interest to replicate these observation by using a constant-velocity running exercise.

3.2 INCREMENTAL EXERCISE

To evaluate exercise capacity in athletes, it is conventional to perform incremental exercises such as traditional cardiopulmonary exercise testing (Williams, 2018) or various graded exercises (e.g., Assadi and Lepers, 2012; Bangsbo et al., 2008). In these exercises, cycling power output or running velocity (or slope) is progressively increased until the athlete cannot sustain the required cycling power output or running velocity. Such test can provide interesting insights to researchers and coaches as maximal heart rate, oxygen consumption, and power output or running velocity can be obtained and used subsequently in the prescription of training programs.

For team sport such as soccer, one of the most used graded exercise is the Yo-Yo intermittent recovery test (Yo-Yo test; Bangsbo et al., 2008, Krustrup et al., 2003). In this test, the athletes run a set up and back distance between two cones (i.e., one bout) at progressively increasing velocities, with each bout interspaced by 10 s recovery. The literature investigating the impact of mental fatigue on sport-related performance demonstrated a negative impact of mental fatigue on the distance covered during the Yo-Yo test (Smith et al., 2016a; Veness et al., 2017). Smith et al. (2016a) observed a ~15% reduction in the distance covered by moderately trained soccer players following a 30-min engagement in the incongruent Stroop Task. Veness et al. (2017) observed similar results in elite cricket players. In these two studies, the reduced performance in the Yo-Yo test was associated with a higher perception of effort in the mental fatigue condition compared to the control condition. Interestingly, by inducing mental fatigue in the recovery period between the completion of two cycling graded exercises, Vrijkotte et al. (2018) recently failed to observe a negative impact of mental fatigue on cycling peak power output. This result suggests that when mental fatigue is induced following completion of a previous exhausting exercise, the negative impact of mental fatigue on incremental exercise seems to be counteracted by the previous physical exertion performed.

Future studies should investigate the impact of mental fatigue on incremental exercise without prior completion of physically exhausting exercise. As a recent study in the sport psychology literature demonstrated that a prior short mental exertion (10.5 min) induces an underestimation of both peak power output and peak oxygen consumption (Zering et al., 2017), it is likely that the presence of mental fatigue can lead to inappropriate estimation of exercise capacity in athletes. Therefore, we suggest that measurement of exercise capacity via the use of incremental exercises in athletes should be performed without prior engagement in demanding cognitive tasks (e.g., tactical training session or long interview sessions with the media).

3.3 SELF-PACED EXERCISE

Both time to exhaustion test (i.e., constant load exercise) and time trial (self-paced exercise) are known to be valid measures of endurance performance (Amann et al., 2008). However, as time to exhaustion tests are performed at a fixed power output or running velocity, only time trials and therefore self-paced exercises can provide insights into the impact of mental fatigue on the self-regulation of cycling power output or running velocity (i.e., pacing).

The first study investigating the impact of mental fatigue on pacing is Brownsberger et al. (2013). In this study, 12 participants performed two 10-min cycling bouts at a fixed perceived effort (fairly light and hard), in the presence and absence of mental fatigue. The specificity of these two cycling bouts was the possibility for the participants to regulate cycling power output to keep a fixed perceived effort during the whole duration of the cycling bout. In the presence of mental fatigue, the authors observed a reduction in self-selected cycling power output in the two cycling bouts, confirming per se previous results showing that perception of effort is increased in the presence of mental fatigue. Similar results have been reproduced by Smith et al. (2015) during running exercise.

Based on the observations of Brownsberger et al. (2013) and Smith et al. (2015), it is very likely that time trial performance could be altered by the presence of mental fatigue. This possibility has been confirmed by MacMahon et al. (2014) and Pageaux et al. (2014) during running time trials, as well as during swimming (Penna et al., 2018) and cycling (Martin et al., 2016; Pires et al., 2018) time trials. In all studies aforementioned, it is important to note that despite pacing being altered by the presence of mental fatigue, the pacing strategy chose by the participant or athlete was unchanged. In other words, in the presence of mental fatigue, healthy participants or athletes choose an overall lower cycling power output or running/swimming velocity, without altering how they decide to distribute their "work" overtime.

Interestingly, Martin et al. (2016) did not only demonstrate a reduced time trial performance in recreational cyclists following engagement in the Stroop task for 30 min, they also demonstrated that for the same cognitive task duration, professional cyclists time trial performance was not impaired. The authors explained the maintenance of performance in professional cyclists by a higher inhibitory control compared to recreationally active participants (Martin et al., 2016). This result suggests a positive impact of endurance training on the ability to resist to the negative impact of mental fatigue on endurance performance. This hypothesis is also reinforced by the observed relation between performance during highly demanding cognitive tasks and performance during an ultra-marathon (Cona et al., 2015). To test the strength of the link between cognitive and physical endurance performance, it seems of great interest to test the possibility to increase endurance performance by adding specific cognitive training on the top of traditional physical training (Marcora et al., 2015).

3.4 INTERACTION BETWEEN MENTAL FATIGUE, ENVIRONMENTAL MANIPULATIONS AND ENDURANCE PERFORMANCE

The recent interest of exercise physiologists in the impact of mental fatigue on endurance performance led to the development of studies manipulating environmental conditions to test a possible additional negative impact of mental fatigue on the top of the environmental condition on endurance performance. Otani et al. (2017) demonstrated that hot water immersion (40 °C) following 60 min of prior demanding cognitive task reduces endurance performance to a greater extent than mental fatigue alone or hot water immersion alone. On the contrary, Van Cutsem et al. (2017a) did not observe an additional decrement in endurance performance when measured in a hot condition (30 °C and 30% relative humidity). The results of these two studies suggest that the additional negative impact of mental fatigue on the top of environmental manipulations on endurance performance is likely to be "environmental-dependent." Future studies should therefore replicate the results of the aforementioned studies, as well as examining the impact of mental fatigue on endurance performance performed in other environmental conditions known to impact cognitive performance during physical exercise (e.g., hypoxia; Komiyama et al., 2017).

3.5 HOW TO EXPLAIN THE NEGATIVE IMPACT OF MENTAL FATIGUE ON ENDURANCE PERFORMANCE?

As originally proposed by Pageaux et al. (2014), a plausible explanation for the negative impact of mental fatigue on endurance performance is that prolonged mental exertion could induce adenosine accumulation in the anterior cingulate cortex, leading to a higher than normal perceived effort during a subsequent endurance exercise. This hypothesis finds experimental support in previous studies showing that the anterior cingulate cortex is strongly activated during cognitive tasks involving response inhibition (e.g., Bush et al., 1998; Carter et al., 1998), and that this brain area is associated with the perception of effort (Williamson et al., 2001, 2002). Additionally, animal studies suggest that neural activity increases extracellular concentrations of adenosine (Lovatt et al., 2012) and that brain adenosine impairs endurance performance (Davis et al., 2003). Finally, there is recent evidence that caffeine (an antagonist of adenosine) counteracts the negative impact of mental fatigue on endurance performance (Azevedo et al., 2016).

Despite the literature suggesting a link between mental fatigue and brain adenosine accumulation (Martin et al., 2018; Pageaux and Lepers, 2016; Pageaux et al., 2014, 2015), this hypothesis still needs to be proven and explored. To date, most studies demonstrating a negative impact of mental fatigue on endurance performance failed to identify a physiological alteration causing the impaired endurance performance. Therefore, the traditional models existing in the exercise physiology literature to explain the regulation of endurance performance cannot provide a theoretical explanation on how mental fatigue reduces endurance performance (e.g., Amann, 2011; Hepple, 2002). As the reduction in endurance performance in the presence of mental fatigue is mediated by a higher-than-normal perception of effort (i.e., a psychological variable), it seems crucial to adopt multidisciplinary approaches and models merging the fields of psychology and physiology. For this purpose, the psychobiological model of endurance performance (Marcora, 2008, 2010; Marcora et al., 2008; Pageaux, 2014) could explain the reduced endurance performance. In this model, two levels of explanation (Cacioppo et al., 2000; Panhuysen and Tuiten, 1993) are proposed to describe the athlete's behavior (i.e., endurance performance): the psychological or higher level, and the physiological or lower level. Using such multi-level of explanation approach does not exclude the impact of physiology on endurance performance, it only states that any change in physiology—lower level of the model—will have a direct impact on the psychological level—higher level—that will in turn impact endurance performance, i.e., athlete behavior. The psychobiological model of endurance performance, via its psychological level of explanation, provides coherent theoretical explanation for the negative impact of mental fatigue on endurance performance. The identification of perception of effort as the key variable in the regulation of endurance performance (Marcora and Staiano, 2010; Marcora et al., 2008; Pageaux and Lepers, 2016) should stress the need for future studies exploring the physiological level of the psychobiological model of endurance performance, in order to better understand how changes in physiology could impact perception of effort and thus endurance performance.

4 MENTAL FATIGUE DOES NOT REDUCE MAXIMAL FORCE, POWER OR SPEED PRODUCTION

In this section, maximal force production refers to the ability of an athlete to produce a maximal force, power or speed for a short duration during isolated or whole-body exercise. Therefore, only studies involving all-out effort are included (see Table 2).

Table 2 Comprehensive List of Studies Investigating the Impact of Mental Fatigue on Maximal Force Production

References	Subjects	Mental Fatigue Protocol	Markers of Mental Fatigue	Maximal Force Production Test	Impact of Mental Fatigue on Maximal Force Production
Budini et al. (2014)	12 ♂ no information on physical activity level	100 min of a switch task test	↓ in cognitive performance	Knee extensors MVC	↓ in MVC
Duncan et al. (2015)	7 active ♂ and 1 active ♀	40 min of a vigilance task	Presence of mental fatigue not measured	4 × 30 s Wingate test	No change in cycling power output
Le Mansec et al. (2018)	12 experienced table tennis ♂ in the mental fatigue group	90 min of AX-continuous performance test	↑ in self-reported fatigue	Elbow flexors MVC	No change in MVC
Martin et al. (2015)	7 active ♂ and 5 active ♀	90 min of AX-continuous performance test	↑ in self-reported fatigue Trend ↓ in cognitive performance	3 min all out cycling test, CMJ, knee extensors MVC	No change in cycling power output, CMJ parameters and MVC
Pageaux et al. (2013)	10 active ♂	90 min of AX-continuous performance test	↑ in self-reported fatigue	Knee extensors MVC	No change in MVC
Pageaux et al. (2015)	12 active ♂	30 min of incongruent Stroop task	↑ in self-reported fatigue	Knee extensors MVC	No change in MVC
Smith et al. (2015)	10 recreationally active ♂	90 min of AX-continuous performance test	↑ in self-reported fatigue	45 min self-paced intermittent running protocol replicating team sports physical demand	No change in high-intensity and peak running velocities

All studies presented in this table are discussed within this chapter. CMJ = counter movement jump; MVC = maximal voluntary contraction.

4.1 EFFECTS ON ISOLATED EXERCISE

As previously briefly stated, it has been suggested that mental fatigue could induce central fatigue (Bray et al., 2012; Di Giulio et al., 2006), defined as a reduction in the voluntary activation level (Gandevia, 2001). As (i) cognition and decision-making process are associated with activation of premotor and motor areas (Morsella et al., 2016; Ramkumar et al., 2016; Tomasino and Gremese, 2016), and (ii) the reduction in voluntary activation level seems to be caused, at least in part, by changes in brain areas upstream of the primary motor cortex (Taylor et al., 2000), it is plausible that prolonged mental exertion leading to mental fatigue could alter maximal muscle activation and, thus impair force production capacity. Pageaux et al. (2013) tested this hypothesis by measuring maximal isometric knee extensors force production and voluntary activation level. Contrary to their hypothesis, the authors did not observe any reduction in maximal voluntary contraction peak torque and voluntary activation level following 90 min of AXCPT leading to mental fatigue. However, this study cannot exclude the possibility that mental fatigue induces a different time course of central fatigue during a physical exercise, leading to a quicker development of central fatigue and a premature disengagement from the subsequent endurance task. Two years later, Pageaux et al. (2015) tested the replication of these results following completion of 30 min of incongruent Stroop Task, as well as following a subsequent 6 min cycling exercise at 80% subjects' peak power output. In line with the results of the aforementioned study, the authors did not observe any reduction in maximal voluntary contraction peak torque and voluntary activation level following the Stroop Task and the cycling exercise. As maximal force production was not decreased to a greater extent in the presence of mental fatigue, these results reinforce the fact that mental fatigue and central fatigue are two distinct phenomena, and also confirmed that the decreased endurance performance in the presence of mental fatigue is mediated by a higher-than-normal perceived effort and not by central fatigue.

These observations on the knee extensors have been confirmed by Martin et al. (2015) and extended to the upper limbs during isometric elbow flexions by Le Mansec et al. (2018). Taken all together, the aforementioned studies suggest that prolonged mental exertion leading to mental fatigue does not reduce the ability of a muscle group to produce maximal force. Consequently, the evaluation of a muscle group force production capacity for clinical evaluation, rehabilitation or pre-season evaluation purposes can be performed following prior mental exertion without affecting the validity of the test performed. However, it has to be noted that one study observed a reduction in isometric knee extensors MVC following 100 min of a demanding cognitive task (Budini et al., 2014), in association with a reduced tremor during submaximal contractions. Consequently, future investigations should replicate the experimental design of the previous studies to firmly confirm the absence of effects of mental fatigue on force production capacity during isolated exercise.

4.2 EFFECTS ON WHOLE-BODY EXERCISE

Most maximal efforts during sporting events, such as sprinting or jumping, require the fine coordination between different muscle groups. Therefore, it seems of great importance to test the reproducibility of the results obtained during isolated exercises with maximal whole-body exercises. Duncan et al. (2015) demonstrated that a 40-min engagement in a demanding cognitive task leading to mental fatigue does not impair cycling power production capacity during four Wingate tests interspaced by 4 min of recovery. The Wingate test lasts only 30 s; it cannot be excluded that a longer all-out effort could be negatively impacted by the presence of mental fatigue. Martin et al. (2015) rejected this possibility with a study where mental fatigue induced by 90 min of AXCPT did not reduce power output during a 3-min all-out cycling exercise. These authors also demonstrated that counter movement jump performance parameters were not affected by mental fatigue. Finally, the lack of impact of mental fatigue on cycling power production capacity has also been observed for running exercise. In a study investigating the effects of mental fatigue on self-selected running velocities, Smith et al. (2015) demonstrated that only submaximal running velocities, and not sprint running velocities, decreased following mental exertion leading to mental fatigue.

By integrating the results gathered during isolated and whole-body exercises, it exists strong experimental evidences that mental fatigue does not reduce the ability of an athlete to maximally use his working muscles. In other words, when mentally fatigued, we can still jump as high and sprint as fast as usual. Therefore, it seems that the negative impact of mental fatigue on sport-related performance is confined to submaximal exercise requiring regulation of the physical effort over time.

5 MENTAL FATIGUE ALTERS MOTOR SKILLS PERFORMANCE

In this section, motor skills performance refers to the ability of an athlete to perform goal-directed movements during isolated or whole-body exercise. Studies included in this section (see Table 3) include measurement of goal-directed movements in a controlled laboratory environment (e.g., pointing tasks) or in the field (e.g., soccer shooting accuracy test).

5.1 MENTAL FATIGUE ALTERS THE SPEED-ACCURACY TRADE-OFF

In a laboratory controlled environment, motor control and motor skills are well investigated in the neuroscience literature via the use of pointing task (e.g., Missenard et al., 2009; Rozand et al., 2015). In such experimental protocol, participants have to point targets of various sizes located at different locations as fast and accurately as possible. By manipulating the target sizes and the distance between targets, it is possible to modulate the movement difficulty and therefore to investigate the

Table 3 Comprehensive List of Studies Investigating the Impact of Mental Fatigue on Motor Skills Performance

References	Subjects	Mental Fatigue Protocol	Markers of Mental Fatigue	Motor Skills Test	Impact of Mental Fatigue on Motor Skills Performance
Badin et al. (2016)	20 soccer ♂	30 min of incongruent Stroop task	↑ in self-reported fatigue	Small-sided game, video analysis of technical variables	↓ in passing accuracy and tackle success
Duncan et al. (2015)	7 active ♂ and 1 active ♀	40 min of a vigilance task	Presence of mental fatigue not measured	Minnesota Manual Dexterity Turning test	↑ in time to complete the test
Le Mansec et al. (2018)	22 experienced table tennis ♂	90 min of AX-continuous performance test	↑ in self-reported fatigue	Table tennis performance test	↓ in table tennis stroke accuracy and ↓ in ball speed
Smith et al. (2016a)	14 experienced soccer ♂	30 min of incongruent Stroop task	↑ in self-reported fatigue	Loughborough Soccer Passing Test and Shooting Test	↑ in penalty time, ↓ in shot speed and accuracy
Smith et al. (2017)	14 experienced soccer ♂	30 min of incongruent Stroop task	↑ in self-reported fatigue	Loughborough Soccer Passing Test	↓ in passing accuracy, no change in movement speeds
Rozand et al. (2015)	10 active ♂	90 min of incongruent Stroop task	↑ in self-reported fatigue	Pointing task with different difficulty level	↑ in movement duration at all difficulty levels
Rozand et al. (2015)	6 ♂ and 6 ♀, no information on physical activity level	100 imagined pointing movements, =30 min	↑ in self-reported fatigue	Pointing task	↑ in movement duration
Veness et al. (2017)	12 elite cricket ♂	30 min of incongruent Stroop task	↑ in self-reported fatigue	Cricket-run-two test	↑ in time to complete the test

All studies presented in this table are discussed within this chapter.

relation between the movement speed and the movement difficulty. It is well known that it exists a relationship between the movement speed and the movement accuracy (i.e., speed-accuracy trade-off), with the movement duration increasing in relation to the movement difficulty (Fitts, 1954; Fitts and Peterson, 1964). While muscle fatigue has been shown to increase the movement duration (Missenard et al., 2009), until 2015, no study investigated the possible negative effects of mental fatigue on movement duration. Following a 90-min engagement in the Stroop task, Rozand et al. (2015) demonstrated that mental fatigue increased the movement duration of both actual and imagined movements (Fig. 2). Due to (i) the concomitant alteration of both actual and imagined movements, and (ii) the prolonged activation of the anterior cingulate cortex during highly demanding cognitive tasks and its role in cognition, movement preparation and action monitoring (for review, see Paus, 2001), the authors proposed a negative impact of mental fatigue on the preparatory state of movement execution (Rozand et al., 2015). The observed increased movement duration in the presence of mental fatigue has been replicated by Duncan et al. (2015) who demonstrated an increased time to complete a manual dexterity test.

Of particular interest for training and rehabilitation purposes, Rozand et al. (2016) extended this observation to mental fatigue induced by prolonged motor

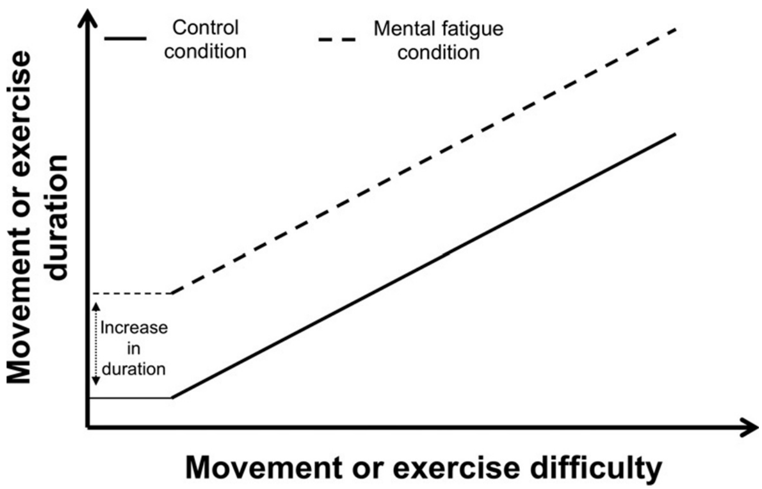

FIG. 2

Theoretical explanation of the negative impact of mental fatigue on motor skills performance. Increasing the movement difficulty leads to an increase in the movement duration (black line). In the presence of mental fatigue (doted line) we can observe an increase in movement or exercise duration at all difficulties. This figure is an illustration of the results of Rozand et al. (2015) investigating the impact of mental fatigue on movement duration during pointing tasks of different difficulties. It also illustrates the results of other studies included in this chapter and showing an increased sport-specific movement or exercise duration at a given difficulty.

imagery. The authors observed that imagining 100 pointing movements induced mental fatigue and slowed down the movement duration of actual movement. Therefore, caution should be taken with the duration of motor imagery sessions during training sessions, and actual movement should be regularly performed to avoid inducing a state of mental fatigue (Rozand et al., 2016). Taken altogether, the slower movement duration during movement performed with the upper limb in the presence of mental fatigue suggests a possible reduced performance in specific isolated upper-limb movements requiring a high speed or power and a high accuracy, such as fencing attacks or boxing punches.

5.2 MENTAL FATIGUE ALTERS SPECIFIC SPORT-TECHNICAL SKILLS

Outside the laboratory, motor control is traditionally investigated with testing involving the completion of specific sport-technical skills. As mental fatigue alters the speed-accuracy trade-off, it is likely that more complex sport-technical skills such as soccer passing or shooting could be also impaired. This hypothesis has been confirmed first by Smith et al. (2016a) who observed a decrease in shot speed and accuracy in soccer players. Other studies confirmed a decrease in soccer-technical performance in the presence of mental fatigue by exhibiting an altered passing accuracy and tackle success (Badin et al., 2016; Smith et al., 2016a, 2017). Importantly, the impact of mental fatigue goes beyond soccer specific technical performance. Le Mansec et al. (2018) demonstrated a reduction in ball speed and accuracy during a table tennis performance test involving 45 forehand strokes. Veness et al. (2017) also demonstrated a reduction in cricket-technical skills performance in the presence of mental fatigue via the completion of the run-two cricket test, an English Cricket Board standard test.

By integrating the results gathered from the aforementioned experiments involving the upper-limbs (e.g., table tennis stroke) and the lower-limbs exercise (e.g., soccer pass accuracy), it seems clear that mental fatigue impairs the execution of sport-related specific technical skills in both upper and lower limbs. It is likely that the negative impact of mental fatigue could be extended to other sport motor skills such as basketball free throw, rugby drop-goal or darts throwing. Therefore, we suggest avoiding any prolonged demanding cognitive tasks before competitions. We also suggest that to prevent the negative impact of mental fatigue on performance during sporting events, coaches should include specific technical training in the presence of mental fatigue to train the athletes to coop with the presence of mental fatigue.

6 MENTAL FATIGUE ALTERS SPORT-RELATED DECISION-MAKING

In this section, we focus on the impact of mental fatigue on sport-related decision making. Decision-making is important in sport performance as it includes cognitive processes involved in the multitude of action observed on the field. It could be related to the ability of an athlete to accurately evaluate a ball trajectory to catch it, or the ability of a team sport player to choose the best pass option and place his teammate in the best position to score a goal.

It is well known in the neuroscience and psychology literature that mental fatigue decreases cognitive performance and consequently negatively impact decision-making during laboratory controlled tests (e.g., Boksem and Tops, 2008; Boksem et al., 2005, 2006). For example, it has been shown that mental fatigue alters coincidence anticipation (Duncan et al., 2015). Since 2016, several studies confirmed these results on the field with tests specifically designed in line with the demand of different sports. Studies focusing on soccer demonstrated alterations in specific soccer-decision making skills (Smith et al., 2016b), as well as alteration in players positioning on the pitch (Coutinho et al., 2018). With regard to the impact of mental fatigue on engagement in training sessions, Head et al. (2016) demonstrated an alteration in the strategy to engage in a bodyweight training, as showed by a decreased time on task. The same research group, in a subsequent study (Head et al., 2017), also demonstrated impairment in soldiers' decision to shoot the correct target, suggesting a possible negative impact on sport involving pistol-shooting performance. Finally, Veness et al. (2017) demonstrated a decreased performance induced by mental fatigue in a test specifically designed to assess hand-eye coordination.

Taken all together, the aforementioned studies (see Table 4) suggest a negative impact of mental fatigue on the decision taken by the athletes during sporting events. This negative impact of mental fatigue on sport-related decision-making skills might be specifically relevant to team sports where decisions are important within a game (e.g., pass selection, tactical positioning).

7 CONCLUSION AND PERSPECTIVES FOR FUTURE STUDIES

The present chapter, by reviewing the results of 29 studies published from 2009 to April 2018, presents strong experimental evidence that mental fatigue does impair sport-related performance. However, it has to be noted that contrary to endurance performance, motor skills performance and decision-making performance, maximal force production is not altered by the presence of mental fatigue. This important observation suggests that the negative impact of mental fatigue on sport-related performance is confined to any exercise involving regulation of the athlete effort over time.

In line with the previous conclusion, the negative impact of mental fatigue on sport-related performance is likely due to a higher perception of effort, a perception thought to be involved in the engagement and the regulation of physical behavior (Cos, 2017; De Morree and Marcora, 2015; Hreljac, 1993; Marcora, 2016; Pageaux, 2016; Pageaux and Gaveau, 2016). Consequently, future studies should investigate the underlying mechanisms causing the increased perceived effort in the presence of mental fatigue. Such advances will provide important knowledge regarding the neurophysiological mechanisms of mental fatigue and could lead to the

Table 4 Comprehensive List of Studies Investigating the Impact of Mental Fatigue on Sport-Related Decision Making Performance

References	Subjects	Mental Fatigue Protocol	Markers of Mental Fatigue	Sport-Related Decision Making Performance Test	Impact of Mental Fatigue on Sport-Related Decision Making Performance
Coutinho et al. (2018)	10 youth ♂ soccer players	30 min of incongruent Stroop task	Presence of mental fatigue not measured	Small-sided game, video analysis of tactical variables	Alteration of players positioning on the pitch
Duncan et al. (2015)	7 active ♂ and 1 active ♀	40 min of a vigilance task	Presence of mental fatigue not measured	Coincidence anticipation test	↑ in errors
Head et al. (2016)	11 active ♂ and 7 active ♀	52 min of a vigilance task	↓ in cognitive performance	Time on task in bodyweight resistance training	↓ in time on task
Head et al. (2017)	20 ♂ infantry soldiers	49 min of a sustained attention to response task	↓ in cognitive performance	Marksmanship task	↑ in errors (shooting the wrong target) with no change in shooting accuracy
Smith et al. (2016b)	12 experienced soccer ♂	30 min of incongruent Stroop task	↑ in self-reported fatigue	Soccer-specific decision-making task	↓ in accuracy and ↑ in response time
Veness et al. (2017)	12 elite cricket ♂	30 min of incongruent Stroop task	↑ in self-reported fatigue	Batak Lite hand-eye coordination test	Trend ↓ in total score

All studies presented in this table are discussed within this chapter.

development of new training methods or intervention aiming at counteracting the negative impact of mental fatigue, with application beyond the field of sport-related performance. As an example, caffeine has recently been shown to counteract the negative impact of mental fatigue on physical and cognitive performance (Azevedo et al., 2016; Van Cutsem et al., 2018), as well as to reduce self-reported fatigue during a golf event (Mumford et al., 2016).

Finally, as muscle fatigue is well known to differently impact men and women performance (Hunter, 2016), and men and women present differences in perception and response to stress (e.g., Maffiuletti et al., 2008; Pereira et al., 2015; Yoon et al., 2009), there is an urgent need for studies aiming at investigating sex differences in resistance to mental fatigue. Such studies could lead to the development of tailored training methods that takes into account differences in mental fatigue resistance between men and women.

AUTHOR CONTRIBUTIONS

B.P. drafted the manuscript. B.P. and R.L. edited and revised the manuscript. B.P. and R.L. approved the final version of the manuscript.

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