



Review

The application of mental fatigue research to elite team sport performance: New perspectives



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ABSTRACT

Objectives: Mental fatigue resulting from prolonged periods of demanding cognitive activity, has been found to impair endurance exercise performance and performance in some sport-specific tasks. The application of such research to the elite sporting environment however is limited.

Design & Methods: This article reviews the literature relevant to mental fatigue and team sporting performance with aim to provide perspectives on the transferability and significance of currently available evidence to the applied elite sporting context.

Results: Inconsistent findings in the limited available literature can be attributed to large variations in the participants involved, the nature of the cognitively demanding tasks used to induce mental fatigue and the tests used to assess performance outcomes. Few studies have used trained athletes in combination with performance tests that accurately represent the physiological and technical demands experienced by athletes in competition. While there is growing interest in the acute influence of mental fatigue on exercise performance, a potential cumulative effect of mental fatigue on performance over, for example, a competitive season is an area yet to be investigated.

Conclusions: If it is accepted that mental fatigue impairs the performance of some athletes, then improving the ecological validity of research in the area of mental fatigue and sport will significantly advance our understanding of how to better monitor and manage mental fatigue. At the elite level of competition, where outcomes are determined by very small margins of difference, reducing the impact of mental fatigue on performance has potential to be significant.

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Practical implications

- The limited research available suggests mental fatigue may impair sporting performance: via changes in physical, technical, tactical and decision-making performance.
- Studies that involve athletes and use tasks and tests that mimic the demands of specific sports will significantly improve the capacity of support staff to monitor MF in their athletes.

- The extent to which mental fatigue accumulates over, for example a competitive season, will inform training practices and help in devising strategies to minimize its development.
- Identifying particular individuals who are more vulnerable to MF will allow opportunities to develop strategies to not only identify these athletes but also tailor programs to reduce the impact of MF.

1. Introduction

Fatigue, which has been defined as a 'reduced capacity for maximal performance'¹ is recognized as a significant determinant of exercise capacity and sporting performance.^{2–4} Fatigue is a multifaceted phenomenon⁵; performance in a range of tasks is known to be influenced by fatigue that does not necessarily originate within the neuromuscular system.⁶ Mental fatigue (MF) is a facet of fatigue that is rapidly gaining scientific attention in the exercise and phys-

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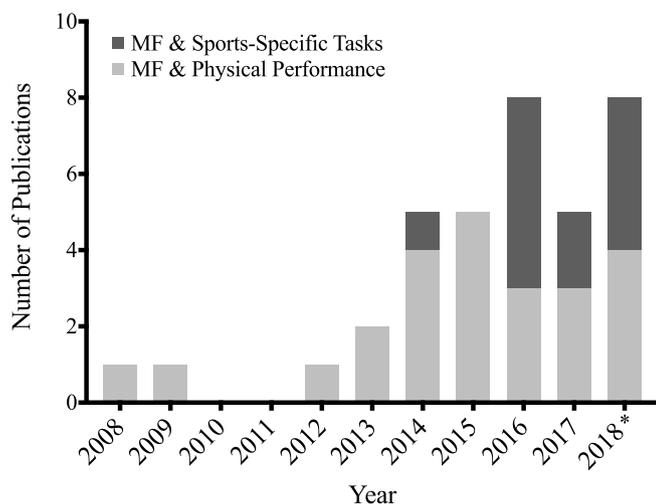


Fig. 1. Bibliometric counts for journal article publications from 2008–2018* investigating the impact of MF on Physical Performance or Sports-Specific Tasks. *July of 2018.

ical performance domain; Fig. 1 shows the increasing number of publications investigating MF and physical performance with a notable surge in research into sports-specific tasks from 2016–18. MF is defined as a psychobiological state caused by prolonged periods of demanding cognitive activity.^{7,8} Therefore, MF manifests as increased subjective feelings of mental (psycho) fatigue and often decreased cognitive performance (biological), following prolonged, challenging cognitive tasks. Separate to the field of research of self-control or ego-depletion investigations, that typically use cognitive tasks of short duration (see Englert⁹ for a review of this research in an athletic context); MF has been shown to impair aspects of exercise performance.⁶ Additionally, editorials have commented on the mental demands of team sport at the elite level.^{10,11} Some research has suggested that elite athletes may be more resistant to mental fatigue through superior inhibitory control¹²; speculatively a result of the unique disciplinary demands placed upon athletes in the elite sporting environment. However, due to unique environmental stressors coupled with the high training and competition demands experienced by athletes, a large potential for MF exists. Given that success at the elite level of competition is determined by very small margins, it is reasonable to suggest that MF can influence the outcomes in elite sport.

Van Cutsem et al.⁶ in their recent systematic review, concluded that MF has the potential to negatively impact endurance performance. However, a disconnect remains in translating the current largely laboratory-based research findings to the training and competition practices unique to elite athletes.¹³ Smith et al.¹³ have highlighted this gap in soccer, emphasizing the practical importance of avoiding or attenuating the negative effects of MF. Despite this paper progressing the application of MF research to the sporting context, the broad transferability of research to the elite team sporting environment remains sparse. The purpose of this article is to provide perspectives on the current transferability and significance of the available research findings in MF and performance (physical, technical and tactical) domains to the applied elite sporting context and to suggest directions for future investigations.

2. Current knowledge

Van Cutsem et al.⁶ reported MF to be associated with both a decline in endurance performance and an increase in perceived exertion; they also concluded that maximal strength, power and anaerobic work are not consistently affected by MF. Smith et al.¹³

complimented this work through their specific review summarizing the impact of MF on soccer-specific physical, technical, decision-making and tactical performance. Those studies that have investigated the influence of MF on exercise capacity have generally employed a mentally fatiguing task or a control condition immediately prior to an exercise task. Both the tasks used to induce MF and the exercise tasks used to assess performance or capacity have differed between investigations. Furthermore, of all the studies on MF and athletic performance very few have involved trained or youth elite athletes.^{12,14–16} Thus, although previous work has led to general conclusions on the impact of MF on physical performance, the transferability of the research findings are limited by population and task specificity; a lack of direct application of research findings to the elite sporting environment thus exists.¹³

The following sections of this perspectives article briefly consider the more important details and findings from the available literature examining the influence of MF on endurance exercise, on high intensity (HI) exercise tasks and on sport-specific tasks. Limitations to each study are identified to inform recommendations for future research, particularly with regard to monitoring and reducing the potential influence of MF on elite athletic performance.

The majority of studies have found a decline in endurance performance (i.e., sustained prolonged dynamic exercise >75s) following a mentally fatiguing task.⁶ A significant decline in mean power output ($p=0.028$),¹⁷ 20-min time trial cycling performance ($p=0.014$)¹² and lower time to exhaustion cycling at 80% of peak power ($p=0.003$)¹⁸ have all been found. However, no differences in a 3-min incremental ramped maximal task,¹⁹ time to exhaustion at critical power²⁰ or maximal voluntary torque and activation²¹ have been found in cycling tasks. Interestingly, professional road cyclists were more resistant to MF than recreational cyclists in the aforementioned 20-min time trial cycling performance.¹² A greater number of correct responses in the Stroop task and lesser impact on cycling performance¹² suggests that elite athletes and lesser trained individuals may respond differently to mentally fatiguing tasks. These findings suggest that some elite athletes may have a greater resistance than others to MF, and thus in order for physical performance to be affected by MF, a stronger or different mentally fatiguing task to the 30-min modified incongruent Stroop task may be needed. Given the inconsistencies in the endurance exercise performance/MF literature, further research in this particular domain is needed. With regards to running performance, a significant negative influence of MF has been found over both 3000-m ($p=0.009$)²² and 5000-m ($p=0.008$)²³ distances and MF has been associated with a significant decline in distance covered in the Yo-Yo intermittent recovery Level 1 (Yo-Yo IRT1).^{14,24} This demonstrates an impact on running performance and capacity to perform intermittent exercise with maximal activation of the aerobic system.²⁵ Conversely, the use of a 10-min modified incongruent Stroop task had no significant influence on 20-m shuttle score.¹⁶ Penna et al.¹⁵ examined swimming endurance performance with 16 elite youth swimmers who completed a range of strokes and events, following a 30-min incongruent Stroop task. A 1.2% difference in completion time was reported for 1500-m swimming performance between conditions ($p<0.05$). Such research translates well into potential competition impacts; a 0.7% time difference separated the three medalists at the 2016 Olympic Games.¹⁵ Whilst the impact of MF on time-trial performance can be translated to competition events such as running, cycling and swimming, a notable limitation of previous research is considering the translation of MF on the endurance demands experienced by elite team sport athletes during competition.^{26,27}

In contrast to the evidence on endurance performance, the impact of MF on high intensity (HI), maximal or all out tasks of short duration, assessing anaerobic capacity and/or strength and power,⁶ is inconclusive. No significant differences between

mental fatigue and control conditions have been found for 3-min all out cycling performance,²⁸ mean power output during 4 × 30-s all out sprints²⁹ or body-weight resistance training repetition completion.³⁰ However, these previously utilized tasks do not arguably reflect the demands of elite team sport activity, and thus the applicability of these findings to elite team sporting performance are again limited. Further investigations are required to apply such findings to elite team sport, as many athletes perform repeated bouts of HI effort over an hour or longer in training and competition environments. Indeed, many sports specific performance tasks include HI components, and the impact of MF on these is reviewed below. Repeated HI tasks which demand both aerobic loading and anaerobic energy turnover,²⁵ along with proposed theoretical models of adenosine accumulation,³¹ make it reasonable to speculate MF may negatively influence repeat HI task performance embedded within endurance-based activities (i.e., intermittent bouts of HI exercise performed over an extended period). Previous findings by Smith et al.³² are acknowledged, however further investigations into the effect of MF on HI activity towards the end of longer duration team sporting competitions³³ are required.

Much of the research that has investigated the influence of MF on physical performance has been completed in a laboratory-based environment using a range of discrete physiological tests. However, there have been recent studies that have used sport-specific tasks to evaluate the potential impact of MF on the physical, technical and tactical components of performance.^{14,24,32,34–37} This increase has occurred in recognition that components other than those tested using discrete laboratory-based physiological protocols are potentially affected by MF. These components include effective execution of technical³⁸ and tactical³⁷ skills, response or reaction time³ and decision making.³⁹

Veness et al.¹⁴ reported a decline in performance in the English Cricket Board 'run-two' test following a 30-min incongruent Stroop task. This test simulates running between wickets with bat in hand and assesses components of acceleration, running at maximal speed, decelerating and completing a 180° turn; running a total of 35.36-m over a duration of approximately six and a half seconds.¹⁴ Run-two time increased significantly ($p=0.002$) when mentally fatigued (6.29 ± 0.17 -s), compared to the control condition (6.19 ± 0.18 -s). To address the gap regarding the impact of MF on running protocols representative of team sport demands, Smith et al.³² developed a continuous 45-min running protocol on a non-motorized treadmill. A 90-min AX-Continuous Performance Task (AX-CPT) was utilized as the mentally fatiguing task, with ten intermittent sports players with a minimum three year competitive playing age across soccer, Australian rules football, rugby codes and field hockey recruited.³² Overall, low intensity activity velocity and distance were significantly lower following the mentally fatiguing task compared to the control but there were no significant differences in HI activity velocity (70–100% of maximal effort) or peak velocity between conditions.³² In contrast to the findings of Veness et al.,¹⁴ the study by Smith et al.³² suggests that HI running may not be influenced by MF.

Despite the singular laboratory study proposing MF may not negatively influence HI running during intermittent protocols, the decrease in overall velocity and distance³² supports the need for future investigation into the impact of MF on sports specific intermittent running protocols. Studies utilizing protocols that closely replicate the intermittent demands of elite team sporting activity are recommended. As such, use of the data from Global Positioning System (GPS) or Inertial Movement Analysis devices, regularly collected by professional sporting organizations, may assist in evaluating the impact of MF on the demands in elite games. Badin et al.³⁴ demonstrated the potential for this, assessing physical activity profiles using GPS units during soccer small sided games (SSG) in

response to MF. Twenty soccer players, competing in the Australian National Premier League, played 5-vs-5 SSGs on two occasions in a cross-over design. On each testing occasion, separated by one week, one team was exposed to a mentally fatiguing 30-min modified incongruent Stroop task and the other, 30-min of an emotionally neutral documentary.³⁴ Despite a reported increase in perceived exertion, only minor physical activity profile differences were found; a possible positive effect for standing/walking, trivial decrease in accelerations, and likely positive effects on repeated sprints were reported.³⁴ No differences for low, high or very high speed running zones were found between conditions.³⁴ The disparity in results from previous physical performance findings were suggested to be a result of the more ecological setting of SSGs, with the nature of a freely paced match allowing for tactical adjustments. The authors speculated that if the SSG were extended or a regulation match undertaken, RPE would further increase and a reduced physical activity profile would be seen with the MF condition.³⁴ Similar results were reported by Coutinho et al.³⁷ with unclear effects of MF on physical performance profiles during 6-vs-6 SSG. Despite similar distance being covered, and acceleration and deceleration variables reported between conditions, the mentally fatigued individuals showed a likely increase in RPE comparative to the control condition.³⁷ Coutinho et al.³⁵ also tracked positional data using GPS, analysing accelerations and distances covered in 10 amateur youth soccer players from a Portuguese regional soccer academy during 5-vs-5 SSG. Again the 30-min modified incongruent Stroop task was used as the mentally fatiguing task. In contrast to the aforementioned findings,^{34,37} a decrease in physical performance variables was seen in the MF condition compared to the control with a likely ~3% decrease in total distance covered and possible ~32% decrease in high speed distance ratio. These findings were attributed to both teams being mentally fatigued, opposed to one side experiencing MF and the other not. This suggests that players' movements can be influenced by contextual and tactical factors, such as the coupling tenancy i.e. the capacity for the behavior of one team to influence the opposition to behave in a similar way.³⁵ These findings emphasize the benefit of further investigating player's physical activity profiles in ecologically valid game simulations using GPS devices to evaluate the effects of MF.

The majority of team-sport applied MF research has, to date, been undertaken in soccer.¹³ Smith et al.²⁴ investigated the influence of MF on soccer-specific technical performance with 14 well-trained, competitive and 'experienced' soccer players. In the MF condition, the 30-min incongruent Stroop preceded the Loughborough Soccer Passing (LSPT) and Shooting Tests (LSST) which were used to assess technical performance. The LSPT assesses passing time and accuracy, whilst the LSST primarily assesses soccer shooting skill, at the same time as incorporating passing, ball control, agility and sprinting components; two trials of each test were completed, making the duration similar to half a soccer match.²⁴ For the LSPT, time taken to complete the test did not significantly differ between conditions, however penalty time (added for errors, inaccurate passes and slow performance), tended to be greater in the MF condition.²⁴ For the eight-shot sequence of the LSST, MF decreased shot accuracy and shot speed compared to the control.²⁴ Combining these findings, the authors concluded that MF may impair soccer-specific technical performance, in particular, the accuracy of skill execution. A notable strength of this study was that it involved 14 experienced soccer players; competing in divisions 2–7 in the Belgian leagues.²⁴ Badin et al.³⁴ transitioned their previous laboratory based findings²⁴ to a more ecologically relevant environment and found MF to negatively affect technical performance during SSG.³⁴ Decreased technical performance was demonstrated through an increase in number of ball control errors, and a lower percentage of technical involvements resulting

in a positive outcome, possessions, accurate passes and successful tackles.³⁴

Limited research has investigated the influence of MF on response time and accuracy in sports specific contexts, despite response time being identified as an important technical cognitive component of agility and thus team sporting performance.³ To date, only the study by Smith et al.³⁶ has assessed the impact of a mentally fatiguing task (a 30-min incongruent Stroop task) on soccer-specific decision making using a film simulation; participants were instructed to select the appropriate action in response to each scenario as quickly and accurately as possible. The MF condition was associated with a very likely lower decision-making accuracy, and likely higher response time, compared to the control.³⁶ Due to the visual search variables revealing unclear effects between the conditions, it was proposed that visual search behavior does not appear to be the mechanism behind the decline in soccer-specific decision making skill.³⁶ The study used 12 well-trained and experienced soccer players, making the findings relevant to competitive athletic populations. Furthering research in the area of tactics, Coutinho et al.³⁷ investigated the impact of MF and additional corridor pitch sector lines on physical and tactical variables using small sided soccer games with 12 highly trained amateur youth soccer players. A motor coordination task was used to induce MF. The 20-min task requires participants to perform exercises in a ladder drill whilst juggling, with the exercise task changed when performance increases; thus, requiring whole body coordination, sustained attention, cognitive processing and perceptual skills.³⁷ Following exposure to the 20-min mentally fatiguing task, players' positioning was impacted, with participants demonstrating a reduced ability to effectively use environmental information.³⁷ The addition of a greater number of reference lines during SSGs were also proposed to exacerbate the negative effects of MF on soccer performance. A second study by Coutinho et al.³⁵ advanced the exploration into the effects of MF on soccer tactical performance during 5-vs-5 SSG with ten amateur youth soccer players. In addition to the aforementioned physical performance declines, clinically important changes in tactical team performance variables were found; when both teams were mentally fatigued, compared to both being exposed to the control condition, there was a ~3% increase in regularity between players on the same team, sharing the same space with intention to achieve the same goal, a ~2% decrease in mean distances from each player to the geometrical team center of gravity, and a ~7% decrease in time spent synchronized in longitudinal displacements.³⁵ These findings demonstrate the effects of MF on soccer players' capability to perceive environmental information in a time-appropriate manner.³⁵ The combined findings demonstrate the potential for MF to negatively impact decision making accuracy, increase response time and impair the ability to effectively use environmental information in a time-appropriate manner.^{35–37} Decision-making capacities and the successful application of tactical strategies to achieve optimal performance across a number of both team and individual sports distinguish elite from sub-elite populations.⁴⁰ Thus, it is reasonable to propose aspects of elite sporting performance may be negatively influenced when mentally fatigued. Further studies are however needed to inform changes in practice.

3. Future recommendations

Although the volume of research examining the influence of MF on sports-specific outcomes is growing, a number of significant challenges in translating the findings to the applied elite sporting environment remain.

There is significant scope to improve the ecological validity of both the method of inducing MF and sports-specific perfor-

mance tests. Although the incongruent Stroop task and AX-CPT have been effectively used to invoke MF in investigations involving athletes,^{14,24,36} Smith et al.³² question whether such methods to produce MF accurately represent tasks in the elite environment that may organically lead to MF. This is an important question; such tasks demand attentional focus requiring participants to perceive information and make quick and accurate decisions in response to alphabetical stimuli. However, the translation to the applied context is limited and use of a mentally fatiguing task with greater relevance may progress the translation of such findings to the elite sporting environment. The mentally fatiguing task used by Coutinho, Gonçalves, Travassos et al.³⁷ provides a potential solution; MF is induced through a 20-min whole body coordination task requiring motor coordination, sustained attention, cognitive processing and perceptual skills. The task was shown to be effective at inducing MF using the subjective visual analogue scale (VAS) report, with a *most likely* increase in perception of MF ($p=0.001$). Accordingly, the use of this or similar protocols will potentially benefit future research, however as raised by Coutinho et al.,³⁵ the impact of the physical training stimulus should be considered. A challenge exists in separating physical or mental fatigue as the primary cause of deterioration in performance; the impact of physically fatiguing training in isolation (without a mentally fatiguing stimulus) on perceived MF is yet to be examined. Considering the complex multifaceted nature of fatigue, the potential interaction effects should be considered, perhaps by a subjective measure of both mental and physical fatigue. Despite these potential limitations, research directed at investigating activities perceived to cause MF in the elite sporting environment, and determining how such activities compare to the commonly utilized Stroop and AX-CPT, and perhaps the protocol used by Coutinho et al.³⁷ would be a useful addition to the field. Potential to explore a multitude of factors exist; such as differences between team and individual sports, the number of decisions made by each positional player during competition and the potential influence of competition equipment or ball size. Additionally, on the premise of the response-inhibition nature of commonly utilized mentally fatiguing tasks, the need for an athlete emotional regulation⁴¹ to control their temper in response to officiating calls they internally disagree with, negative reactions from a crowd, or media interactions, are areas of future research. Further, it should be considered that pre-competition and match demands may differ between sports, as such different mentally fatiguing tasks may need to be used with different groups of athletes.

To strengthen the application of findings to the elite setting, performance tasks should be selected based on whether they replicate the demands of competition and produce useful information on tangible changes in elite sporting performance. In particular, more studies that assess the impact of MF on competitive performance outcomes, such as that by Penna et al.,¹⁵ are needed. Although there are challenges associated with gaining access to athletes, the need to demonstrate impact on, or effectiveness with, the targeted population i.e. elite or sub-elite athletes, is pertinent. The differences in response to MF between elite athletes and recreationally active or healthy individuals emphasizes the importance of undertaking research with the targeted population for whom the outcomes are intended for. Why elite and non-elite athletes potentially respond differently is unclear. Genetics, environmental factors leading to functional adaptations of brain areas responsible for resistance to MF, and regular athlete exposure to MF through media intrusion and self-regulation behaviors have been postulated.¹² Factors such as age and regular engagement with cognitively demanding activities may further influence individual athlete responses. Findings by Fliipas et al.⁴² support this notion; with athletically trained school students demonstrating resistance to the negative effects of mental exertion on 1500 m rowing performance.

Despite athlete fatigue being a closely monitored and carefully considered variable from both a chronic and acute perspective in the elite sport setting^{1–4,43,44} (with 91% of individuals involved in high performance programs indicating they implemented a form of training monitoring⁴⁵), MF is not consistently considered by coaching staff as something that can be easily assessed or changed. A notable limitation to the current literature in relating the findings to elite sport is the apparent focus on the acute impact of MF on performance outcomes. Studies that investigate the potential influence of MF on performance over, for example, a competition week or a competitive season are required. Whether MF develops over the course of the season, or if in fact low levels of MF may act as a training stimulus,^{46,47} and thus whether there be an optimal level of MF exposure to benefit performance requires exploration.

With MF positioned as a factor that may influence performance in the elite sporting environment, consideration of confounding variables when undertaking performance research is important to inform the true biological and performance impact of MF. Factors such as sleep and dehydration have previously been demonstrated to impact cognitive and physical performance variables yet are not normally measured or controlled in research investigating MF and physical or sports-specific performance tasks. Assessment of such variables is commonly attained through athlete self-report measures, actigraphy or simple hydration tests in the elite sport setting; accounting for these variables, even in the most applied of studies, is a reasonable proposition. Standardization of diet is seldom reported in previous MF and physical performance research. Future research should assess or control dietary factors, such as food intake that significantly influence blood glucose concentrations and perhaps more importantly, caffeine intake,³¹ to confidently determine the exclusive impact of MF. In alignment, research that further investigates relationships between subjective reports of MF and potential physiological or behavioral measures suitable for use in the applied setting would be of value. Although relatively well-established physiological markers of MF are known, e.g. electroencephalography,⁴⁸ the set up and potential noise of signal make even mobile EEG impractical for use in the applied sporting environment. Accordingly, the identification of a practical yet robust physiological marker of MF may help to lessen the impact of the potential response bias present when subjectively questioning individuals about levels of MF.

Despite the lack of research undertaken to date examining MF in sport, the limited available evidence suggests that not only can MF potentially have a negative effect on performance but that investigations examining strategies to manage MF are warranted. Previous interventional studies propose that caffeine,⁴⁹ a caffeine-maltodextrin mouth rinse,⁵⁰ oral creatine monohydrate supplementation,⁵¹ and supplementary glucose administration⁵² improve physical performance. However, the effectiveness of legal ergogenic aids to mitigate the effects of MF has not yet been examined in the elite sporting context. Further approaches, such as training interventions to increase resistance to MF,^{46,47} implementation of recovery practices to assist in the management of MF,⁵³ and optimization of competition day structure to avoid the inducement and thus potential negative consequences of MF, are key areas for future applied research. Research investigating how training or other activities commonly undertaken by athletes impacts on MF is critical to the development of practical recommendations which can be implemented by high performance staff. For example, investigating how differing training tasks may lead to MF and, the maximal duration of specific drills which are not perceived to induce MF, the duration of impact, and the restoration time required to recover from MF may be useful information for coaches to consider when structuring training. Further, scope exists to assess the effect of drill complexity on cognitive demands and fatigue experienced by athletes. Such information may aid selec-

tion of training details and assist in structuring pre-competition warm-up. Accordingly, MF may become a variable that can be monitored by coaching staff. The use of a subjective VAS provides a practically feasible, evidence-based methodology to monitor MF. As per the definition, combining reports of subjective changes, with behavioral and physiological observations is recommended.

4. Conclusions

Available evidence suggests that MF has the potential to negatively influence elite sporting performance not only via deterioration in physical performance, but also via changes in technique, decision-making and tactical and skill execution. However, the majority of research undertaken holds limited applicability or transferability to elite sporting performance. Opportunity exists to extend the sports-specific and ecologically valid research undertaken to date in soccer. Translatable research findings to create evidence-based practical recommendations for MF in elite sport are required. As such, using not only sports-specific physical tasks, but also perceptual-cognitive sport specific tasks to understand the full-extent through which MF may impact the many physiological, psychological, technical and tactical components of elite sporting performance is required. Currently, evidence suggests practitioners may benefit from monitoring MF and considering its potential impact on training and competition performance.

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Authors' contributions

All authors were involved in writing, reviewing and editing the manuscript.

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References

- Knicker AJ, Renshaw I, Oldham ARH et al. Interactive processes link the multiple symptoms of fatigue in sport competition. *Sports Med* 2011; 41(4):307–328.
- Coutts AJ, Slattery KM, Wallace LK. Practical tests for monitoring performance, fatigue and recovery in triathletes. *J Sci Med Sport* 2007; 10(6):372–381.
- Joyce D, Lewindon D. High-performance training for sports. In: *Human Kinetics*, 2014.
- Kellmann M. Preventing overtraining in athletes in high-intensity sports and stress/recovery monitoring. *Scand J Med Sci Sports* 2010; 20(s2):95–102.
- Halson SL. Monitoring training load to understand fatigue in athletes. *Sports Med* 2014; 44(2):139–147.
- Van Cutsem J, Marcora S, De Pauw K et al. The effects of mental fatigue on physical performance: a systematic review. *Sports Med* 2017; 47(8):1569–1588.
- Desmond P, Hancock P. Active and passive fatigue states, in *Stress, workload, and fatigue*, Hancock P, editor, Mahwah, NJ, US, Lawrence Erlbaum Associates Publishers, 2001.
- Job R, Dalziel J. Defining fatigue as a condition of the organism and distinguishing it from habituation, adaptation, and boredom, in *Stress, workload, and fatigue*, Hancock PA, editor, Mahwah, NJ, US, Lawrence Erlbaum Associates Publishers, 2001.
- Englert C. The strength model of self-control in sport and exercise psychology. *Front Psychol* 2016; 7:314.
- Walsh V. Is sport the brain's biggest challenge? *Curr Biol* 2014; 24(18):R859–R860.

11. Coutts AJ. Fatigue in football: it's not a brainless task! *J Sports Sci* 2016; 34(14):1296.
12. Martin K, Staiano W, Menaspà P et al. Superior inhibitory control and resistance to mental fatigue in professional road cyclists. *PLoS One* 2016; 11(7):e0159907.
13. Smith MR, Thompson C, Marcora SM et al. Mental fatigue and soccer: current knowledge and future directions. *Sports Med* 2018; 48(7):1525–1532.
14. Veness D, Patterson SD, Jeffries O et al. The effects of mental fatigue on cricket-relevant performance among elite players. *J Sports Sci* 2017:1–7.
15. Penna EM, Wanner SP, Campos BT et al. Mental fatigue impairs physical performance in young swimmers. *Pediatr Exerc Sci* 2017; 20(XX):1–8.
16. Schücker L, MacMahon C. Working on a cognitive task does not influence performance in a physical fitness test. *J Sport Exerc Psychol* 2016; 25:1–8.
17. Brownsberger J, Edwards A, Crowther R et al. Impact of mental fatigue on self-paced exercise. *Int J Sports Med* 2013; 34(12):1029–1036.
18. Marcora SM, Staiano W, Manning V. Mental fatigue impairs physical performance in humans. *J Appl Physiol* 2009; 106(3):857–864.
19. Vrijlkotte S, Meeusen R, Vandervaeren C et al. Mental fatigue and physical and cognitive performance during a 2-bout exercise test. *Int J Sports Physiol Perform* 2018; 13(4):510–516.
20. Salam H, Marcora SM, Hopker JG. The effect of mental fatigue on critical power during cycling exercise. *Eur J Appl Physiol* 2018; 118(1):85–92.
21. Pageaux B, Marcora SM, Rozand V et al. Mental fatigue induced by prolonged self-regulation does not exacerbate central fatigue during subsequent whole-body endurance exercise. *Front Hum Neurosci* 2015; 9. <http://dx.doi.org/10.3389/fnhum.2015.00067>. Article 67.
22. MacMahon C, Schücker L, Hagemann N et al. Cognitive fatigue effects on physical performance during running. *J Sport Exerc Psychol* 2014; 36(4):375–381.
23. Pageaux B, Lepers R, Dietz KC et al. Response inhibition impairs subsequent self-paced endurance performance. *Eur J Appl Physiol* 2014; 114(5):1095–1105.
24. Smith MR, Coutts AJ, Merlini M et al. Mental fatigue impairs soccer-specific physical and technical performance. *Med Sci Sports Exerc* 2016; 48(2):267–276.
25. Bangsbo J, Iaia FM, Krstrup P. The Yo-Yo intermittent recovery test: a useful tool for evaluation of physical performance in intermittent sports. *Sports Med* 2008; 38(1):37–51.
26. Gray AJ, Jenkins DG. Match analysis and the physiological demands of Australian football. *Sports Med* 2010; 40(4):347–360.
27. Helgerud J, Engen LC, Wisløff U et al. Aerobic endurance training improves soccer performance. *Med Sci Sports Exerc* 2001; 33(11):1925–1931.
28. Martin K, Thompson KG, Keegan R et al. Mental fatigue does not affect maximal anaerobic exercise performance. *Eur J Appl Physiol* 2015; 115(4):715–725.
29. Duncan MJ, Fowler N, George O et al. Mental fatigue negatively influences manual dexterity and anticipation timing but not repeated high-intensity exercise performance in trained adults. *Res Sports Med* 2015; 23(1):1–13.
30. Head J, Tenan M, Tweedell A et al. Cognitive fatigue influences time-on-task during bodyweight resistance training exercise. *Front Physiol* 2016; 7(373).
31. Martin K, Meeusen R, Thompson KG et al. Mental fatigue impairs endurance performance: a physiological explanation. *Sports Med* 2018:1–11.
32. Smith MR, Marcora SM, Coutts AJ. Mental fatigue impairs intermittent running performance. *Med Sci Sports Exerc* 2015; 47(8):1682–1690.
33. Tomlin DL, Wenger HA. The relationship between aerobic fitness and recovery from high intensity intermittent exercise. *Sports Med* 2001; 31(1):1–11.
34. Badin O, Smith M, Conte D et al. Mental fatigue: impairment of technical performance in small-sided soccer games. *Int J Sports Physiol Perform* 2016; 11(8):1100–1105.
35. Coutinho D, Gonçalves B, Wong DP et al. Exploring the effects of mental and muscular fatigue in soccer players' performance. *Hum Mov Sci* 2018; 58:287–296.
36. Smith MR, Zeuwts L, Lenoir M et al. Mental fatigue impairs soccer-specific decision-making skill. *J Sports Sci* 2016; 34(14):1297–1304.
37. Coutinho D, Gonçalves B, Travassos B et al. Mental fatigue and spatial references impair soccer players' physical and tactical performances. *Front Psychol* 2017; 8:1645.
38. Smith DJ. A framework for understanding the training process leading to elite performance. *Sports Med* 2003; 33(15):1103–1126.
39. Baker J, Cote J, Abernethy B. Sport-specific practice and the development of expert decision-making in team ball sports. *J Appl Sport Psychol* 2003; 15(1):12–25.
40. Farrow D. A multi-factorial examination of the development of skill expertise in high performance netball. *Talent Dev Excellence* 2010; 2(2):123–135.
41. Wagstaff CR. Emotion regulation and sport performance. *J Sport Exerc Psychol* 2014; 36(4):401–412.
42. Fliipas L, Tagliabue G, La Toree A et al. Does mental exertion influence rowing performance in young athletes?, MetropolisRuhr, European College of Sport Science, 2017.
43. Rampinini E, Bosio A, Ferraresi I et al. Match-related fatigue in soccer players. *Med Sci Sports Exerc* 2011; 43(11):2161–2170.
44. Kempton T, Sirotic AC, Cameron M et al. Match-related fatigue reduces physical and technical performance during elite rugby league match-play: a case study. *J Sports Sci* 2013; 31(16):1770–1780.
45. Taylor K, Chapman D, Cronin J et al. Fatigue monitoring in high performance sport: a survey of current trends. *J Aust Strength Cond* 2012; 20(1):12–23.
46. Staiano W, Merlini M, Marcora S. A randomized controlled trial of brain endurance training (BET) to reduce fatigue during endurance exercise ACSM Annual Meeting, 2015. San Diego.
47. Dallaway N, Lucas SJE, Ring C. Effects of brain endurance training on endurance, MetropolisRuhr, European College of Sport Science, 2017.
48. Pires FO, Silva-Júnior FL, Brietzke C et al. Mental fatigue alters cortical activation and psychological responses, impairing performance in a distance-based cycling trial. *Front Physiol* 2018; 9(227).
49. Azevedo R, Silva-Cavalcante MD, Gualano B et al. Effects of caffeine ingestion on endurance performance in mentally fatigued individuals. *Eur J Appl Physiol* 2016; 116(11–12):2293–2303.
50. Van Cutsem J, De Pauw K, Marcora S et al. A caffeine-maltodextrin mouth rinse counters mental fatigue. *Psychopharmacology* 2017:1–12.
51. Rae C, Digney AL, McEwan SR et al. Oral creatine monohydrate supplementation improves brain performance: a double-blind, placebo-controlled, cross-over trial. *Proc Biol Sci* 2003; 270(1529):2147–2150.
52. Kennedy DO, Scholey AB. Glucose administration, heart rate and cognitive performance: effects of increasing mental effort. *Psychopharmacology* 2000; 149(1):63–71.
53. Rattray B, Argus C, Martin K et al. Is it time to turn our attention toward central mechanisms for post-exertional recovery strategies and performance? *Front Physiol* 2015; 6:79.