Sports Medicine (2021) 51:1527–1548
https://doi.org/10.1007/s40279-021-01429-6

SYSTEMATIC REVIEW

Mental Fatigue and Sport-Specific Psychomotor Performance: A Systematic Review

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Accepted: 27 January 2021 / Published online: 12 March 2021

Abstract

Background Mental fatigue (MF) is a psychobiological state that impairs endurance performance in healthy athletes. Recently, multiple studies indicated that MF could also impair sport-specific psychomotor performance (SSPP). Nevertheless, a systematic overview detailing the effects of MF on SSPP is currently lacking.

Objective The objective of this study is to collate relevant literature and examine the effect of MF on SSPP. A secondary aim was to create an overview of the potential subjective and physiological factors underlying this MF effect.

Methods PubMed (MEDLINE), Web of Science, PsycINFO and SPORTDiscus were searched (5th of November 2020). Studies were eligible when study outcomes encompassed any form of SSPP skill in a sport-specific context, the intervention was targeted to induce MF, and the population included healthy individuals. The presence of a manipulation check, to indicate the successful induction of MF, was obligatory for inclusion. Secondary outcomes were all outcomes (either physiological or psychological) that could explain the underlying mechanisms of the effect of MF on SSPP.

Results In total, 21 papers were included. MF was successfully induced in all but two studies, which were excluded from further analysis. MF negatively impacts a myriad of SSPP outcomes, including decision-making, reaction time and accuracy outcomes. No changes in physiological outcomes, that could underlie the effect of MF, were reported. Subjectively, only ratings of perceived of exertion increased due to MF in some studies.

Conclusions Overall, the selected papers indicated that MF negatively affects SSPP. Research that assesses brain function, while evaluating the effect of MF on SSPP is essential to create further insight.

1 Introduction

Mental fatigue (MF) is a psychobiological state that arises during prolonged demanding cognitive activity and results in an acute feeling of tiredness and/or a decreased cognitive ability [1–3]. In healthy individuals, MF has been found to impair both physical and cognitive performance by compromising planning [4], reducing sensorimotor function [5], increasing risk of error [6], and decreasing cognitive control [7] and emotion regulation [8]. Possible mechanisms underlying these MF effects are linked to complex neural mechanisms [9, 10], motivation [11, 12] and resource depletion (e.g., brain phosphocreatine) [13, 14]. Although the consequences of MF have been assessed in multiple fields of research, the exact mechanisms leading to the occurrence of MF remain unknown [15].

About a decade ago the focus on the effects of MF on physical performance was introduced in sport science by Marcora et al. [3]. They observed that cycling time to exhaustion worsened due to MF. Remarkably, this performance decrement was not associated with a change in any of the measured physiological parameters (e.g., oxygen uptake, lactate concentration, and heart rate). The impaired physical performance was solely associated with an increased rating of perceived exertion (RPE) [3]. Recently published systematic reviews further confirmed these findings and indicated

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Key Points

Mental fatigue impairs sport-specific psychomotor performance in a variety of sports.

Apart from perception of effort, no other physiological or psychological mediators of the effect of mental fatigue on sport-specific psychomotor performance could be detected. Future research should try to investigate the possible important role of the brain in this effect.

Coaches and staff that are employed in sports involving psychomotor performance need to be aware that the sport-specific performance of players can be negatively influenced by mental fatigue.

that MF impairs dynamic as well as isometric endurance performance [2, 16, 17]. However, MF does not seem to impair maximal anaerobic performance in healthy humans [2, 16, 17]. Another important area of the sports context is sport-specific psychomotor performance (SSPP), yet this area was often overlooked in MF research at the beginning of the previous decade [18], possibly due to the difficulty in assessing SSPP. SSPP can be defined as highly complex motor behaviour that results from the cognitive processing of sensory and perceptual information in a sport-specific context [19]. Typical outcome measures of SSPP encompass reaction time and accuracy. Recently, the focus of MF-research has shifted to this aspect of the sports context, as evidenced by an increased number of scientific publications on the topic of MF and sport-specific psychomotor tasks in the last three years [18].

Overall, a mainly negative impact of MF on SSPP was apparent in topic-related narrative reviews [16, 18] and one soccer-specific systematic review [20]. Amongst others, MF impairs sport-specific cricket [21] and table tennis [22] performance, marksmanship decision-making performance [23], and soccer-specific technical and perceptual-cognitive psychomotor performances [20, 24–26]. Athletes, athletic coaches and sports clinicians are also aware and acknowledge that MF negatively affects athletic performance and are looking for strategies to counter MF to optimize training and performance outcomes [18, 27]. Furthermore, a slower reaction time and decreased accuracy have been associated with an increased sport injury risk [28, 29]. A thorough and systematic survey of available evidence could further inform the sporting community which SSPP outcomes are affected by MF. This would enable the relevant stakeholders to make better decisions about which performance outcomes to monitor in relation to MF and potentially counter MF. Nonetheless, a robust systematic literature review on the state-of-the art of MF and whether it affects SSPP outcomes is currently lacking. Therefore, the primary aim of this systematic review was to examine whether MF affects SSPP. Alongside this primary aim, the goal was also to critically review the included literature on the methodology used to induce MF and provide recommendations for future research on mental fatigue-inducing methods.

Besides the effect of MF on SSPP, our insight into the underlying mechanisms of the MF-associated impairment in SSPP is limited. Recently, Giboin et al. [30] provided some insights in this matter. In their meta-analyses, Giboin et al. [30] suggested that MF impacts subsequent physical performance if it requires mental effort (see Giboin et al. [30] for a definition of mental effort). Important factors that contribute to a physical performance requiring mental effort are the attentional demand of the physical task and motivational processes [30]. Subsequently, Giboin et al. [30] provided results that demonstrate there is truth in these suggestions. In terms of attentional demand, Giboin et al. [30] reported that the negative impact of mental fatigue on isolation tasks (i.e., local muscle endurance tasks) is greater than on whole-body endurance tasks (e.g., cycling, running). Based on the idea that isolation tasks, with their often-specific task demands (e.g., produce and maintain a certain force at a specific level), place higher demands on the attentional capacity than whole-body endurance tasks, one can interpret this finding to substantiate a role for attentional demand in the MF-associated drop in physical performance. While for the role of motivational processes, the observation that the MF-associated reduction in performance is higher when the person-situation fit is low (e.g., when a non-cyclist is asked to perform a cycling task) [30] can serve as substantiation. Despite these first insights in the role of attentional demand and motivational processes, further research is required to confirm these notions.

Therefore, our secondary aim in the present systematic review was to display and interpret the effects of MF on the physiological and psychological outcomes that were monitored in the included studies and which helped to explain the underlying mechanisms of the MF-effect on SSPP. Moreover, the present review also provides the opportunity to interpret whether task representativeness (i.e., the degree to which perception and action are coupled similarly to the performance context [31]) and subject expertise (i.e., the degree to which subjects demonstrate expert performance [32]), two factors that are known to impact attentional demands and motivational processes [33, 34], play a role in the MF-associated SSPP-impairment. This would significantly increase our insight into the role of attentional demands and motivational processes in the MF-effect. Based on MF-research within generic motor behaviour [7, 35–37] it can be hypothesized that the effect of MF will be less present with high level-athletes, i.e., when sport-specific motor behaviour becomes more automatized (see for example Martin et al. [38]).

2 Methods

This systematic review was made in accordance with the "Preferred Reporting Items for Systematic review and Meta-analyses (PRISMA)" guidelines [39]. Details of the review protocol were registered on PROSPERO (ID: CRD42020157178) and can be accessed at https://www.crd.york.ac.uk/prospero/display_record.php?ID=CRD42020157178.

2.1 Eligibility Criteria

Studies were eligible when study outcomes encompassed any form of sport-specific psychomotor skills (= primary outcome of this systematic review), the intervention was targeted to induce MF, and the population included healthy individuals. The following terms were accepted as possible equivalents of MF: mental fatigue, cognitive fatigue, self-control strength depletion and ego depletion. The sport-specific psychomotor skill requirement was met when a study assessed highly complex motor behaviour resulting from the cognitive processing of sensory and perceptual information in a sport-specific context [19]. To consider a psychomotor skill to be sport-specific, one had to relate to sport performance (e.g., reaction time, accuracy, decision-making skills, etc), while measurements were conducted in a sport-specific context (i.e., high task representativeness; e.g., small sided soccer games to test soccer performance). Furthermore, an evaluation of the SSPP after the MF-inducing intervention was required. When available in studies, control tasks had to serve the purpose of not inducing MF or at least triggering less MF than the intervention task. Only randomised controlled trials, non-randomised controlled trials or non-randomised non-controlled trials published in peer-reviewed scientific journals were considered eligible. No limitations concerning age, sex and study language were applied. In accordance with the review of Van Cutsem et al. [2] we also stress that the present review does not include dual-task performance studies. Moreover, studies were excluded when no manipulation check that substantiated the presence of MF, was reported. The manipulation check could be behavioural (e.g., Stroop task performance), subjective [e.g., visual analogue scale (VAS)] and/or (neuro)physiological [e.g., electroencephalography (EEG)]. Additionally, secondary outcomes were all outcomes, either physiological (e.g., heart rate) or psychological (e.g., RPE), that could help explain the underlying effects of a possible change in SSPP.

2.2 Information Sources and Search Strategy

The sources used in this review were the PubMed (MEDLINE) database (best match option), Web of Science (WoS) database (all databases searched), the PsycINFO database and the SPORTDiscus database. All databases were searched up to the 5th of November 2020. There were no limits applied to the employed databases. The complete search strategy of all databases can be found in Table 1.

2.3 Study Selection

Articles were gathered from all databases and duplicates were removed using the open source Mendeley-software.

Table 1 Number of hits for the complete search strategy for the PubMed (MEDLINE), Web of Science, PsycINFO and SPORTDiscus databases

Database	Complete search strategy	Hits (05/11/2020)
PubMed (MEDLINE)	(((((((performance) OR "Athletic Performance"[Mesh]) OR skills) OR speed) OR accuracy) OR "Psychomotor Performance"[Mesh])) AND (((((((((("mental strain") OR "cognitive strain") OR "mental fatigue") OR "Mental Fatigue"[Mesh]) OR "central fatigue") OR "cognitive fatigue") OR "cognitive exertion") OR "mental exertion") OR "self-control strength depletion") OR "ego depletion")	1810
Web of Science	TS = ((performance OR skills OR speed OR accuracy) AND ("mental strain" OR "cognitive strain" OR "mental fatigue" OR "central fatigue" OR "cognitive fatigue" OR "cognitive exertion" OR "mental exertion" OR "self-control strength depletion" OR "ego depletion"))	2902
PsycINFO	("mental fatigue" OR "central fatigue" OR "cognitive fatigue" OR "central fatigue" OR "cognitive exertion" OR "mental exertion" OR "mental strain" OR "cognitive strain" OR "self-control strength depletion" OR "ego depletion") AND (performance OR skills OR speed OR accuracy)	893
SPORTDiscus	("mental fatigue" OR "central fatigue" OR "cognitive fatigue" OR "central fatigue" OR "cognitive exertion" OR "mental exertion" OR "mental strain" OR "self-control strength depletion" OR "ego depletion") AND (performance OR skills OR speed OR accuracy)	478

Then, all retrieved studies were imported into Rayyan [40], where two authors (J.H. and J.V.C.) screened the articles on title and abstract. Following the first screening stage, the screening process progressed with five authors (J.H., J.V.C, J.V., S.D.B. and B.R.) who assessed the remaining full text articles for eligibility. A general meeting with all authors was held to decide on final in- or exclusion. All included articles were assessed for risk of bias and reference lists and citations were checked in this stage of the review process, to make sure that no eligible articles were missed.

2.4 Data Extraction

The effects of mental fatigue on sport-specific psychomotor skills and associated secondary outcomes (see 2.1 Eligibility criteria) were collected from the included articles. Extracted details of these outcomes included: the used outcome task, the effect of the intervention and the effect size [ES; Cohen's *d* and dz, h^2, partial eta square (η^2) and standardized mean difference (SMD)]. Other information that was extracted included study design, participant demographics, intervention details, manipulation check, sample size, treatment groups, control and statistical analysis. Missing data were not pursued in any form and were, if relevant, added to the risk of bias assessment.

2.5 Risk of Bias Assessment

The Revised Cochrane Risk of Bias tool for randomized trials (RoB 2.0) was used to determine risk of bias of the individual studies independently by three authors (J.V., M.P. and J.D.W.). Based on the signalling questions provided in the RoB 2.0-tool, each of these five domains received a rating which was either "low risk of bias", "high risk of bias" or "some concerns of bias". Finally, an overall risk of bias judgement was made for each study. The authors followed the guidelines provided by the Cochrane community. Disagreements between authors were resolved through discussion and consensus.

3 Results

3.1 Study Selection

The systematic literature search yielded 3739 unique articles. After full text screening, 21 studies were included in this systematic review. A forward search (i.e., assessing the citations of the included articles) and backward search (i.e., assessing the reference lists of the included articles) provided no additional papers. The level of agreement between the two authors that participated in the title and abstract screening was 99.97%. The level of agreement between the five authors that participated in the full texts screening was 82.20%. The full study selection process is presented in Fig. 1.

3.2 Risk of Bias

The level of agreement between the three authors who assessed the risk of bias of the included articles was 93.3%. Risk-of-bias assessment of the 21 included studies with the RoB 2-tool determined that 20 studies had high risk of bias, while only the study of Gantois et al. [41] was scored as having some concerns of bias (see Figs. 2, 3). The main items that resulted in an overall high risk of bias in 20 of the 21 studies were inadequate blinding of participants and personnel (which is challenging in this line of research; e.g., keeping participants naïve to the aims and hypotheses of the study, to avoid possible expectancy-effects), the use of patient-reported outcome measures (e.g., visual analogue scales) and the employment of statistical techniques like magnitude-based interferences.

3.3 Study Characteristics

All information regarding relevant study characteristics can be found in Table 2. The total population of all articles was 522 participants. The ratio of male–female participants was 67%–33% (260 males and 130 females, for a total of 390 participants). The average age of the participants ranged from 13.5 years [42] to 26.9 years [22]. The selected studies used a variety of different populations, ranging from untrained to trained to elite participants. The sports that were investigated by the selected studies included soccer [24–26, 41–48], sprint [49, 50], shooting/aiming sports [23, 51], racket sports [22, 52, 53], basketball [54], golf [55], and cricket [21].

3.4 Mental Fatigue-Inducing Interventions

Most studies ($n = 13$) selected a Stroop task to induce MF (see Table 2). The Stroop tasks were either incongruent [21, 25, 46, 47, 51–54], a combination of both incongruent and congruent [24, 41, 44] or a combination of a Stroop task with another cognitive task [42]. One study used a Stroop task which was administered via "the Stroop effect" app for Android systems [45]. Other interventions that were used to induce MF were mainly other forms of a demanding cognitive task, such as a transcription task [49, 50, 55], smartphone use [43, 48], playing video games [43], sustained attention to response task [23] and the AX-Continuous Performance Test (AX-CPT) [22]. One study [26] used a whole-body coordination task to induce MF. The duration of the interventions differed across studies, and ranged from a 6-min transcription task [49, 50] to a 90-min modified Stroop task [52].

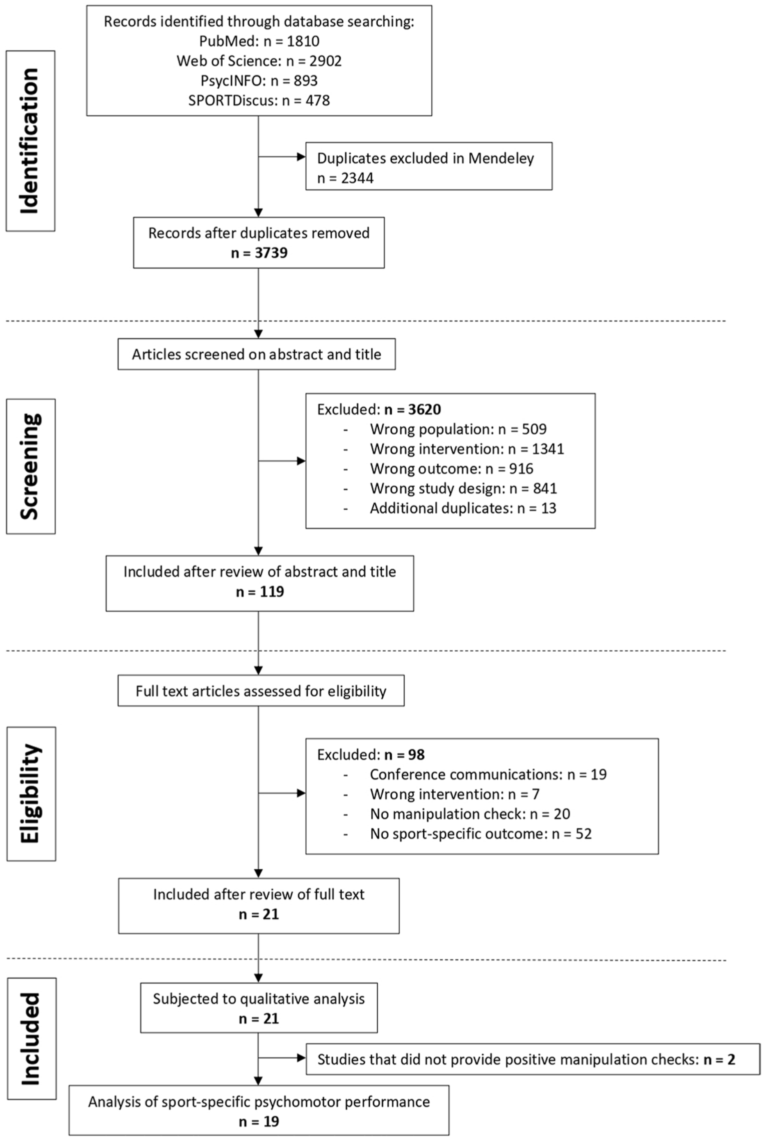


Fig. 1 PRISMA chart

The control tasks used by the included studies varied widely and encompassed watching documentaries [23, 24, 45, 52, 53], movies [22], advertising videos [41, 43], or coaching videos [48]; transcribing a neutral text [49, 50]; performing light aerobic exercises [26], or relaxation [54]; reading shopping [55] or emotionally neutral magazines [21, 25, 46, 47]; performing a modified (congruent) Stroop task [51]; a variety of the aforementioned interventions ("reading emotionally neutral magazines, watching non-arousing football highlights, talk to other participants") [42]; and no control task [44]. Most studies ($n = 19$) matched the duration of their control task with their mentally fatiguing task, except for the studies by Coutinho et al. [44], where no control task was used, and by Filipas et al. [46], which used a 15-min control task compared to a 30-min intervention.

3.5 Manipulation Checks

17 Studies used one or more subjective manipulation check(s). These include a VAS to assess self-reported MF [21, 22, 24–26, 42, 44–47, 51–53]; RPE (measured by the CR10 scale [26, 51]); Likert scale (4-point Likert scale [49, 55] and 7-point Likert scale [50]); and the Brief Mood Inspection Scale [51]. All subjective manipulation checks showed an increase in MF in the experimental condition, with the exception of the study by McEwan et al. [51]. Seven studies used a behavioural manipulation check: assessing performance on the transcription task [49, 50], assessing differences in accuracy [43, 46, 48, 52–54] and reaction time [43, 46, 48, 53, 54] on the Stroop task, and assessing the amount of errors of omission [23] and the amount of

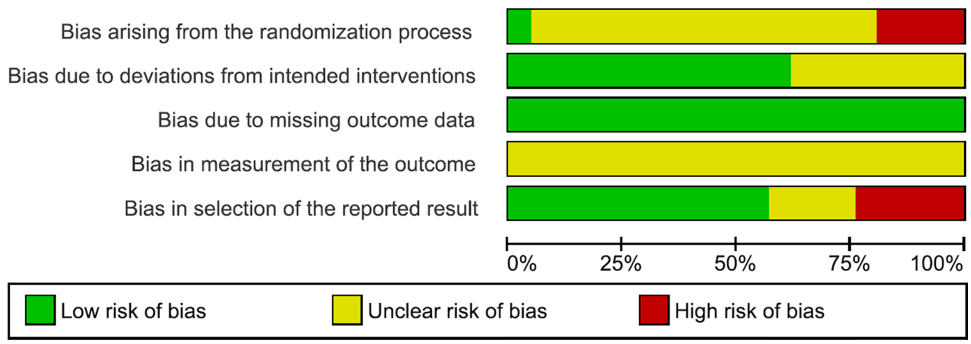


Fig. 2 Risk of bias across studies

toss errors [51]. All but three studies [46, 51, 54] showed significant signs of the presence of MF in the experimental group when examining the employed behavioural manipulation checks. Only one study used a physiological manipulation check: Head et al. [23] included heart rate variability to assess MF and found a decrease in heart rate variability in MF versus the control condition. Since the studies of McEwan et al. [51] and Moreira et al. [54] could not demonstrate that MF was successfully induced, they were excluded from further analysis (see Fig. 1).

3.6 The Effect of MF on Sport-Specific Psychomotor Performance

All available results regarding the SSPP outcomes (i.e., SSPP outcomes and results, ES, significance and performance related physiological and psychological measurements) can be found in Table 3. All studies were subdivided in categories based on the sport in which the psychomotor outcomes were evaluated. Additionally, Table 4 shows an overview of all individual outcomes of the included studies divided by sport and the direction (positive/negative/no effect) of the effect of MF.

3.6.1 Soccer

The tasks employed in the eleven identified studies [24–26, 41–48] could be divided into two specific categories in which soccer-specific psychomotor performance had been evaluated: during a soccer specific task [25, 42, 46, 47] or during a simulated soccer match [24, 26, 41, 44, 48]. Soccer specific tasks include the "Footbonaut" system 4 [42], a soccer specific decision-making task [47], and the Loughborough soccer passing and shooting tests [25, 46]. Vogt et al. [42] found no difference in performance on the "Footbonaut" task between the MF and the control condition [speed of action (mean ± SD): MF = 0.88 ± 0.15 s; control = 0.94 ± 0.11 s/ball control (mean ± SD): MF = 4.32 ± 0.15 points; control = 4.20 ± 0.18 points]. In contrast, two studies [25, 47] found a negative effect of MF on soccer-specific performance. Performance on a soccer specific decision-making task [47] [i.e., decrease in overall response time (mean ± SD: MF = 768 ± 134 ms; control = 685 ± 156 ms; ES: 0.49 ± 0.47), overall accuracy (mean ± SD: MF = 80.9 ± 6.4%; control = 85.7 ± 4.9%; ES: − 0.89 ± 0.73)] and performance parameters [e.g., penalty time (mean ± SD: MF = 9.9 ± 6.5 s; control = 5.2 ± 7.6 s; ES: 0.76) and shot accuracy (mean ± SD: MF = 1.3 ± 0.6 points; control = 2.0 ± 0.5 points; ES: 0.75)] of the Loughborough soccer passing and shooting test [25] were found to be impaired due to MF. Lastly, Filipas et al. [46] also investigated the effect of MF on the Loughborough soccer passing and shooting test while dividing the population based on age. The only significant negative effects of MF were found on performance of the Loughborough soccer passing test in the U18 group [original time (mean ± SD: MF = 51.90 ± 5.0; control = 49.1 ± 3.9; $p = 0.013$), penalty time (mean ± SD: MF = 15.3 ± 4.7; control = 8.0 ± 3.1; $p < 0.001$) and performance time (mean ± SD: MF = 67.2 ± 7.4; control = 57.2 ± 6.7; $p < 0.001$)]. Methods used to evaluate SSPP during a soccer match were small sided soccer games (6×6 [26], 5×5 [24] and 4×4 [44, 45]), a full training match [41] and a simulated soccer game [43, 48]. All studies that used small sided soccer games found decreases in at least multiple of the measured tactical and technical variables [e.g., pass accuracy (mean ± SD: MF = 81 ± 7%; control = 83 ± 8%; ES = − 0.25), longitudinal synchronization (mean ± SD: MF = 44.2 ± 10.5%; control = 47.9 ± 10.2) and contraction speed (Δ_{mean} = − 14.2 ± 10.2 in MF compared to control)] in the MF condition compared to the control condition [24, 26, 44, 45]. Also, in the full training match and simulated soccer games a negative effect of MF was reported; passing decision-making was always impaired when the MF intervention lasted 30 min or longer [41, 43, 48]. No decline in passing decision-making was observed in the conditions when the MF-intervention lasted for 15 min [41, 48].

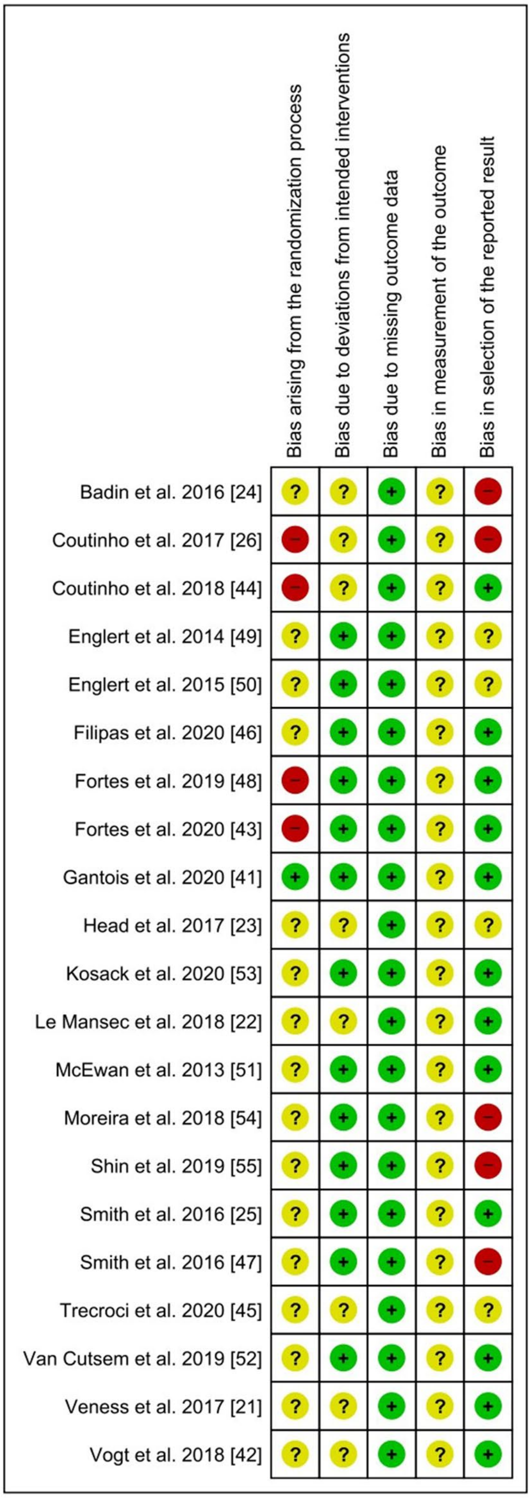


Fig. 3 Risk of bias within studies (+ = low risk of bias; ? = unclear risk of bias; – = high risk of bias)

3.6.2 Sprint Start

Two studies by the same author examined the effect of MF on sprint start performance [49, 50]. Participants were asked to perform three maximal sprints of 10 m [49] or 20 m [50], before and after a transcription task. To evaluate performance, reaction time and false starts were assessed in both studies [49, 50]. Englert et al. [49] observed a slower reaction time when mentally fatigued (Δ_{mean} reaction time = 27 ms; ES = 0.18), while no significant difference was present in reaction time from pre to post in the control group. There were no false starts in both groups. In the follow-up study, Englert et al. [50] found a significant negative effect of MF on the number of false starts (Δ_{mean} number of false starts = 0.89; ES = 0.50). Reaction time could, however, not be analysed because of the abundance of false starts in both groups [50].

3.6.3 Shooting/Aiming

Head et al. [23] was the only study to use a marksmanship performance task to examine the possible negative effect of MF on this outcome. This marksmanship task was a high-shoot, low no-shoot target detection task which requires "active response inhibition" (three types of targets, and only one target was to be shot at) [23]. There was no significant effect on hit proportion, distance of the centre of the shot group (i.e., how close a group of shots are relative to the centre aiming point of a target), shot group precision (i.e., how close a group of shots are to each other), errors of omission and response time in the MF condition compared to the control condition [23]. The only observed significant effect was a negative effect in the MF condition on marksmanship decision accuracy (i.e., shots taken during exposure of a no shoot target; mean ± SD: MF = 48.05 ± 22.42%; control = 32.00 ± 17.94%) compared to the control condition [23].

3.6.4 Racket Sports

Three studies [22, 52, 53] examined the effect of MF on SSPP related to racket sports. Le Mansec et al. [22] evaluated table tennis performance when mentally fatigued, while Van Cutsem et al. [52] and Kosack et al. [53] assessed performance in badminton players. Concerning table tennis performance, Le Mansec et al. [22] found a decrease in ball speed (− 2.2 ± 3.5%) and total score (i.e., target reached = 2 points, target not reached but ball on the table = 1 point, fault = 0 points; − 6.6 ± 8.9%) and an increase in the number of faults (+ 5.4 ± 6.3%) when mentally fatigued compared to the control condition. In addition, Van Cutsem et al. [52] found that MF made trained badminton players and controls react slower (+ 90 ± 7 ms) during a visuomotor

Table 2 Overview of population characteristics, mental fatigue inducing interventions and manipulation checks

References	Sample	Characteristics	Intervention	Control	Duration	Outcome
Badin et al. [24]	20 Soccer players	Age: 17.80 ± 1.00 y Mass: 72.40 ± 6.80 kg Height: 179.00 ± 5.00 cm Level: Australian National Premier League soccer club	50% Incongruent Stroop task	Documentary	30 min	S: MF ↑ in I vs C (assessed using VAS) (MBI)
Coutinho et al. [26]	12 Soccer players	Age: 15.90 ± 0.80 y Mass: 59.50 ± 5.20 kg Height: 172.80 ± 5.20 cm Peak running speed: 23.30 ± 2.80 km/h Years of experience: 8.90 ± 2.40 y	Whole-body coordination task	Light general aerobic exercises	20 min	S: MF ↑ in I vs C (assessed using VAS) (MBI)
Coutinho et al. [44]	10 Soccer players	Age: 13.70 ± 0.50 y Mass: 56.20 ± 4.20 kg Height: 163.10 ± 6.10 cm Years of experience: 6.10 ± 0.90 y	50% Incongruent Stroop task	No previous intervention	30 min (only in I)	S: MF ↑ in I vs C (assessed using VAS) (MBI)
Englert et al. [49]	37 Sport students	Age: 22.00 ± 1.90 y Years of experience: 4.10 ± 3.90 y	Omitting the letters e and n while transcribing a neutral text	Transcribing a neutral text	6 min	S: MF ↑ in I vs C (assessed using 4-point Likert scale)
Englert et al. [50]	38 Soccer players	Age: 20.58 ± 2.10 y Sex: ♀ Years of experience: 14.13 ± 3.88y Level: Collegiate level, no prior track and field experience	Omitting the letters e and n while transcribing a neutral text	Transcribing a neutral text	6 min	S: MF ↑ in I vs C (assessed using 7-point Likert scale)
Filipas et al. [46]	12 Soccer players U14	Sex: ♂ Mass: 55.00 ± 8.00 kg Height: 1.68 ± 0.04 m Level: Local soccer team competing at national level (> 3 years of experience)	Computerised and modified version of an incongruent Stroop task	Reading a selection of emotionally neutral online magazines	I: 30 min C: 15 min	S: MF ↑ in I vs C (assessed using VAS) B: No differences between I and C on ACC and RT of the Stroop task
	12 Soccer players U16	Sex: ♂ Mass: 62.00 ± 8.00 kg Height: 1.70 ± 0.05 m Level: Local soccer team competing at national level (> 3 years of experience)				
	12 Soccer players U18	Sex: ♂ Mass: 69.00 ± 8.00 kg Height: 1.77 ± 0.07 m Level: Local soccer team competing at national level (> 3 years of experience)				
Fortes et al. [48]	20 Soccer players	Age: 24.70 ± 3.60 y Mass: 78.2 ± 6.90 kg Height: 1.70 ± 0.07 m Level: 3rd division Brazilian soccer league	Smartphone use (Social networking apps)	Watching coaching video	I: 15, 30, 45 min C: 30 min	B: ACC ↓ and RT ↑ Stroop in I (30, 45 min) vs C and I (15 min)
Fortes et al. [43]	25 Soccer players	Age: 23.40 ± 2.80 y Mass: 76.10 ± 5.60 kg Height: 1.70 ± 0.08 m Level: Professional Years of experience: 8.70 ± 3.30 y	1. Smartphone use (Social networking apps) 2. Playing video games (FIFA 2018)	Watching advertising videos	30 min	B: ACC ↓ and RT ↑ in Stroop in I (SMA, VID) vs C

Table 2 (continued)

References	Sample	Characteristics	Intervention	Control	Duration	Outcome
Gantois et al. [41]	20 Soccer players	Age: 22.60 ± 3.30 y Sex: ♂ Mass: 78.20 ± 5.40 kg Height: 1.70 ± 0.09 m Level: Professional	Stroop task (congruent, incongruent, neutral)	Watching advertising videos	I: 15, 30 min C: 30 min	B: ACC Stroop = in I and C RT Stroop ↑ in I (30 min) vs C and I (15 min)
Head et al. [23]	20 Soldiers	Sex: ♂ Level: Trained	Sustained Attention to Response Task	Documentary	49 min	P: ↓ HRV in I vs C B: ↑ errors of omission (incorrectly withholding to distractor) as a function of time
Kosack et al. [53]	19 Badminton players	Age: 20.00 ± 2.80 y Sex: ♂ Mass: 74.95 ± 8.70 kg (n = 17) Years of experience: 12.50 ± 3.50 Level: National elite (national Danish ranking: 67.00 ± 58.60; n = 9))	Modified Stroop task	Documentary	60 min	S: MF ↑ in I vs C (assessed using VAS) B: RT ↓ in time in I
Le Mansec et al. [22]	22 Table tennis players	Age: 26.90 ± 8.90 y Sex: ♂ Mass: 72.20 ± 10.30 kg Height: 1.79 ± 0.07 m Level: Regional-national	AX-CPT	Movie	90 min	S: F ↑ in I vs C (assessed using VAS)
McEwan et al. [51]	62 Participants	Age: 22.8 ± 3.95 y Sex: 31♂/31♀ Level: Novices/recreational players	Modified Stroop (incongruent)	Modified Stroop (congruent)	5 min	S: No differences between I and C (Borg CR-10, VAS, Brief mood inspection scale)
Moreira et al. [54]	32 Basketball players	Age: 15.20 ± 1.20 y Sex: ♂ Mass: 72.00 ± 15.00 kg Height: 1.80 ± 0.11 m Level: High level youth Brazil	Incongruent Stroop task	Focus on black cross on screen + relaxation	30 min	B: ACC Stroop ↑ over time (for both groups) RT Stroop ↓ over time (for both groups)
Shin et al. [55]	51 College students	Age: 23.60 ± 2.40 y Sex: ♀ Mass: 73.90 ± 12.20 kg Height: 1.76 ± 0.08 m Level: No golf putting experience	Transcription task: the letters e and t while transcribing a neutral text	Browsing shopping magazines	7 min	S: MF ↑ in I vs C (assessed using 4-point Likert scale)
Smith et al. [25]	14 Soccer players	Age: 19.60 ± 3.50 y Sex: ♂ Mass: 67.80 ± 8.30 kg Height: 1.77 ± 0.06 m Level: Competitive Belgian (13.60 ± 3.20 y player experience)	Modified Stroop task (paper version)	Reading emotionally neutral magazines	30 min	S: MF ↑ in I vs C (assessed using VAS)
Smith et al. [47]	12 Soccer players	Age: 19.30 ± 1.50 y Sex:♂ Level: Well-trained Belgian	Modified Stroop task (paper version)	Reading emotionally neutral magazines	30 min	S: MF ↑ in I vs C (assessed using VAS) (MBI)
Trecroci et al. [45]	9 Soccer players	Age: 17.60 ± 0.50 y Mass: 68.50 ± 6.20 kg Height: 1.81 ± 4.40 m Level: Sub-elite players from the same U19 team from a semi professional soccer academy	Stroop task	Documentary	30 min	S: MF ↑ in I vs C with a significant increase over time in I (assessed using VAS)

Table 2 (continued)

References	Sample	Characteristics	Intervention	Control	Duration	Outcome
Van Cutsem et al. [52]	11 Participants 9 Badminton players	Age: 25.00 ± 4.00 y Sex: 6♀/5♂ Mass: 70.20 ± 13.80 kg Height: 1.69 ± 0.07 m Level: Healthy, not engaged in regular PA Age: 23.00 ± 3.00 y Sex: 4♀/5♂ Mass: 67.00 ± 12.80 kg; Height: 1.73 ± 0.11 m; Level: Competitive Belgian	Modified Stroop task	Documentary	90 min	S: MF ↑ in I vs C (assessed using VAS) B: ACC ↓ in time in I (Stroop task)
Veness et al. [21]	10 Cricket players	Age: 21.00 ± 8.00 y Sex: ♂ Mass: 77.10 ± 9.90 kg Height: 1.85 ± 0.08 m Level: elite	Modified Stroop task	Reading emotionally neutral magazines	30 × 60 s Stroop	S: MF ↑ in I vs C (assessed using VAS)
Vogt et al. [42]	33 Soccer players	Age: 13.50 ± 1.00 y Sex: ♂ Mass: 77.10 ± 9.90 kg Height: 1.67 ± 0.08 m Level: Highest regional or national youth level in their respective age in Germany	Incongruent Stroop task (10 min), determination test (10 min)	Reading emotionally neutral magazines, watching non-arousing football highlights, talking to other participants	20 min	S: MF ↑ in I vs C (assessed using VAS)

ACC accuracy, *AX-CPT* AX-continuous performance test, *B* behavioural, *BRUMS* Brunel mood scale, *C* control, *cm* centimetre, *CR10* CR10 scale ratings of perceived exertion, *HRV* heart rate variability, *I* intervention, *kg* kilograms, *km/h* kilometre per hour, *m* meter(s), *ME* mental exertion, *MF* mental fatigue, *min* minutes, *NASA-TLX* 6 item workload measure, *P* physiological, *RPE* rate of perceived exertion, *RT* reaction time, *S* subjective, *sec* seconds, *VAS* visual analogue scale, *y* years, ♂ male, ♀ female, ↑ higher, ↓ lower

Table 3 Overview of the effect of MF on sport-specific psychomotor performance

References	Task	Time	SSPP outcomes	Results	*p*	ES (95% CI)	Secondary outcomes	Remarks
Soccer								
Badin et al. [24]	5 vs 5 small-sided games	Post	Involvements (*n*)	Likely + effect of MF compared to CON		$d = 0.42$ (0.04; 0.81)	HR: Possibly lower RPE: Likely increase	MBI
			Involvements (%)	Very likely—effect of MF compared to CON		$d = -0.73$ (−1.19; −0.28)		
			Passes (*n*)	Possibly + effect of MF compared to CON		$d = 0.23$ (−0.15; 0.38)		
			Pass accuracy (%)	Possibly—effect of MF compared to CON		$d = -0.25$ (−0.63; 0.13)		
			Tackles (*n*)	Unclear effect of MF compared to CON		$d = 0.18$ (−0.28; 0.64)		
			Tackles success (%)	Likely—effect of MF compared to CON		$d = -0.76$ (−1.32; −0.20)		
			Control errors (*n*)	Very likely + effect of MF compared to CON		$d = 0.61$ (0.23; 0.99)		
			Possessions (*n*)	Unclear effect of MF compared to CON		$d = 0.11$ (−0.25; 0.47)		
			Possessions (%)	Very likely—effect of MF compared to CON		$d = -0.63$ (−1.01; −0.26)		
			Possession time (min)	Unclear effect of MF compared to CON		$d = -0.32$ (−1.99; 1.36)		
Coutinho et al. [26]	6 vs 6 small sided games (excl. GK)	Post	Accuracy (m/s^2)	Unclear effect of MF compared to CON			No effect on neuromuscular performance (CMJ)	MBI
			Distance covered (m/min)	Possible ↓ of MF compared to CON		$d = -2.50; \pm 3.30$		
			Space Exploration Index (m)	Unclear effect of MF compared to CON		$d = -0.70; \pm 8.30$		
			Longitudinal Sync (%)	Unclear effect of MF compared to CON		$d = -0.30; \pm 5.60$		
			Lateral Sync (%)	Possibly ↓ of MF compared to CON	0.001	$d = -13.40; \pm 7.90$		
			Length (m)	Unclear effect of MF compared to CON		$d = 2.10; \pm 9.40$		
			Width (m)	Unclear effect of MF compared to CON		$d = 0.60; \pm 7.30$		
			Dispersion Speed (m/s)	Possibly ↓ of MF compared to CON		$d = -5.60; \pm 9.30$		
			Contraction speed (m/s)	Very likely ↓ of MF compared to CON	0.004	$d = -14.20; \pm 10.20$		
Coutinho et al. [44]	5 vs 5 small-sided games (excl. GK)	Post	**Muscular variables**					MBI
			Total distance (m)	Likely ↓ in MF vs CON				
			High ratio distance (m)	Possibly ↓ in MF vs CON				
			Moderate ratio distance (m)	Possibly ↓ in MF vs CON				
			Low ratio distance (m)	Likely trivial in MF vs CON				
			Number of accelerations	Unclear effect				
			Number of decceleration	Unclear effect				
			Positional variables					
			Distance between dyads (m)	Likely trivial in MF vs CON				
			Entropy distance dyads (au)	Possibly ↓ in MF vs CON				
			Stretch index (m)	Possibly ↓ in MF vs CON				
			Longitudinal sync (%)	Likely ↓ in MF vs CON				
			Lateral sync (%)	Unclear effect				

Table 3 (continued)

References	Task	Time	SSPP outcomes	Results	*p*	ES (95% CI)	Secondary outcomes	Remarks
Filipas et al. [46]	Loughborough soccer passing and shooting tests	Post	**LSPT**				Motivation: No difference	
			Original time (s)	U14: No effect between MF and CON	0.177			
				U16: No effect between MF and CON	0.962			
				U18: Negative effect (↑ in MF vs CON)	0.013			
			Penalty time (s)	U14: No effect between MF and CON	0.107			
				U16: No effect between MF and CON	0.135			
				U18: Negative effect (↑ in MF vs CON)	< 0.001			
			Performance time (s)	U14: No effect between MF and CON	0.075			
				U16: No effect between MF and CON	0.260			
				U18: Negative effect (↑ in MF vs CON)	< 0.001			
			LSST					
			Shot accuracy (points)	U14: No effect between MF and CON	0.159			
				U16: No effect between MF and CON	0.661			
				U18: No effect between MF and CON	0.907			
			Shot speed (km/h)	U14: No effect between MF and CON	0.053			
				U16: No effect between MF and CON	0.342			
				U18: No effect between MF and CON	0.148			
			Shot sequence time (s):	U14: No effect between MF and CON	0.103			
				U16: No effect between MF and CON	0.420			
				U18: No effect between MF and CON	0.115			
Fortes et al. [48]	Simulated soccer game (excl. GK)	Post	Decision making index (%):	Negative effect in 30 sma (↓ in MF)	0.01	h2 = 0.60	Internal load (RPE)no effect	
				Negative effect in 45 sma (↓ in MF)	0.01	h2 = 0.60		
				No effect in 15 sma				
Fortes et al. [43]	Simulated soccer game	Post	Decision making index (%)	Negative effect in SMA (↓ in MF)	0.01	$d = 0.05$	Lactate: No effect Internal load (RPE)no effect	
				Negative effect in VID (↓ in MF)	0.01	$d = 0.05$		
Gantois et al. [41]	Training match (Excl. GK)	Pre-post	Decision making index (%)	Negative effect in ST30vsST15 (↓ in MF)	0.02	$d = 0.31$	Internal load (RPE)no effect	
				Negative effect in ST30vsCON (↓ in MF)	0.05	$d = 0.30$		
				No effect in ST15vsCON				

Table 3 (continued)

References	Task	Time	SSPP outcomes	Results	p	ES (95% CI)	Secondary outcomes	Remarks
Smith et al. [25]	Loughborough Soccer Passing and Shooting Tests	Post	**LSPT**				Motivation: No difference	
			Original time (s)	No effect between MF and CON	0.893	$d=0.04$		
			Penalty time (s)	Negative effect (↑ in MF vs CON)	0.012	$d=0.76$		
			Performance time (s)	No effect between MF and CON	0.061	$d=0.55$		
			LSST					
			Shot accuracy (points)	Negative effect (↓ in MF vs CON)	0.006	$d=0.75$		
			Shot speed (km/h)	Negative effect (↓ in MF vs CON)	0.024	$d=0.75$		
			Shot sequence time (s)	No effect between MF and CON	0.080	$d=0.48$		
Smith et al. [47]	Soccer-specific decision-making task	Post	Overall accuracy (%)	Very likely ↓ in MF compared to CON		$d=-0.89\pm0.73$		MBI
			Overall response time (ms)	Likely ↓ in MF compared to CON		$d=-0.49\pm0.47$		
			Overall visual search data					
			Mean number of fixations per second	No effect between MF and CON		$d=0.41\pm0.79$		
			Mean fixation duration (ms)					
			Overall fixation (%)	No effect between MF and CON		$d=0.05\pm0.54$		
			Overall time fixating on YP, A/D, K or U (%):	Likely ↓ in MF compared to CON No effect between MF and CON		$d=-0.81\pm1.00$		
Trecroci et al. [45]	4 vs 4 Small sided games (excl. GK and one wildcard)	Post	**Technical variables**				RPE: No difference Motivation: trivial difference	MBI
			Possessions (n)	Unclear effect of MF compared to CON		$d=0.08$ (− 0.54; 0.69)		
			Negative passes (n)	Likely—effect of MF compared to CON		$d=0.67$ (0.01; 1.32)		
			Positive passes (n)	Unclear effect of MF compared to CON		$d=-0.44$ (− 1.25; 0.37)		
			Total passes (n)	Unclear effect of MF compared to CON		$d=-0.25$ (− 1.11; − 0.61)		
			Passes Accuracy (%)	Likely—effect of MF compared to CON		$d=-0.49$ (− 1.16; 0.17)		
			Negative shots (n)	Unclear effect of MF compared to CON		$d=0.25$ (− 1.21; 1.71)		
			Positive shots (n)	Unclear effect of MF compared to CON		$d=-0.26$ (− 1.14; 0.63)		
			Total shots (n)	Unclear effect of MF compared to CON		$d=-0.31$ (− 1.09; 0.48)		
			Shot accuracy (%)	Likely—effect of MF compared to CON		$d=0.01$ (− 1.01; 1.03)		
			Control error (n)	Unclear effect of MF compared to CON		$d=0.27$ (− 0.35; 0.89)		
			Negative tackles (n)	Unclear effect of MF compared to CON		$d=0.25$ (− 0.50; 1.00)		
			Positive tackles (n)	Unclear effect of MF compared to CON		$d=-0.48$ (− 1.35; 0.39)		
			Total tackles (n)	Unclear effect of MF compared to CON		$d=0.10$ (− 0.50; 0.69)		
			Tackle success (%)	Unclear effect of MF compared to CON		$d=-0.43$ (− 1.12; 0.26)		
			Decision making variables					
			Negative passes (n)	Likely—effect of MF compared to CON		$d=0.74$ (0.05; 1.44)		
			Positive passes (n)	Unclear effect of MF compared to CON		$d=-0.48$ (− 1.31; 0.35)		
			Total passes (n)	Unclear effect of MF compared to CON		$d=-0.25$ (− 1.11; 0.61)		
			Passes accuracy (%)	Likely—effect of MF compared to CON		$d=-0.53$ (− 1.23; 0.16)		
			Negative shots (n)	Unclear effect of MF compared to CON		$d=-0.32$ (− 1.11; 0.48)		
			Positive shots (n)	Unclear effect of MF compared to CON		$d=-0.86$ (− 1.38; − 0.30)		
			Total shots (n)	Unclear effect of MF compared to CON		$d=-0.31$ (− 1.09; 0.48)		
			Shots accuracy (%)	Unclear effect of MF compared to CON		$d=0.00$ (− 1.33; 1.33)		
			Negative dribbling (n)	Unclear effect of MF compared to CON		$d=-0.23$ (− 0.24; 0.78)		
			Positive dribbling (n)	Unclear effect of MF compared to CON		$d=-0.34$ (− 1.16; 0.48)		
			Total dribbling (n)	Unclear effect of MF compared to CON		$d=-0.09$ (− 0.76; 0.58)		
			Dribbling accuracy (%):	Likely—effect of MF compared to CON		$d=-0.69$ (− 1.52; 0.13)		

Table 3 (continued)

References	Task	Time	SSPP outcomes	Results	p	ES (95% CI)	Secondary outcomes	Remarks
Vogt et al. [42]	Footbonaut ball control task	Pre-post	Speed of action (s) Ball control (points)	No effect between MF and CON No effect between MF and CON	0.85 0.88		HR: No effect	
Sprint								
Englert et al. [49]	Sprint start reaction time	Pre-post	False starts (*n*) Reaction time (ms)	No effect between MF and CON Negative effect (↑ in MF not in CON)	0.01	$\eta^2=0.18$	Self-efficacy: No difference Affect: No difference	
Englert et al. [50]	Sprint start reaction time	Pre-post	False starts (*n*) Reaction time (ms)	Negative effect (↑ in MF, not in CON) No effect within MF and CON	<0.001	$\eta^2=0.50$		
Shooting/aiming								
Head et al. [23]	Marksmanship task	Post	**Target accuracy**					
			Hit proportion (%)	No effect between MF and CON	0.57			
			DCSG (cm)	No effect between MF and CON	0.34			
			SGP (cm)	No effect between MF and CON	0.86			
			Response time (ms)	No effect between MF and CON	0.81			
			Marksmanship decision accuracy					
			Errors of commission (%)	Negative effect (in MF vs CON)	0.001			
			Errors of omission (%)	No effect between MF and CON	0.51			
			Workload score	No effect between MF and CON	0.10			
Racket sports								
Kosack et al. [53]	Badminton-specific test	Post	Time to completion (s)	No effect between MF and CON	0.99		CMJ: No effect on height HR: No difference Lactate: No difference RPE: No difference Motivation: No difference	
Le Mansec et al. [22]	Specific table tennis performance test	Pre-Post	Ball speed (km/h) Accuracy (%) Number of faults (%) Total performance (points)	Negative effect (↓ in MF; PRE vs POST) No effect (tended ↓ in MF; PRE vs POST) Negative effect (↑ in MF; PRE vs POST) Negative effect (↓ in MF; PRE vs POST)	0.035 0.057 0.014 0.015	dz = 0.669 dz = 0.553 dz = 0.850 dz = 0.759	RPE: Tendency of ↑ in ($p=0.067$) MVC: no effect	
Van Cutsem et al. [52]	Badminton-specific visuomotor task	Pre-Post	Accuracy (%) Response time (ms)	No effect between MF and CON Negative effect (↑ in MF vs CON)	0.040	$d=0.49$	Motivation: no difference Blood glucose: no difference	
Golf								
Shin et al. [55]	Putting performance	Pre-post	Putting performance (cm)	Negative effect (↓ in MF vs CON)				HLM analysis
Cricket								
Veness et al. [21]	(a) Run-two test (b) Batak Lite test	Post	Completion time (s) Average score	Negative effect (↑ in MF vs CON) No effect between MF and CON	0.002 0.137	$d=-0.51$ (−0.72; 0.30) $d=0.41$ (−0.05; 0.87)	RPE: ↑ in MF compared to CON Motivation: no difference	MBI (partial)

Range of effect sizes (Cohen's d) < 0.2 = trivial; 0.2–0.6 = small; 0.6–1.2 = moderate; 1.2–2.0 = large; > 2.0 = very large

Range of effect size (Cohen's dz) < 0.2 = trivial; 0.2–0.5 = small; 0.5–0.8 = moderate; > 0.8 = large

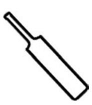
Range of effect size (h2) < 0.25 = trivial; 0.25–0.5 = small; 0.5–1.0 = moderate; ≥ 1.0 = large

Range of effect size (η^2) < 0.02 = trivial; 0.02–0.13 = small; 0.13–0.26 = moderate; > 0.26 = large

Range of effect size (SMD) < 0.2 = trivial; 0.2–0.5 = small; 0.5–0.8 = moderate; > 0.8 = large

A/D closely marked attacker, *CMJ* counter movement jump, *CON* control condition, *d* Cohen's d, *DCSG* distance to the center of the shot group, *dz* cohen's dz, *EMG* electromyography, *ES* effect size, *GK* goal keeper, *h2* special magnitude of Cohen's d, *HLM* hierarchical linear model, *HR* heart rate, *K* goal keeper, *m* meter, *MBI* magnitude based interferences, *MEP* motor evoked potential, *MF* mental fatigue, *MVC* maximal voluntary contraction, *n* number, *RPE* rate of perceived exertion, *SAA* salivary alpha amylase, *SC* salivary cortisol, *SGP* shot group precision, *SMA* smartphone, *SMD* standardized mean differences, *SSPP* sport-specific psychomotor performance, *S-RPE* session RPE, *ST* salivary testosterone, *ST15* 15 min Stroop task, *ST30* 30 min Stroop task, *U* unspecified category, *YP* yellow player, η^2 partial eta squared, ↑ increase, ↓ decrease

Table 4 Summary of the effect of mental fatigue on the measured outcomes in the present review

Sport	Effect of MF	# of outcomes	# of studies
	Positive effect	●● (2)	11
	Unclear/no effect	●● (56)	
	Negative effect	●●● (34)	
	Positive effect	(0)	2
	Unclear/no effect	●● (2)	
	Negative effect	●● (2)	
Shooting 	Positive effect	(0)	1
	Unclear/no effect	●●●●●●● (6)	
	Negative effect	● (1)	
Racket sports 	Positive effect	(0)	3
	Unclear/no effect	●●● (3)	
	Negative effect	●●●● (4)	
Golf 	Positive effect	(0)	1
	Unclear/no effect	(0)	
	Negative effect	● (1)	
Cricket 	Positive effect	(0)	1
	Unclear/no effect	● (1)	
	Negative effect	● (1)	

Traditional statistics were interpreted as follows: non-statistically significant = no effect, statistically significant = outcome was attributed to the direction (positive/negative) of the effect

Magnitude based interference statistics were interpreted as follows: unclear/trivial effect = no effect, effects of which a certain direction (positive/negative) was suggested were interpreted as the direction that was specified

Every ● represents a single outcome of an included study

task compared to the control condition. Both studies found no significant effect of MF on accuracy [22, 52]. Finally, Kosack et al. [53] used a badminton specific test to assess the effect of MF on elite badminton players, but found no effect on total badminton performance.

3.6.5 Golf

One study [55] examined the effect of MF on putting performance in golf. Golf putting performance was measured using the mean radial error (which was defined as: "the distance a ball stops from the target in centimetres") for the number of putts [55]. The authors found a decrease due to MF in golf putting performance compared to the control group in the early stage of the trials, but not in the late stage of the trials [55].

3.6.6 Cricket

One study [21] examined the effect of MF on cricket relevant psychomotor performance using two different sport specific tests: the cricket run two test and a reaction time and hand eye coordination test (Batak Lite test) [21]. Deteriorations were found in the completion time of the cricket run two test (MF = 6.29 ± 0.17 s; control = 6.19 ± 0.18 s) when mentally fatigued compared to the control condition, implying a decrease in test performance in the MF condition [21]. There was no effect of MF found in performance on the Batak lite test [21].

3.7 Secondary Outcomes to Explain the Underlying Mechanisms of MF on SSPP

3.7.1 Psychological Secondary Outcomes

Psychological measurements employed by the selected studies included RPE [21, 22, 24, 41, 43, 45, 48, 53], motivation [21, 25, 45, 46, 52] and self-efficacy [50]. Only Badin et al. [24], and Veness et al. [21] found a negative influence of MF on RPE. There were no significant differences reported in motivation [21, 25, 45, 46, 52] or self-efficacy [50].

3.7.2 Physiological Secondary Outcomes

In soccer, no significant effects of MF were reported on the measured parameters, which included heart rate [24, 42, 53], blood lactate [53] and neuromuscular performance (counter movement jump) [26, 53]. The measured parameters in racket sports (i.e., maximal voluntary contraction [22] and blood glucose [52]) were also not affected by MF.

4 Discussion

This review primarily aimed to collect and appraise available evidence regarding the effect of MF on SSPP and, as a secondary purpose, to investigate possible mediators of this effect. To evaluate the effect of MF on SSPP it was crucial that MF was successfully induced; therefore, we also reviewed the different methods that had been used to attempt to cause MF. Overall, this review documents that MF has a negative effect on a myriad of SSPP outcomes, including decision-making, reaction time and accuracy outcomes, which is noticeable throughout the range of included sports (i.e., soccer, sprint start, shooting/aiming, racket sports, golf and cricket; see Table 4). The current body of evidence reveals no effect of MF on the included physiological outcome measures. When examining the psychological secondary outcomes, only RPE was negatively affected by MF in some studies that measured it. Additionally, we cannot clearly confirm the suggestions made by Giboin et al. [30] regarding the possible role of subject expertise or task representativeness in the effect of MF on SSPP.

4.1 Critical Appraisal of Methods Used to Induce MF

Most often, laboratory-based tasks were used to induce MF (e.g., Stroop task), with only one study [26] using a soccer-specific task of 30 min to induce MF. Although the usage of laboratory-based tasks enables researchers to control for multiple confounding variables (e.g., muscle fatigue), this does not correspond with the way MF would occur in an athletic context. For this reason, multiple studies within this line of research have already emphasized the importance of moving towards more sport-specific representative designs [18, 56–58] to induce MF. Moreover, even if fundamental research is obligated to induce MF in a non-context specific way, researchers should carefully consider which cognitive task they choose to employ. The study of Moreira et al. [54] was unable to induce MF (behaviourally) in a population of high level youth basketball players with a 30-min incongruent Stroop task, while the studies of Badin et al. [24] and Coutinho et al. [44] observed MF (subjectively) utilizing a 30-min 50% incongruent Stroop Task. Van Cutsem et al. [52] and Filipas et al. [46] also found subjective MF responses following a 90-min and 30-min Stroop Task, respectively, while performance on the cognitive task remained mostly unaffected.

A recent meta-analysis of Brown et al. [17] concluded that the incorporation of a time-threshold to in- or exclude studies in MF-reviews and -studies could potentially bias results and/or conclusions, as there are studies that show an induction of MF in interventions lasting only 3–5 min [59–61]. The results of the current review, however, point out that time might still be an important parameter in MF-induction. The study of McEwan et al. [51] was excluded from data-analysis because the manipulation check documented that the 5-min congruent Stroop task was unable to subjectively induce MF. Furthermore, two studies [41, 48] compared different durations of a mentally fatiguing task (i.e., smartphone use [48] and a Stroop task [41]), and both reported that the 15-min task failed to induce MF to the same extent as the 30- and 45-min tasks [41, 48]. Borragan et al. [62] also pointed out that tasks of long duration will eventually trigger MF, regardless of the cognitive load of that task, but that the rate of increase in MF will not be the same.

Current research implies that the ability to induce MF might be explained by a combination of three important components: the nature (sport-specific vs laboratory-based tasks), the duration and difficulty of the MF tasks. O'Keeffe et al. [56] recently compared five different tasks (set up control, documentary control, AX-CPT, a dual task test and an individualized dual task test) in their ability to induce MF, and achieved MF to a greater extent in a short (16-min), but more difficult, individualized dual task, compared to the longer (90-min) AX-CPT. Altogether, this highlights the importance of including valid subjective/behavioural/(neuro) physiological manipulation checks that respect the multidimensional nature of MF when researching its effect on different types of performance. When choosing their respective task, researchers should consider the nature and difficulty of the utilized cognitive task as well as the employed duration of the intervention to optimally induce MF.

4.2 Effect of MF on Sport-Specific Psychomotor Performance

Sport-specific performance is negatively affected by MF across a variety of included sports. Only two studies [42, 53] showed no effect of MF on any measured psychomotor component. Vogt et al. [42] reasoned that this absence of a MF-effect on the Footbonaut test was due to possible talent influence (more talent might equal better technical skills while facing fatigue; i.e., high person-situation fit), motivation-related aspects and missing evidence of the validity of the Footbonaut task. Kosack et al. [53] found no effect of MF on badminton performance, which they associated with the anaerobic nature of the task, which has been shown to not be affected by MF [2, 17]. Therefore, it can be inferred that MF impairs SSPP. However, as shown in Table 4, this MF-associated impairment is not apparent in every measured SSPP-outcome. This indicates further research is needed to document which specific SSPP-outcomes are most vulnerable to MF and why.

In general, two principal factors determining psychomotor performance, accuracy and reaction time [63], are continuously interacting. The effect of MF on these factors is linked, from a neurocognitive standpoint, to incorrect or delayed interpretation of visual stimuli, unadjusted movement responses or delayed movement executions [64]. In the subsequent sections, accuracy and reaction time are discussed separately to potentially gain further insight into the negative effect of MF on SSPP.

4.2.1 MF and Sport-Specific Psychomotor Accuracy

Based on the reported results, this review chose to divide accuracy in two broadly defined categories (i.e., shooting accuracy and response accuracy). Shooting accuracy was defined as "the ability to shoot an object within a minimal distance of a central aiming point" (e.g., shot accuracy in football [25], and the precision of a marksman [23]). Four [22, 25, 45, 55] of the six studies that examined shooting accuracy showed negative effects of MF, while two studies [23, 46] did not find any significant effect of MF on shooting accuracy in infantry soldiers and football players. Response accuracy can be defined as "the proportion of correct answers in a given time window" [16]. Most articles categorize this type of accuracy as decision-making performance. Most studies examining decision-making performance ($n=17$) found decrements in measured outcomes because of MF. The three studies [21, 42, 52] that reported no effect of MF only used single parameters (i.e., single accuracy outcome and ball control) to evaluate sport-specific psychomotor accuracy.

4.2.2 MF and Sport-Specific Psychomotor Reaction Time

The effect of MF on psychomotor reaction time was examined by nine studies [21, 23, 25, 42, 46, 47, 49, 50, 52, 53]. Psychomotor reaction time includes both reaction time (see Hülsdünker et al. [64] for the subdivisions of reaction time) and total performance time which is the time it takes to end a task. Overall, reaction time seemed to be negatively influenced by MF [47, 49, 52]. In contrast, total performance time remained mostly unaffected [21, 23, 25, 42, 53]. Only Veness et al. [21] and Filipas et al. [46] found a negative effect of MF on total performance time using a run two test and the Loughborough soccer passing test, respectively.

To facilitate interpretation, SSPP was categorized into sport-specific psychomotor accuracy and reaction time. The heterogeneity of the included studies' tasks and the wide variety of techniques to measure accuracy and reaction time demonstrate the artificial nature of this division. Moreover, accuracy and reaction time are in continuous interaction, shown by the speed accuracy trade off (i.e., the phenomenon, where the accuracy of a movement decreases the faster the movement is executed, and vice versa) [65]. It is, therefore, difficult to separate these skills and divide them into smaller subcategories. Overall, the results above should be interpreted with caution. However, this division still gives important information regarding the effect of MF on SSPP from a neurocognitive standpoint.

4.3 Identifying Potential Underlying Mechanisms of the Effects of MF on SSPP

The mechanisms explaining the onset of MF and the negative consequences MF has on different aspects of performance, remain elusive. If we consider the literature on the MF-effect on endurance performance it is clear that RPE is the only parameter (within all measured physiological and psychological variables) that is observed to be affected when performing a physical endurance task in a mentally fatigued state [2, 17]. In the review of Van Cutsem et al. [2] some hypotheses to explain this increased RPE when mentally fatigued were put forward: the afferent feedback model in which the intensity of the feedback from working muscles and other physiological systems is increased when mentally fatigued [66]; the corollary discharge model in which the intensity of the central motor command and, therefore, also the efferent corollary discharges (i.e., neural copies of the central motor command that are sent from (pre)motor areas to sensory areas of the brain [67]) increases when mentally fatigued; and the processing model, in which, independently from whether the neural signals originate from the periphery or from the corollary discharges of the central motor command, the processing of the neural signals in the brain is altered [2]. Contrarily, ego depletion-researchers justify the negative effects on performance due to extended mental effort by arguing that there is a depletion of a global self-control resource, which negatively affects performance on subsequent self-control tasks and replenishes only slowly over time [30, 68].

While research into the mechanisms of MF and its effect on endurance performance soars [69, 70], the present review shows that thus far, studies that assessed at the effects of MF on SSPP focused on the more practical, performance-related outcomes. Attempts to mechanistically explain what caused these MF-associated SSPP-impairments are scarce. Of the physiological and psychological variables that were followed up, only RPE was reported to be increased by MF in two studies (ES: moderate [24] to large [21]). The lack of data to explain potential underlying mechanisms could be explained by the fact that the parameters that were followed-up are possibly not the most performance determining factors of psychomotor performance. Most physiological variables that were assessed were general physiological parameters such as heart rate and blood lactate. However, most of the components of SSPP (accuracy, reaction time, decision-making) have been shown to be mainly brain-related [28, 64]. Moreover, the proposed mechanisms of MF/ego depletion assume that the brain plays an important role in the manifestation of the different negative effects of these interventions. Thus, if our goal is to objectively explain the mechanism behind the decrements of sport-specific performance due to MF, sport performance-researchers should begin to use measures that can detect brain changes while performing physical tasks. An example of such a measure is EEG, which has been applied in multiple studies examining the effect of MF on cognitive performance [37, 71, 72] or to measure brain activity during physical performance [69]. Other assessment possibilities include functional near infrared spectroscopy [73, 74], functional magnetic resonance imaging [73], positron emission tomography [73] and pupil dynamics [75]. In summary, the negative effect of MF on SSPP is mostly evident in changes in accuracy/decision-making and reaction time, both parameters of performance which are primarily influenced by the brain. To expand the knowledge on MF, researchers should innovate using different valid measures that could theoretically be influenced by MF. An example of such a measure is the saliva parameters used by Moreira et al. [54] to assess neuro-endocrine responses to MF. Englert et al. [49] showed that sprint reaction time is negatively affected by MF, so another example could be the rate of force development [64]. The efforts in combining the mentioned parameters should provide answers that help in unravelling the mechanisms involved in the onset of MF.

Some research (see for example Martin et al. [38]) has shown that elite athletes are more resistant to MF, meaning that training could potentially help athletes to better control the negative effects. However, we must point out that subsequent research has had mixed results [76–80]. Possible mechanisms behind a certain resistance of elite athletes to MF could stem from task representativeness and movement automatization (see Giboin et al. [30]), which is higher in trained individuals [30, 38, 81, 82]. This review could not provide any proof of a decreased effect of MF on SSPP due to the level of subject expertise, as both recreational athletes and high-level athletes were shown to be impacted by MF. One included study (Van Cutsem et al. [52]) even found no difference between non badminton players and trained badminton players in terms of MF. This might, however, be related to the lower task representativeness of the employed SSPP-task. Van Cutsem et al. [52] developed a Fitlight-task that triggered the execution of badminton-like movements, but it is certainly possible that this resemblance was insufficient for the trained badminton players to address their badminton-automatisms. In two separate studies, Englert et al. [49, 50] showed that MF has different effects on sprint performance based on subject expertise (decrements in reaction time in trained athletes vs a negative effect of false starts in novices). This might mean that there exists a continuum between athlete expertise, task representativeness and the different effects of MF on all types of performance. As research further explores the role of subject expertise and task representativeness in the effect of MF on performance, different important mechanisms of MF might come to light.

4.4 Limitations

The heterogeneity that is represented on multiple levels is, on the one hand, clearly useful for obtaining an overall overview of the effect of MF on SSPP-outcomes. However, on the other hand, it is probably the greatest limitation when trying to generate a definitive conclusion, and as such, the previously proposed effects should be interpreted with caution. This heterogeneity exists in the used outcomes (e.g., reaction time measured by visuomotor task [52] compared to pressure switches [49, 50]), practised sports (e.g., differences in decision-making in table tennis [22] compared to soccer [58, 83]), included population (e.g., ranging from novice [55] to elite athletes [21]) and different analysis (e.g., magnitude based interferences (MBI) [21, 24, 26, 44, 47]) carried out by the selected studies. Moreover, due to the difference in analysis, the calculation of effect sizes could not always be accomplished. These differences are probably also the primary reason for the lack of a clear-cut negative MF-effect on all SSPP-outcomes (see Table 4) and the difficulty in assessing primary (such as reaction time and accuracy) and secondary (such as motivation) outcomes. However, as mentioned before, the general conclusion of the present review remains unaltered, as 17 out of the 19 analysed studies found decrements in at least one outcome of SSPP due to MF. Additionally, almost all articles (20/21) included in this review were considered as at high risk of bias by the Cochrane RoB 2.0. tool. The primary reasons for this were randomisation bias, bias in measurement of the outcome and bias in reported results (which is primarily caused by the use of MBI). This high risk of bias was also found by Brown et al. [17], who used the same RoB 2.0 tool. When interpreting this overall high risk-of-bias the reader should keep in mind that a judgement of 'high' risk of bias within one of the domains of the Cochrane RoB 2.0. tool results in an overall high risk of bias for that study. As such, taking into account the specific difficulty to blind participants as well as researchers in this kind of research and the use of patient-reported outcome measures, high risk of bias does frequently occur in MF-research. Besides these known difficulties, Figs. 2 and 3 demonstrate that within most of the studies many domains were also scored as low risk-of-bias. Subsequently, this indicates that the overall high risk-of-bias should be nuanced and interpreted with caution. Although a high risk of bias includes the possibility that results become over- or underestimated, the consistent findings expose a global effect of MF on SSPP that warrants further high-quality research.

4.5 Future Guidelines and Clinical Implications

Future applied studies should approximate the athletic context when evaluating the effects of MF on SSPP. One way to do this could be to use scientifically sound real-life interventions to elicit MF, such as smartphone use [57, 84]. Meanwhile, fundamental research should aim to identify central mechanisms that coincide with MF and the associated impairment of SSPP. To ensure a high level of study quality, researchers should consider utilising a vast array of valid manipulation checks, more profound blinding procedures (e.g., double or even triple blinding if possible; measure the presence of any expectancy effects once data collection is finished) and comprehensively report data and associated data analysis procedures. Additionally, both applied and fundamental research studies should employ measures which can objectively detect changes in the brain to better understand the mechanisms behind MF.

Coaches and staff that are employed in sports involving psychomotor performance need to be aware that the sport-specific performance of players can be negatively influenced by MF. The decrements in performance of elite athletes should be prevented, as these negative influences could mean the difference between winning and losing. More standardized manipulation checks in the field should be developed, and athletes should be better educated on the manifestations of MF. Although more research is required, there are already some studies that suggest that athletes could potentially employ counter measures (e.g., creatine supplementation [14] and a caffeine maltodextrin mouth rinse [85]) to minimalize the negative effect of MF. More studies should also try to compare elite with basic level athletes in a sport-specific setting to better understand the effect of subject expertise on the manifestations of MF, as specific training to combat MF could potentially be identified from the outcomes of these studies.

Even though no studies have yet investigated the influence of MF on injury risk, it could be that athletes are indirectly at higher risk of injury when performing in a mentally fatigued state, since MF has been shown to decrease reaction time and accuracy scores and these outcomes have been related to an increased injury risk [28, 29]. This link still needs to be evaluated in prospective research designs within the injury prevention domain. Both these ideas are interesting domains when performing future research on the effects of MF. However, this systematic review enables the relevant stakeholders to make better decisions about which performance outcomes to monitor in relation to MF and potentially counter MF.

5 Conclusions

Seventeen out of the 19 included studies in this review showed a negative effect of MF on SSPP across a variety of different outcomes and sports. The decrements in SSPP were seen in both reaction time and accuracy, which are important components of psychomotor performance. Of the physiological and psychological variables that were followed up, only RPE was reported to be increased by MF in three studies. The brain should be the main focus of future studies that attempt to understand the effect of MF on SSPP.

In practical terms, coaches and staff that are employed in sports involving psychomotor performance need to be aware that the sport-specific performance of players can be negatively influenced by MF. More standardized and comprehensive manipulation checks in the field should be developed, and athletes should be better educated on the manifestations of MF.

Acknowledgements We would like to thank the Luxemburg Institute of Research in Orthopedics, Sport Medicine and Science (LIROMS) for their valuable contribution to this work.

Compliance with Ethical Standards

Funding No sources of funding were used to assist in the preparation of this article.

Conflict of Interest Jelle Habay, Jeroen Van Cutsem, Jo Verschueren, Sander De Bock, Matthias Proost, Jonas De Wachter, Bruno Tassignon, Romain Meeusen, and Bart Roelands have no conflicts of interest relevant to the content of this review.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Ethical Approval Jelle Habay, Jeroen Van Cutsem, Jo Verschueren, Sander De Bock, Matthias Proost, Jonas De Wachter, Bruno Tassignon, Romain Meeusen, and Bart Roelands declare that the systematic review complies with all ethical standards.

Availability of Data and Material The authors declare that all data supporting the findings of this study are available within the article.

Authorship Contribution The design of the search strategy was performed by JH, and subsequently revised by JVC, JV, SDB and BR. Screening on title and abstract was done by JH and JVC, while full text screening was conducted by five authors, i.e., JH, JVC, SDB, JV and BR. Data analysis was first conducted by SDB, JVC and JH, and was later revised and updated by JH. RoB assessment was performed by JV, JDW and MP, who also designed the RoB figures together with JVC. JH wrote the first draft of the manuscript which was later altered by JH, JVC, BR, BT and RM. All authors read, revised and approved the final manuscript.

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