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LEADING ARTICLE

Mental Fatigue and Soccer: Current Knowledge and Future Directions

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Abstract Fatigue is a complex state with multiple physiological and psychological origins. However, fatigue in soccer has traditionally been investigated from a physiological perspective, with little emphasis on the cognitive demands of competition. These cognitive demands may induce mental fatigue, which could contribute to the fatigue-related performance decrements observed during and after soccer matches. Recent research investigating the relationship between mental fatigue and soccer-specific performance supports this suggestion. This leading article provides an overview of the research in this emerging field, outlining the impact of mental fatigue on soccer-specific physical, technical, decision-making, and tactical performances. The second half of this review provides directions for future research in response to the limitations of the existing research. Emphasis is placed on translating the current body of knowledge into practical applications and developing a greater understanding of the mechanisms underpinning the negative impact of mental fatigue on soccer performance. A conceptual model is presented to help direct this future research.

Key Points

Mental fatigue impairs multiple aspects of soccer-specific performance.

Future research should focus on understanding the mechanisms underlying performance impairments and applying these findings within the performance environment.

Soccer clubs should consider strategies to avoid and/or attenuate the negative effects of mental fatigue on soccer performance.

1 Introduction

Soccer requires prolonged low-intensity activity interspersed with repeated short bouts of high-intensity activity [1]. This physically demanding activity profile causes fatigue, which may reduce distances covered towards the end of a match and following high-intensity periods of a match [2–4]. This "match-related fatigue" may also reduce the quantity and quality of technical performance towards the end of a match [5].

The perceptual–cognitive demands of soccer competition are also extremely challenging [6]. Indeed, soccer players must remain alert for extended periods, constantly scanning their dynamic performance environment and attending only to relevant information. Players must then integrate this information with tactical strategies and opposition and teammate tendencies (previously stored in

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memory) to make accurate decisions under strict time constraints [7]. Competing at a high level with potentially congested playing schedules may increase these psychological demands [8]. Therefore, players likely experience mental fatigue during competition, which may contribute to the performance reductions observed towards the end of a match.

Mental fatigue is a psychobiological state characterised by feelings of tiredness and a lack of energy and induced by prolonged periods of demanding cognitive activity [9, 10]. The negative impact of mental fatigue on endurance performance is well-established and has been attributed to increased perception of effort (for review see Van Cutsem et al. [11]). Comprehensive evidence also demonstrates that mental fatigue impairs cognitive [9, 12] and skilled motor [13, 14] performances. These impairments have been attributed to altered attentional focus [9], reduced performance monitoring/adjustment [10], slower and less accurate reactions [12], and poor use of visual cues for action preparation [12, 15]. Therefore, as these executive functions are important for sport-specific performance, researchers have recently begun investigating the effects of mental fatigue on soccer performance [16–20].

This review summarises the recent literature on mental fatigue and soccer performance and provides direction for future research in this emerging field. The paper comprises two sections: (1) a review of existing literature, outlining the impact of acute mental fatigue on various factors associated with successful soccer performance and (2) suggested avenues for future research, based on the limitations of the existing literature. This second section emphasises the practical application of this research and provides a conceptual mechanistic model to direct future research.

2 Current Knowledge

2.1 Physical Performance

Time–motion analysis investigations have revealed reductions in physical activity as matches progress [2–4]. Most existing research attributes these changes to cardiorespiratory, metabolic, and neuromuscular mechanisms of fatigue (physical fatigue) [1]. However, our understanding of fatigue in soccer is broadening, acknowledging the significant psychological stress of competition and its impact on performance [8, 21]. Therefore, several recent investigations have assessed the impact of mental fatigue on soccer-specific physical performance [16–18, 22].

Using a non-motorised treadmill protocol simulating the activity profile of team sport gameplay, Smith et al. [22] demonstrated that mental fatigue impairs intermittent running performance. In this investigation, ten team sport athletes performed a 45-min intermittent running protocol following a 90-min cognitively demanding computer task (mental fatigue) and a control treatment (documentary). Mental fatigue reduced running velocities at low intensities, while high-intensity and peak sprint velocities remained similar between conditions. These observed impairments of performance were attributed to higher perception of effort in the mentally fatigued condition rather than physiological differences [22].

A subsequent study was conducted to verify these initial findings using the Yo–Yo Intermittent Recovery Test, Level 1 (Yo–Yo IR1), a validated protocol correlated to match running profiles [23] and more familiar to soccer players [18]. Results of this study confirmed previous findings, as all 12 recreational soccer players ran shorter distances in the Yo–Yo IR1 following a 30-min mentally fatiguing Stroop task, compared to an emotionally neutral control. In line with previous investigations [22, 24, 25], this reduction in running performance in mentally fatigued players was mediated by an increased perception of effort.

In contrast to laboratory-controlled conditions, mental fatigue has an unclear influence on soccer-specific physical performance in applied settings [16, 17, 26]. Badin et al. [16], and Coutinho et al. [17] investigated the effects of mental fatigue on performance during 5 vs. 5, and 6 vs. 6 (plus goalkeeper) small-sided games (SSGs), respectively, with only one mentally fatigued team per SSG. Coutinho et al. [26] mentally fatigued both teams before 5 vs. 5 (plus goalkeeper) SSGs and compared performance with that of a control vs. control SSG. Perception of effort during the SSG was likely higher in mentally fatigued players in Badin et al. [16], and Coutinho et al. [17], but, players' physical activity profiles, assessed using global positioning systems, were not clearly different between conditions. [16, 17]. Indeed, differences in most physical performance variables (distances covered, accelerations and decelerations) were either unclear or trivial. Coutinho et al. [26] did not assess ratings of perceived exertion during the SSG but reported a likely small reduction in total distance (possibly small reductions in moderate- and high-intensity ratios; likely trivial differences in low-intensity ratio) in mentally fatigued players. Therefore, although it is possible, whether mental fatigue influences soccer-specific physical performance in applied settings is unclear and is likely to depend on the fatigue status of the opposition. The contrast in findings between laboratory-based (clear impairment) and applied settings (unclear influence) is likely due to the open nature of SSGs, which involve technical skills, tactical considerations, decision making, and competition against an opposing team [27]. During SSGs, these factors likely dictate player movement patterns to a greater extent than does perception of effort.

2.2 Technical Performance

Although physical activity profiles are important in soccer, technical skill performance generally determines match success [28]. Some [5, 28], but not all [2], research indicates that performance of technical skills declines over the course of a match. Again, these changes are typically associated with physical fatigue [5]. However, recent research demonstrated that mental fatigue impairs performance of fundamental motor skills (manual dexterity, anticipation timing, and goal-directed arm movements) [13, 29]. Additional evidence suggests that these mental-fatigue-related impairments to fundamental motor skills transfer to soccer-specific skills [16, 18, 20].

Recent studies have investigated the impact of mental fatigue on technical performance in both controlled and applied settings. Following a 30-min Stroop task, 14 well-trained players performed less accurate passes, and slower, less accurate, shots on goal in the Loughborough Soccer Passing (LSPT) and Shooting Tests (LSST) [18, 20]. No between-condition differences existed for players' movement speed during the tests, suggesting that a possible speed-accuracy trade-off exists. Similar reductions in LSPT performance have previously been observed following a soccer match [5], indicating that mental fatigue may contribute to performance decrements during competition. However, results from the LSPT must be interpreted with care, as recent research suggests that this test has impractical criterion validity in elite youth soccer players [30]. Nevertheless, research assessing the impact of mental fatigue on soccer skills during SSG supports the hypothesis that mental fatigue contributes to technical impairments during match play [16]. Indeed, mental fatigue reduced players' passing accuracy during the SSG. Additionally, mentally fatigued players had a lower percentage of positive involvements and possessions, less successful tackles, and more ball control errors. Taken collectively, these findings show that mental fatigue impairs several offensive and defensive soccer-specific technical skills and may be partially responsible for reductions observed during competition [5, 28].

2.3 Decision-Making and Tactical Performance

Soccer players' capability to quickly identify and interpret relevant cues and formulate an appropriate response is critical for successful performance [31–33]. Players utilise these perceptual–cognitive skills to decide on appropriate technical involvements and movements based on the positioning of other players and the ball (tactical behaviour). Indeed, players with superior perceptual–cognitive skills are typically better decision makers [34] and play at a higher competitive level [33]. Research has shown that mental fatigue impairs perceptual–cognitive performance during computer-based tasks [9, 10, 12, 15]. Therefore, researchers have recently investigated whether mental fatigue also affects soccer-specific perceptual–cognitive performance [17, 19].

Preliminary findings suggest that mental fatigue impairs perceptual–cognitive performance of soccer players [17, 19]. Smith et al. [19] studied 12 well-trained soccer players as they performed a film-based soccer-specific decision-making task [33, 34] following a 30-min Stroop task or control treatment. Mental fatigue impaired both the speed and the accuracy of soccer-specific decisions but had minimal impact on visual search behaviour [19]. The investigations by Coutinho et al. [17, 26] (see Sect. 2.1. Physical Performance) also assessed the impact of mental fatigue on tactical performance in SSG. When mentally fatigued, players in Coutinho et al. [17] possibly spent less time synchronised in the lateral direction. Mental fatigue also possibly reduced the speed of team dispersion and very likely reduced the speed of team contraction. Mentally fatigued players in Coutinho et al. [26] likely spent less time synchronised in the longitudinal direction, possibly increased the regularity in distance between player dyads, and possibly decreased team dispersion. The differences between these findings are again likely a result of the fatigue status of the opposition (fatigue vs. control, or fatigue vs. fatigue).

In summary, the existing literature demonstrates that mental fatigue impairs soccer-specific physical, technical, and perceptual–cognitive performances. However, additional research is required to confirm whether these impairments, observed mainly in controlled settings, translate into performance reductions during competition. The following section of this review expands on this need and outlines additional avenues for future research.

3 Future Directions

The investigations reviewed above provide preliminary evidence that mental fatigue impairs soccer performance. However, two clear lines of additional research are required to assist coaching staff and players in managing mental fatigue. First, researchers should aim to integrate theory and practice, studying mental fatigue and soccer performance with an applied approach. Second, future investigations should attempt to clarify the mechanisms behind the observed influence of mental fatigue on soccer-specific performance. Several suggestions for this future research are provided below.

3.1 Applied Research

The reductions in performance observed due to mental fatigue appear to align with changes that have been attributed to match-related fatigue [2–5]. However, there is no empirical evidence that soccer players experience mental fatigue during competition. Mashiko et al. [35] used the Profile of Mood State (POMS) questionnaire to assess mood before and after rugby union matches and reported an increase in mental fatigue. However, as the fatigue subscale of the POMS does not differentiate between mental and physical fatigue [36], it is difficult to determine whether the increased fatigue was due to mental or physical exertion or a combination. Additionally, no such investigations exist in soccer players. Therefore, future investigations should directly assess mental fatigue pre- and post-game using as many subjective (specific to mental fatigue) and objective (electroencephalography [37], electrooculography [38], reaction time and accuracy [39]) assessment tools as practical. These investigations should ideally collect data from several games across a season, as factors such as winning/losing, quality of opposition, fixture congestion, and stage of season are likely to affect at least subjective assessments [40]. This research should also consider the positive impact of exercise on arousal and cognitive performance, which may influence results [41].

Another limitation of the existing research is the use of prolonged computer- or paper-based cognitive tasks (e.g. Stroop) to induce mental fatigue. Although the cognitive demands of these tasks (i.e. sustained attention and inhibitory control) are also present during soccer competition, players do not perform these tasks prior to taking the field. Coutinho et al. [17] partially addressed this limitation, inducing mental fatigue with a motor task. Players performed a series of agility ladder drills for 20 min while juggling a tennis ball to increase attentional demands. This novel motor task is an improvement on computer-based tasks but is also an atypical pre-match activity for soccer players. However, it is possible that some pre-match activities/routines (e.g. prolonged tactical sessions, player interviews, or playing video games) do induce mental fatigue. Indeed, activities requiring sustained vigilance [9, 42] and/or emotional regulation [43] can induce mental fatigue and impair subsequent performance. The timing of mentally fatiguing tasks is also critical, as periods of rest can reduce mental fatigue [44]. While players typically rest immediately prior to a match, most existing investigations do not incorporate a break between mentally fatiguing tasks and performance tests. Therefore, future research should investigate whether common pre-match activities induce mental fatigue and assess their impact on performance (after realistic periods of rest). Where this approach is not possible, researchers should induce mental fatigue using 'soccer-specific' tasks as did Coutinho et al. [17], rather than computer- or paper-based tasks.

Although recent investigations have attempted to utilise more applied environments (i.e. SSG) [16, 17], assessing the impact of mental fatigue on performance during a 90-min match (and extra time where possible) would advance our current knowledge. Indeed, Badin et al. [16] suggested that, in their investigation, the short duration of the SSG may explain why mental fatigue had no impact on physical performance. It is possible that if participants played a full-length match, perception of effort would have increased further, decreasing the physical activity profile of mentally fatigued players. Given the likely impairments, researchers should not attempt to mentally fatigue players before competitive matches. Rather, future investigations should assess the impact of mental fatigue on performance during full-length practice matches.

Whether mental fatigue impairs soccer performance of elite players remains unclear. Indeed, the existing literature has investigated well-trained or recreational soccer players. The pressure of elite-level competition likely places greater cognitive demands on elite players as they regulate emotions prior to a match [8]. These demands may induce mental fatigue in elite players during competition. However, recent evidence indicates that professional cyclists are more resistant to mental fatigue than lower-level cyclists [45]. The authors attribute this resistance to the athletes' familiarity with highly demanding cognitive activity during training and competition. Considering the demands of elite soccer training and competition, it is likely that soccer players share this resistance. Nevertheless, research should assess whether soccer-specific cognitively demanding activity induces mental fatigue and/or impairs performance in an elite population. This research may have additional implications for planning training and recovery schedules in an attempt to increase the cognitive demand (e.g. using SSGs rather than general or semi-specific physical training) and allow for appropriate recovery from physiological and psychological stresses.

The findings of Martin et al. [45] also warrant investigation into the efficacy of intentionally training under conditions of mental fatigue to increase resistance and improve performance. Indeed, preliminary evidence suggests that systematically training under conditions of mental fatigue reduces perception of effort and improves endurance exercise performance [46]. Future research should examine whether this novel training strategy enhances soccer-specific performance. If so, additional research will be required to identify the most practical and effective prescription guidelines (e.g. optimal timing, volume, frequency, and format of mentally fatiguing activity).

Finally, in elite players, mental fatigue may interact with sleep restriction/deprivation and/or congested schedules to

influence performance. For example, research has shown that sleepiness and mental fatigue may work synergistically to impair cognitive performance [44]. This may be important for elite soccer players, as the physical and psychological demands of training and competition can reduce the quality and quantity of athletes' sleep, which may affect subsequent performance [47]. Additionally, although congested fixtures appear to have minimal influence on physical performance, injury rates seem to increase during these periods [48]. It is possible that mental fatigue contributes to this increase in injury rates during congested periods. Indeed, many of the mechanisms proposed to impair skilled performance under conditions of mental fatigue (see below) have been linked to increased injury risk in a laboratory-based slipping task [49]. Therefore, future research should examine the interactive influence of mental fatigue, sleep restriction, and fixture congestion on soccer performance and injury incidence/susceptibility.

3.2 Mechanisms

The mechanisms of fatigue in soccer are complex, with multiple physiological and psychological processes contributing to performance declines [31, 48]. Understanding these mechanisms may assist in the development of novel interventions to attenuate performance impairments. The current research on mental fatigue and soccer performance provides little information regarding the mechanisms responsible for the observed impairments. Nevertheless, fundamental investigations on mental fatigue provide insight into certain mechanisms that appear to align with the results of soccer-specific research. Based on this information, we propose a conceptual mechanistic model (Fig. 1) for the impact of mental fatigue on soccer performance. This model was not designed to comprehensively analyse the multifactorial genesis of fatigue, as additional mechanisms are undoubtedly involved in this complex process. Rather, it outlines one mechanistic pathway of many that likely contribute to fatigue-related impairments in soccer. Therefore, this model acts as a tool to direct future research into the mechanisms of mental fatigue in soccer.

As seen in Fig. 1, cognitively demanding tasks requiring response inhibition [50–52], sustained vigilance [9, 42, 53], and monotony [54, 55] induce mental fatigue. These tasks activate the anterior cingulate cortex (ACC), likely leading to elevated adenosine, and a corresponding decrease of dopamine in this brain region [10, 56–61]. The ACC plays a critical role in many executive functions, including effort-based decision making [62], attentional allocation [9, 63], action preparation [12, 15], and performance monitoring/adjustment [10, 12, 64]. Impairments to these functions may be responsible for the observed decrements in soccer-specific tactical, decision-making, and technical performance [16–20]. However, future investigations should directly assess the accuracy of these proposed mechanisms. For example, utilising dual-task procedures and players of varying skill level may clarify whether attentional changes are responsible for the observed reductions in technical performance. Indeed, highly skilled players require less attentional resources to perform well-learned motor skills [65]. Therefore, if mental fatigue reduces the allocation of attention to task demands, highly skilled players may maintain a higher standard of performance than their lesser skilled counterparts when a secondary task is added.

Research demonstrates that mental fatigue increases perception of effort, subsequently reducing endurance performance [11, 24, 25, 66, 67]. However, the mechanisms underlying these observed increases in perception of effort are not clear. Similar to impairments in technical and decision-making performance, altered adenosine/dopamine concentrations in the ACC may be responsible [68, 69]. This suggestion is based on the following theory: (1) the ACC contributes to effort-based decision making [70, 71]; (2) mentally fatiguing tasks (e.g. Stroop) activate the ACC, increasing extracellular adenosine [50, 52, 60, 72]; (3) animal studies show that elevated concentrations of adenosine in the brain impair endurance performance [57]; and (4) the ergogenic effect of caffeine on endurance performance has been attributed to its role as an adenosine antagonist [57]. Although this proposed mechanism is plausible, further studies in both animals and humans should directly examine the role of adenosine/dopamine interactions in the ACC (and other neurological mechanisms) in regulating perception of effort and endurance performance. More specific directions for future research in this area have been discussed in a previous review [11].

Understanding the mechanisms of mental fatigue will allow for the implementation of tailored interventions to attenuate its negative effect on soccer performance. According to our proposed model (Fig. 1), interventions altering adenosine/dopamine levels, actions and interactions may be particularly effective. As stated above, caffeine counteracts mental fatigue [73], at least in part, by blocking adenosine receptors in the brain [57]. This mechanism appears to underpin the cognitive and physical performance benefits of caffeine [74, 75]. Indeed, caffeine consumption reverses the negative impact of mental fatigue on physical performance [76] and improves soccer-specific physical and technical performance [77–79]. Therefore, caffeine and mental fatigue have contrasting effects on soccer-specific performance, potentially due to their opposing impact on adenosine/dopamine concentrations. However, additional research is required to assess the

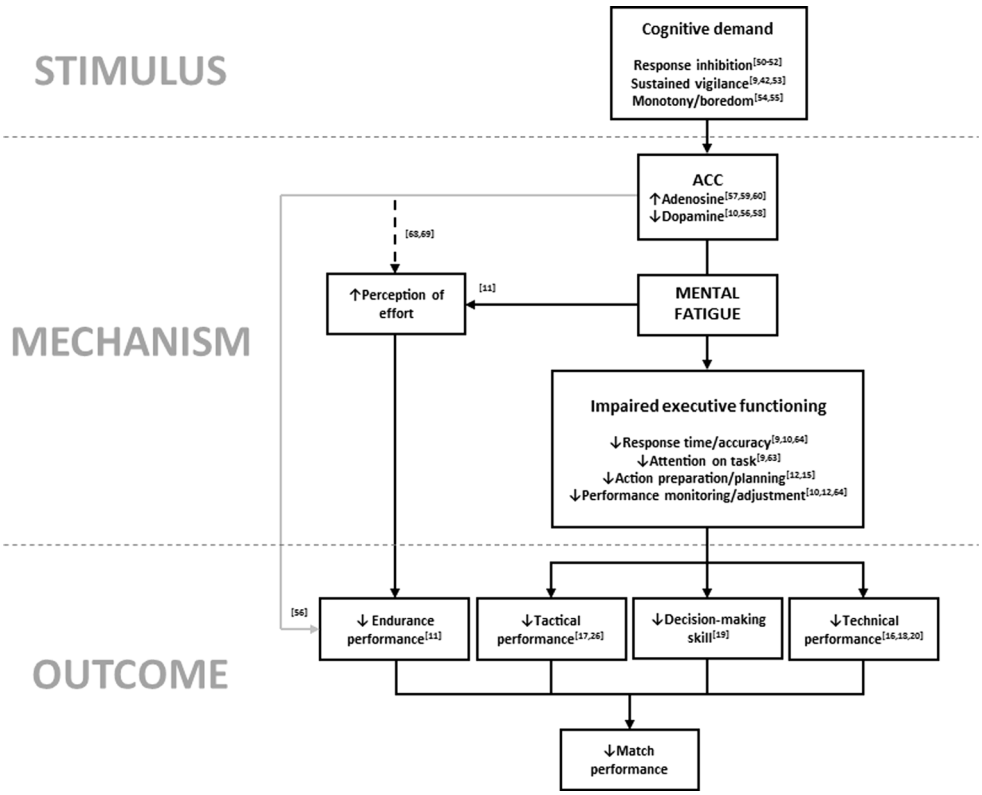

Fig. 1 Conceptual model outlining a potential mechanistic pathway for the impact of mental fatigue on soccer performance. *ACC* anterior cingulate cortex. The gray line indicates evidence from animal research, and the broken line indicates proposed mechanism lacking empirical evidence

interaction between mental fatigue, caffeine consumption, and soccer performance.

4 Conclusions

The recent literature indicates that mental fatigue may contribute to performance decrements associated with "match-related fatigue" in soccer. Indeed, induced mental fatigue impairs soccer-specific physical, technical, decision-making, and tactical performance. These findings provide initial experimental evidence and confirm anecdotal reports of the influence of mental fatigue on soccer performance. However, this remains an emerging field of research, requiring additional investigation. The primary limitation of the existing literature is a lack of direct application to the performance environment. Therefore, future investigations must aim to reconcile research and practice by studying mental fatigue and soccer performance with an applied focus. A deeper understanding of the mechanisms that underpin the negative impact of mental fatigue on soccer performance may assist in directing this future research. A conceptual mechanistic model has been presented for this purpose. Although further research is required in this emerging field, the existing literature provides adequate evidence that soccer clubs should consider strategies to avoid and/or attenuate the negative effects of mental fatigue on soccer performance.

Compliance with Ethical Standards

Conflicts of interest Mitchell R. Smith, Chris Thompson, Samuele M. Marcora, Sabrina Skorski, Tim Meyer and Aaron J. Coutts have no conflicts of interest.

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References

1. Mohr M, Krustrup P, Bangsbo J. Fatigue in soccer: a brief review. J Sports Sci. 2005;23(6):593–9.
2. Carling C, Dupont G. Are declines in physical performance associated with a reduction in skill-related performance during professional soccer match-play? J Sports Sci. 2011;29(1):63–71.
3. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. J Sports Sci. 2003;21(7):519–28.
4. Rampinini E, Coutts AJ, Castagna C, Sassi R, Impellizzeri FM. Variation in top level soccer match performance. Int J Sports Med. 2007;28(12):1018–24.
5. Rampinini E, Impellizzeri FM, Castagna C, Azzalin A, Bravo DF, Wisloff U. Effect of match-related fatigue on short-passing ability in young soccer players. Med Sci Sports Exerc. 2008;40(5):934–42.
6. Walsh V. Is sport the brain's biggest challenge? Curr Biol. 2014;24(18):R859–60.

7. Nédélec M, McCall A, Carling C, Legall F, Berthoin S, Dupont G. Recovery in soccer: part I-Post-match fatigue and time course of recovery. Sports Med. 2012;42(12):997–1015.
8. Coutts AJ. Fatigue in football: it's not a brainless task! J Sports Sci. 2016;34(14):1296.
9. Boksem MAS, Meijman TF, Lorist MM. Effects of mental fatigue on attention: an ERP study. Cogn Brain Res. 2005;25(1):107–16. https://doi.org/10.1016/j.cogbrainres.2005.04.011.
10. Lorist M, Boksem MAS, Ridderinkhof KR. Impaired cognitive control and reduced cingulate activity during mental fatigue. Cogn Brain Res. 2005;24(2):199–205. https://doi.org/10.1016/j.cogbrainres.2005.01.018.
11. Van Cutsem J, Marcora S, De Pauw K, Bailey S, Meeusen R, Roelands B. The effects of mental fatigue on physical performance: a systematic review. Sports Med. 2017;47(8):1569–88.
12. Boksem MAS, Meijman TF, Lorist MM. Mental fatigue, motivation and action monitoring. Biol Psychol. 2006;72(2):123–32. https://doi.org/10.1016/j.biopsycho.2005.08.007.
13. Duncan MJ, Fowler N, George O, Joyce S, Hankey J. 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.
14. Lal SKL, Craig A. A critical review of the psychophysiology of driver fatigue. Biol Psychol. 2001;55(3):173–94. https://doi.org/10.1016/S0301-0511(00)00085-5.
15. Lorist M, Klein M, Nieuwenhuis S, Jong R, Mulder G, Meijman TF. Mental fatigue and task control: planning and preparation. Psychophysiology. 2000;37(5):614–25.
16. Badin OO, Smith MR, Conte D, Coutts AJ. Mental fatigue impairs technical performance in small-sided soccer games. Int J Sports Physiol Perform. 2016;11(8):1100–5. https://doi.org/10.1123/ijspp.2015-0710.
17. Coutinho D, Gonçalves B, Travassos B, Wong DP, Coutts AJ, Sampaio JE. Mental fatigue and spatial references impair soccer players' physical and tactical performances. Front Psychol. 2017. https://doi.org/10.3389/fpsyg.2017.01645.
18. Smith MR, Coutts AJ, Merlini M, Deprez D, Lenoir M, Marcora SM. Mental fatigue impairs soccer-specific physical and technical performance. Med Sci Sports Exerc. 2016;48(2):267–76. https://doi.org/10.1249/MSS.0000000000000762.
19. Smith MR, Zeuwts L, Lenoir M, Hens N, De Jong LMS, Coutts AJ. Mental fatigue impairs soccer-specific decision-making skill. J Sports Sci. 2016;34(14):1297–1304. https://doi.org/10.1080/02640414.2016.1156241.
20. Smith MR, Fransen J, Deprez D, Lenoir M, Coutts AJ. Impact of mental fatigue on speed and accuracy components of soccer-specific skills. Sci Med Footb. 2017;1(1):48–52. https://doi.org/10.1080/02640414.2016.1252850.
21. Paul DJ, Bradley PS, Nassis GP. Factors affecting match running performance of elite soccer players: shedding some light on the complexity. Int J Sports Physiol Perform. 2015;10(4):516–9.
22. Smith MR, Marcora SM, Coutts AJ. Mental fatigue impairs intermittent running performance. Med Sci Sports Exerc. 2015;47(8):1682–90.
23. Castagna C, Impellizzeri F, Cecchini E, Rampinini E, Alvarez JCB. Effects of intermittent-endurance fitness on match performance in young male soccer players. J Strength Cond Res. 2009;23(7):1954–9.
24. Brownsberger J, Edwards A, Crowther R, Cottrell D. Impact of mental fatigue on self-paced exercise. Int J Sports Med. 2013;34(12):1029–36.
25. Marcora SM, Staiano W, Manning V. Mental fatigue impairs physical performance in humans. J Appl Physiol. 2009;106(3):857–64. https://doi.org/10.1152/japplphysiol.91324.2008.
26. Coutinho D, Gonçalves B, Wong DP, Travassos B, Coutts AJ, Sampaio J. Exploring the effects of mental and muscular fatigue in soccer players' performance. Hum Mov Sci. 2018;58(1):287–96.
27. Hill-Haas SV, Dawson B, Impellizzeri FM, Coutts AJ. Physiology of small-sided games training in football. Sports Med. 2011;41(3):199–220.
28. Rampinini E, Impellizzeri FM, Castagna C, Coutts AJ, Wisloff U. Technical performance during soccer matches of the Italian Serie A league: effect of fatigue and competitive level. J Sci Med Sport. 2009;12(1):227–33.
29. Rozand V, Lebon F, Papaxanthis C, Lepers R. Effect of mental fatigue on speed-accuracy trade-off. Neuroscience. 2015;297:219–30.
30. Serpiello FR, Cox A, Oppici L, Hopkins WG, Varley MC. The loughborough soccer passing test has impractical criterion validity in elite youth football. Sci Med Footb. 2017;1(1):60–4. https://doi.org/10.1080/02640414.2016.1254810.
31. Knicker AJ, Renshaw I, Oldham ARH, Cairns SP. Interactive processes link the multiple systems of fatigue in sport competition. Sports Med. 2011;41(4):307–28.
32. Travassos B, Gonçalves B, Marcelino R, Monteiro R, Sampaio J. How perceiving additional targets modifies teams' tactical behavior during football small-sided games. Hum Mov Sci. 2014;38:241–50. https://doi.org/10.1016/j.humov.2014.10.005.
33. Vaeyens R, Lenoir M, Williams AM, Mazyn L, Philippaerts RM. The effects of task constraints on visual search behavior and decision-making skill in youth soccer players. J Sport Exerc Psychol. 2007;29(2):147.
34. Vaeyens R, Lenoir M, Williams AM, Philippaerts RM. Mechanisms underpinning successful decision making in skilled youth soccer players: an analysis of visual search behaviors. J Mot Behav. 2007;39(5):395–408.
35. Mashiko T, Umeda T, Nakaji S, Sugawara K. Position related analysis of the appearance of and relationship between post-match physical and mental fatigue in university rugby football players. Br J Sports Med. 2004;38(5):617–21.
36. Terry PC, Lane AM, Fogarty GJ. Construct validity of the profile of mood states-adolescents for use with adults. Psychol Sport Exerc. 2003;4(2):125–39. https://doi.org/10.1016/S1469-0292(01)00035-8.
37. Balasubramanian V, Adalarasu K, Gupta A. EEG based analysis of cognitive fatigue during simulated driving. Int J Ind Syst Eng. 2011;7(2):135–49. https://doi.org/10.1504/IJISE.2011.038563.
38. Craig A, Tran Y, Wijesuriya N, Nguyen H. Regional brain wave activity changes associated with fatigue. Psychophysiology. 2012;49(4):574–82. https://doi.org/10.1111/j.1469-8986.2011.01329.x.
39. Lamond N, Dawson D, Roach GD. Fatigue assessment in the field: validation of a hand-held electronic psychomotor vigilance task. Aviat Space Environ Med. 2005;76(5):486–9.
40. Brito J, Hertzog M, Nassis GP. Do match-related contextual variables influence training load in highly trained soccer players? J Strength Cond Res. 2016;30(2):393–9.
41. Lambourne K, Tomporowski P. The effect of exercise-induced arousal on cognitive task performance: a meta-regression analysis. Brain Res. 2010;1341(1):12–24.
42. Van Dongen H, Belenky G, Krueger JM. Investigating the temporal dynamics and underlying mechanisms of cognitive fatigue. In: Ackerman PL, editor. Cognitive fatigue: multidisciplinary perspectives on current research and future applications. Washington: Am Psychol Assoc; 2011. p. 127–47.
43. Wagstaff C. Emotion regulation and sport performance. J Sport Exerc Psychol. 2014;36(4):401–12.
44. Balkin TJ, Wesensten NJ. Differentiation of sleepiness and mental fatigue effects. In: Ackerman PL, editor. Cognitive

fatigue: multidisciplinary perspectives on current research and future applications. Washington, DC: Am Psychol Assoc; 2011. p. 47–66.
45. Martin K, Staiano W, Menaspà P, Hennessey T, Marcora S, Keegan R, et al. Superior inhibitory control and resistance to mental fatigue in professional road cyclists. PLoS One. 2016;11(7):e0159907.
46. Marcora SM, Staiano W, Merlini M. A randomized controlled trial of brain endurance training (bet) to reduce fatigue during endurance exercise. Med Sci Sports Exerc. 2015;47(5S):198.
47. Fullagar HHK, Skorski S, Duffield R, Hammes D, Coutts AJ, Meyer T. Sleep and athletic performance: the effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise. Sports Med. 2015;45(2):161–86. https://doi.org/10.1007/s40279-014-0260-0.
48. Silva J, Rumpf M, Hertzog M, Castagna C, Farooq A, Girard O, et al. Acute and residual soccer match-related fatigue: a systematic review and meta-analysis. Sports Med. 2018;48(3):1–45.
49. Lew FL, Qu X. Effects of mental fatigue on biomechanics of slips. Ergonomics. 2014;57(12):1927–32.
50. Bush G, Whalen PJ, Rosen BR, Jenike MA, McInerney SC, Rauch SL. The counting Stroop: an interference task specialized for functional neuroimaging—validation study with functional MRI. Hum Brain Mapp. 1998;6(4):270–82.
51. MacDonald AW, Cohen JD, Stenger VA, Carter CS. Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. Science. 2000;288(5472):1835–8.
52. Mostofsky SH, Simmonds DJ. Response inhibition and response selection: two sides of the same coin. J Cogn Neurosci. 2008;20(5):751–61. https://doi.org/10.1162/jocn.2008.20500.
53. Gunzelmann G, Moore LR, Gluck KA, Van Dongen H, Dinges DF. Fatigue in sustained attention: Generalizing mechanisms for time awake to time on task. In: Ackerman PL, editor. Cognitive fatigue: multidisciplinary perspectives on current research and future applications. Washington: Am Psychol Assoc; 2011. p. 83–101.
54. Desmond PA, Matthews G. Implications of task-induced fatigue effects for in-vehicle countermeasures to driver fatigue. Accid Anal Prev. 1997;29(4):515–23.
55. Lorist MM, Faber LG. Consideration of the influence of mental fatigue on controlled and automatic cognitive processes and related neuromodulatory effects. In: Ackerman PL, editor. Cognitive fatigue: multidisciplinary perspectives on current research and future applications. Washington: Am Psychol Assoc; 2011. p. 105–26.
56. Boksem MAS, Tops M. Mental fatigue: costs and benefits. Brain Res Rev. 2008;59(1):125–39. https://doi.org/10.1016/j.brainresrev.2008.07.001.
57. Davis JM, Zhao Z, Stock HS, Mehl KA, Buggy J, Hand GA. Central nervous system effects of caffeine and adenosine on fatigue. Am J Physiol Regul Integr Comp Physiol. 2003;284(2):R399–404.
58. Holroyd CB, Coles MG. The neural basis of human error processing: reinforcement learning, dopamine, and the error-related negativity. Psychol Rev. 2002;109(4):679–708.
59. Lorist M, Tops M. Caffeine, fatigue, and cognition. Brain Cogn. 2003;53(1):82–94.
60. Lovatt D, Xu Q, Liu W, Takano T, Smith NA, Schnermann J, et al. Neuronal adenosine release, and not astrocytic ATP release, mediates feedback inhibition of excitatory activity. Proc Natl Acad Sci. 2012;109(16):6265–70.
61. Salamone JD, Yohn SE, López-Cruz L, San Miguel N, Correa M. Activational and effort-related aspects of motivation: neural mechanisms and implications for psychopathology. Brain. 2016;139(5):1325–47.
62. Walton ME, Kennerley SW, Bannerman DM, Phillips PEM, Rushworth MFS. Weighing up the benefits of work: behavioral and neural analyses of effort-related decision making. Neural Netw. 2006;19(8):1302–14. https://doi.org/10.1016/j.neunet.2006.03.005.
63. Ackerman PL. 100 years without resting. In: Ackerman PL, editor. Cognitive fatigue: multidisciplinary perspectives on current research and future applications. Washington: Am Psychol Assoc; 2011. p. 11–43.
64. Kato Y, Endo H, Kizuka T. Mental fatigue and impaired response processes: event-related brain potentials in a Go/NoGo task. Int J Psychophysiol. 2009;72(2):204–11.
65. Smith MD, Chamberlin CJ. Effect of adding cognitively demanding tasks on soccer skill performance. Percept Mot Skills. 1992;75(3):955–61.
66. MacMahon C, Schücker L, Hagemann N, Strauss B. Cognitive fatigue effects on physical performance during running. J Sport Exerc Psychol. 2014;36(4):375–81.
67. Pageaux B, Marcora SM, Lepers R. Prolonged mental exertion does not alter neuromuscular function of the knee extensors. Med Sci Sports Exerc. 2013;45(12):2254–64. https://doi.org/10.1249/MSS.0b013e31829b504a.
68. Pageaux B, Lepers R, Dietz KC, Marcora SM. Response inhibition impairs subsequent self-paced endurance performance. Eur J Appl Physiol. 2014;114(5):1095–105. https://doi.org/10.1007/s00421-014-2838-5.
69. Williamson J, McColl R, Mathews D, Mitchell J, Raven P, Morgan W. Hypnotic manipulation of effort sense during dynamic exercise: cardiovascular responses and brain activation. J Appl Physiol. 2001;90(4):1392–9.
70. Rudebeck PH, Walton ME, Smyth AN, Bannerman DM, Rushworth MF. Separate neural pathways process different decision costs. Nat Neurosci. 2006;9(9):1161–8.
71. Walton ME, Bannerman DM, Alterescu K, Rushworth MF. Functional specialization within medial frontal cortex of the anterior cingulate for evaluating effort-related decisions. J Neurosci. 2003;23(16):6475–9.
72. Swick D, Jovanovic J. Anterior cingulate cortex and the Stroop task: neuropsychological evidence for topographic specificity. Neuropsychologia. 2002;40(8):1240–53.
73. Van Cutsem J, De Pauw K, Marcora S, Meeusen R, Roelands B. A caffeine-maltodextrin mouth rinse counters mental fatigue. Psychopharmacology. 2018;235(4):947–58.
74. Ataka S, Tanaka M, Nozaki S, Mizuma H, Mizuno K, Tahara T, et al. Effects of oral administration of caffeine and D-ribose on mental fatigue. Nutrition. 2008;24(3):233–8.
75. Kennedy DO, Scholey AB. A glucose-caffeine 'energy drink'ameliorates subjective and performance deficits during prolonged cognitive demand. Appetite. 2004;42(3):331–3.
76. Azevedo R, Silva-Cavalcante MD, Gualano B, Lima-Silva AE, Bertuzzi R. Effects of caffeine ingestion on endurance performance in mentally fatigued individuals. Eur J Appl Physiol. 2016;116(11):2293–303. https://doi.org/10.1007/s00421-016-3483-y.
77. Del Coso J, Muñoz-Fernández VE, Muñoz G, Fernández-Elías VE, Ortega JF, Hamouti N, et al. Effects of a caffeine-containing energy drink on simulated soccer performance. PLoS One. 2012;7(2):e31380.
78. Foskett A, Ali A, Gant N. Caffeine enhances cognitive function and skill performance during simulated soccer activity. Int J Sport Nutr Exerc Metab. 2009;19(4):410–23.
79. Lara B, Gonzalez-Millán C, Salinero JJ, Abian-Vicen J, Areces F, Barbero-Alvarez JC, et al. Caffeine-containing energy drink improves physical performance in female soccer players. Amino Acids. 2014;46(5):1385–92.