Title: A time and a place: a framework for caffeine periodization throughout the sporting year.

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A time and a place: a framework for caffeine periodization throughout the sporting year

Abstract

Caffeine is a well-established ergogenic aid, with its performance-enhancing effects demonstrated across a variety of sports and exercise types. As a result of caffeine's ergogenic properties, it is widely utilised by athletes at all levels around both competition and training. Caffeine exerts its performance benefits through a variety of mechanisms, each of which may be of increased importance at a given stage of training or competition. In addition, regular caffeine use may diminish the performance enhancing effects of a subsequent dose of caffeine. Recently, interest in the concept of nutritional periodization has grown; here we propose a framework for the periodization of caffeine through the sporting year, balancing its training and competition performance-enhancing effects, along with the need to mitigate any negative effects of habituation. Furthermore, the regular use of caffeine within training may support the development of positive beliefs towards caffeine by athletes—potentially serving to enhance future performance through placebo and expectancy mechanisms—as well as allowing for the optimisation of individual athlete caffeine strategies. Whilst future work is required to validate some of the suggestions made, the framework proposed here represents a starting point for athletes to maximise caffeine's performance benefits across the sporting year.

Key Words: Ergogenic aid, supplementation, training

1. Introduction - The ever-broadening role of periodization in sport and exercise.

Sports coaches have long understood the inherent value within the concept of periodization, broadly defined as the systematic planning of long- and short-term training programs aimed at optimising performance-relevant adaptations [1,2]. Whilst the underpinning scientific rationale [3] and study methodologies [4] suggests that traditional periodization concepts are not the panacea they are often held up to be, there is clear evidence that variation in imposed training demands can enhance performance [1]. Whilst previously limited to the exercise domain, the concept of periodization has expanded, with the underlying principles explored within altitude training [5], body composition [6], heat adaptation [7], recovery [1], and psychological skills [1]. One area in which periodization principles are of increased interest is sports nutrition [1-2, 8-10], with periodized nutrition defined as "the planned, purposeful, and strategic use of specific nutritional interventions to enhance the adaptations targeted by individual exercise sessions or periodic training plans, or to obtain other effects that will enhance performance longer term" [9]. Periodized nutrition has been primarily studied in terms of carbohydrate utilisation within aerobic endurance athletes, whereby carbohydrate availability is manipulated to drive desired molecular and physiological adaptations to exercise [8,10]. Interest in nutritional periodization techniques has grown, with the principles applied to strength athletes [2], and a general framework in the scientific literature has been recently proposed [10]. Here, we expand the concept of nutritional periodization by applying it to caffeine, a widely-used, effective ergogenic aid [11], exploring how manipulation of caffeine's use may support athlete performance across the training year.

2. Caffeine - a potent performance enhancer

Caffeine (1,3,7-trimethylxanthine) is a popular ergogenic substance, widely utilised by athletes [12] and non-athletes [13] alike. The performance-enhancing effects of caffeine have long been established, with the first known study exploring caffeine's use during exercise published over 100 years ago [14]. A recent umbrella review [11] reported a clear ergogenic effect of caffeine on muscle strength, muscular endurance, anaerobic power, and aerobic endurance. Whilst caffeine has significant acute ergogenic effects [11], it also has wider effects that are currently underexplored within sporting contexts. For example, caffeine has the potential to significantly harm sleep [15], but may also enhance post-exercise glycogen recovery [16]. Across a training block that occurs within a traditional exercise periodization model, caffeine may also reduce the sensation of

Delayed Onset of Muscle Soreness (DOMS) [17], mitigate feelings of fatigue [18], and potentially even enhance specific training adaptations [19]. However, regular caffeine use may reduce the subsequent ergogenic effects of a given caffeine dose [20,21]. As such, there is a clear scope for exploring the structured, periodized use of caffeine across the training year, with caffeine utilized to support performance or specific adaptations at a given time, and exposure varied to guard against possible habituation. Whilst much of the focus in research is directed towards exploring acute ergogenic effects of caffeine on different exercise tasks, such data provide little insight into methods that can be utilized by athletes interested in long-term supplementation with caffeine. In this manuscript, the first to our knowledge to examine caffeine in this way, we discuss how caffeine intake might be periodized across the training and competitive year, and provide some tentative recommendations to athletes, coaches and practitioners who are interested in getting the most out of their caffeine supplementation practices.

3. Caffeine use in sport – a time and a place?

3.1 Acute Caffeine Use – Implications for Training & Competition

Caffeine's performance-enhancing effects are well-established and well-replicated, and are overwhelmingly acute in nature [11]. Evidence suggests that caffeine enhances aerobic endurance [22], high-intensity efforts [23], muscular endurance [24], sprint performance [25], and maximum strength [26]. Caffeine also acutely enhances sporting performance, with ergogenic effects of caffeine on sport-specific endurance [27], power-based sports [28], as well as performance in volleyball [29], rugby [30], soccer [31], basketball [32], and swimming [33]. Given these broad ergogenic effects—both in terms of general physical abilities and sport-specific performance—caffeine itself is widely utilised by sportspeople, with research suggesting that 75-90% of athletes consume caffeine prior to, or during, competition [34,35].

Caffeine also has the potential to exert other beneficial effects that may enhance acute sporting performance, such as enhancing cognitive performance [36]—especially when sleep-restricted [37]—and mood, supporting sporting performance when sleep deprived [38], enhancing skill execution [39], and reducing sensations of pain and soreness [40]. Given these benefits, caffeine is widely utilised by athletes as performance-enhancer at different stages of the sporting year.

3.1.2 Caffeine use in competition

During the competition phase of the sporting year, the athlete is focused first and foremost on enhancing physical performance. Given caffeine's ergogenic effects, it would appear sensible to recommend that athletes utilise caffeine either directly before, or during, competition. There are, however, some side effects to be aware of. Caffeine has the potential to increase feelings of anxiety [41]. Increased anxiety can be positive if the athlete requires an increase in arousal pre-competition, but may become performance-limiting prior to competitions when the athletes arousal and anxiety levels are already high, such as the Olympic Games [42]. Additionally, because caffeine has strong stimulant properties, it can increase sleep latency and decrease sleep quality [15,43]. Whilst caffeine's stimulant effects may be positive during competition due to increased performance and wakefulness—especially if the athlete is jet lagged—it also seems that caffeine has the ability to significantly harm post-competition recovery. Clearly, a pragmatic approach would be required here; is the subsequent loss of sleep and impaired recovery a worthwhile price to pay for enhanced competition performance? Many athletes would likely argue that it is, although further research is required to understand how this might affect competitive bouts in close duration—in terms of days—such as within a sporting championship [44,45].

Another area where caffeine ingestion may be beneficial is within repeated competitive bouts that occur on the same day [44,45]. For example, at the recent 2019 World Athletics Championships, the semi-finals and finals of the women's 100m were separated by just 2 hours. A number of issues here require further elucidation; if the second competitive bout takes place within a period of time in which plasma caffeine concentrations are maintained, what effect—if any—does a secondary caffeine dose have? Does the increased work rate afforded by caffeine supplementation [46] cause increased fatigue and/or muscle damage that may harm a subsequent performance bout? An initial study [47] demonstrated no negative effect of caffeine supplementation on exercise bouts on consecutive days, and Bell and McLellan [48] reported that 6 mg/kg of caffeine consumed prior to an exercise bout still exerted an ergogenic effect on a second exercise bout taking place 6 hours later, with no additional performance-enhancement with a second dose of caffeine (2.5 mg/kg). Conversely, Negaresh and colleagues [49] reported increased efficacy of repeated dosing (5x) of caffeine at 2 mg/kg compared to a single caffeine dose (10 mg/kg) during a wrestling tournament of multiple competitive bouts. As future research allows us to better understand the influence of repeated competitive bouts on caffeine ergogenicity, more targeted guidelines may be developed.

3.1.3 The use of caffeine in training

During the general training phase—often termed the "off-season"—the athlete is focused on building performance capacity through the accumulation of training volume (i.e. total workload) and/or intensity (i.e. effort or load). As detailed above, caffeine is a potent performance enhancer [11], which is why athletes utilise caffeine prior to competition. However, caffeine's acute ergogenic effects will also enhance performance in individual training sessions; as a result, athletes also use caffeine pre-training as a performance enhancer [50]. However, caffeine supplementation during training phases may be efficacious for a variety of further reasons. Research suggests that caffeine may attenuate post-exercise DOMS and perception of soreness [51,52], and caffeine can enhance mood and alertness [53], as well as alleviate feelings of fatigue that may be associated with increased training loads [51] and the lack of sleep often associated with early morning training sessions [38]. Caffeine has also been shown to alleviate mental fatigue, enhancing endurance [54] and skill [36] performance. There is the potential that caffeine may enhance post-exercise recovery, with some data suggesting that caffeine, and other ingredients in coffee such as cafestol and caffeic acid, may enhance muscle glycogen recovery [16]. Finally, when an athlete is experiencing soreness in the form of DOMS, caffeine appears to mitigate the pain associated with subsequent exercise [17], enhancing performance within the subsequent training session.

Can caffeine enhance training adaptations?

Caffeine primarily serves to acutely enhance exercise performance, with its effects typically only lasting for 3-4 hours [55]. However, if caffeine acutely enhances performance in individual training sessions, do these acute increases combine to deliver greater adaptations to the training program as a whole, when compared to athletes who do not utilise caffeine supplementation [44]? Very few studies have explored this; however, Malek and colleagues [56] randomised subjects to receive either a placebo or caffeine-containing supplement (201mg of caffeine) prior to each training session within an 8-week aerobic training program, with no significant differences in peak oxygen consumption reported between the groups. In another study, participants performed resistance training three times per week for six weeks [57]. One group ingested 3 mg/kg caffeine 60-minutes before each session, whilst the other ingested a placebo. After six weeks, both groups increased maximum strength in the bench press and squat; however, the improvement was greater in the caffeine ingestion group. This group also had a higher volume load (sets x load x repetitions), suggesting that long-term improvements in strength are likely explained by acute improvements in exercise performance following caffeine ingestion before every session. Whilst this study requires replication, the results suggest that regular pre-exercise caffeine ingestion may enhance training adaptations.

Caffeine may modify the molecular signals that occur post-exercise. At supraphysiological doses (e.g. 5 mM), caffeine appears to inhibit mammalian target of rapamycin (mTOR)—a key intracellular enzyme associated with resistance exercise-induced muscle hypertrophy—activity [58,59], although these results are equivocal when physiological levels (e.g. 0.3 mM) of caffeine are applied [60]. To our knowledge, there are only unpublished observations examining the acute effects of caffeine on anabolic signaling in humans. Here, caffeine intake prior to resistance exercise did not have any effect on p70S6 kinase or muscle protein synthesis following exercise, possibly because the study also did not find an overall ergogenic effect on caffeine on performance [61]. Similarly, prolonged exposure of muscle cells to high concentrations of caffeine appears to enhance mitochondrial biogenesis [62], although further research is required to explore the effects of caffeine, when consumed as an ergogenic aid, on various muscle signaling pathways. Nevertheless, caffeine has a theoretical ability to enhance training adaptations in athletes, either by increasing workload or augmenting post-exercise adaptive signaling, although substantially more research in humans is required in this area.

3.2 Chronic Caffeine Use – A need for periodization?

3.2.1 Habituation

Regular exposure to caffeine is associated with physiological adaptations that may reduce its future ergogenic effects [63,64]. As a result, caffeine habituation is often reported as a potential modifying factor of the acute response to caffeine [21,42,64], although there are a surprisingly small number of studies exploring the influence of caffeine habituation on exercise performance, with conflicting findings reported [20,44]. In general, studies either report no negative influence of regular caffeine intake on its subsequent ergogenic effects [65-67], or a reduced—but not eliminated—subsequent ergogenic effect [21,68,69]. The specific mechanisms driving this loss of ergogenic effects with regular use are poorly understood, but may include increased metabolisation speed, along with increased adenosine receptor densities [20].

If regular caffeine use blunts the subsequent ergogenic effects of caffeine, then there are some potential strategies athletes could utilise to ensure they derive the maximum benefit from caffeine supplementation at the time it matters most—prior to competition. Short-term caffeine withdrawal has been proposed as a method of becoming re-sensitised to caffeine's ergogenic effects [70], which again has been relatively poorly studied [20]. In studies conducted on this topic, short-term (i.e. ~4 day) caffeine withdrawal did not significantly improve the subsequent ergogenic effects of a dose of caffeine [71,72]. Longer periods of caffeine withdrawal have not, to our knowledge, been studied; furthermore, short-term caffeine withdrawal is associated with negative side effects such as fatigue, irritability, muscle pain, sleep disturbances, and nausea [72-74]. From a biological basis, this caffeine dependence is proposed to be because of the increased functional sensitivity to endogenous adenosine [74]. Whilst typically mild, and reversible upon caffeine ingestion [55,75], such sensations are likely to be undesirable in elite athletes prior to competition.

A second potential option is for athletes to consume a greater pre-competition dose of caffeine relative to their habitual, pre-training and daily life caffeine intakes [20]. This pragmatic approach, which balances the daily, non-sporting consumption of caffeine (primarily via caffeinated beverages such as coffee) and the targeted pre-training use of caffeine widely utilised by athletes [50] with the need to maintain an optimised ergogenic response to caffeine pre-competition [20]. In this case, regular consumption of low-to-moderate doses of caffeine (~2-3 mg/kg/d) and a pre-competition caffeine dose of ~4-5 mg/kg would likely suffice, although there is considerable inter-individual variation in the optimal caffeine dose, and this approach has not yet been studied in the literature [20,42].

3.2.2 Building beliefs

A small number of studies have demonstrated the effectiveness of placebo caffeine in enhancing performance [76-80], such that, if an athlete believes they have consumed caffeine, and they believe that caffeine is ergogenic, they likely will experience an ergogenic effect following caffeine supplementation, regardless of whether caffeine has been consumed. As a result, cultivating a belief in the ergogenic effects of caffeine, and the athlete recognising—through taste or physical sensations—that caffeine has been consumed, may be important in maximising the ergogenic response to a pre-competition caffeine dose. Regular caffeine intake may therefore be important in allowing the athlete to both have positive prior experiences following caffeine ingestion, as well as recognise the taste, and other physiological responses, associated with caffeine [81,82]. Finally, ritualistic behaviour—such as consuming caffeine in a set routine and method—supports positive outcomes of placebo

[83]. As such, the regular consumption of caffeine, as part of a pre-training routine, may support ergogenic effects when caffeine is consumed prior to competition.

3.2.3 Optimising individual practice

Whilst there are well-established guidelines suggesting that ingestion of 3-6 mg/kg of caffeine, consumed around 60-minutes prior to exercise, is ergogenic [84], there is considerable variation in both the optimal caffeine dose, and the timing of that dose, between individuals [42]. This individual response appears to occur due to genetic variation between individuals (for example, a common polymorphism (i.e. genetic variation) within *CYP1A2* appears to influence caffeine ergogenicity [85], although the findings on this topic are equivocal [86,87]), along with common environment differences such as habitual caffeine use [21,68-71], age [88], time of day [89-91], training status [89,92], along with caffeine-related beliefs and expectancy [76,79]. As a result, developing an optimised caffeine strategy for individual athletes may require considerable trial and error [42]; by experimenting with caffeine during training periods, athletes can perhaps better develop and refine their pre-competition caffeine strategies, increasing their confidence of success on the day of competition.

4. Practical Implications – Building a caffeine periodization framework

As detailed above, caffeine has clear and well-established performance enhancing effects [11], and, as a result, it is widely used by athletes in training and competition alike [12,50]. The regular use of caffeine during prolonged training phases may lead to caffeine habituation and reduced subsequent ergogenic effects [21,68], although this finding is equivocal [66]. If long-term caffeine ingestion indeed attenuates its ergogenic potential, this adaptation may suggest that athletes might be unable to maximally harness caffeine's ergogenic effects during the competition period. One way to potentially mitigate these effects is to avoid caffeine use during training periods; however, doing so may:

a) Harm performance during individual training sessions, either directly through physiological changes, or by influencing mood and/or perception of effort;
b) Minimise the time available for self-experimentation of optimised caffeine strategies;
c) Minimise the athlete's exposure to caffeine, potentially reducing the capacity of that athlete to build positive beliefs around caffeine use pre-exercise.

Accordingly, it appears that athletes and their support staff—including the coach, sports nutritionist, or Registered Dietician—should balance the use of caffeine across the training year using the principles of periodization (i.e. the use of strategic temporal nutritional interventions in line with the training demands and required adaptations across days [microcycles], weeks [mesocyles], and months [macrocyles] [10]), with the positive and negative adaptations expected following regular caffeine use outlined within this article.

In their recent paper, Stellingwerff and colleagues [10] developed a framework for the periodization of nutrition, in which nutritional interventions are utilised to support the bridging of performance gaps in athletes across macro-, meso-, and microcycles in a strategic manner. As an example, for an elite middle distance athlete preparing for the Olympic Games, the training year could (very broadly) be broken up into an accumulation phase, in which the athlete accumulates lower-intensity aerobic training volumes interspersed with less frequent high-intensity anaerobic training sessions, followed by an intensification phase, in which the relative volume of low intensity training decreases, and high intensity training increases, followed by the competition phrase. Each phrase may also be punctuated by training camps and periods of travel, potentially involving the crossing of multiple time zones.

During the accumulation phase, the aim would be to keep overall daily caffeine intake sufficiently low to mitigate long-term habituation affecting the pre-competition caffeine dose [20]. Therefore, in this phase, the athlete may decide to consume lower doses of caffeine (< 3 mg/kg) before and during their longer sessions, targeted to mitigate sensations of physiological and psychological fatigue [93,94]. Prior to higher intensity sessions, the athlete may decide to consume a relatively greater dose of caffeine (~3 mg/kg) to optimise performance in their “key” sessions, and mediate some of the general fatigue and soreness that may be accumulating [24,51]. Caffeine may also be utilised to augment other nutritional interventions, such as training with low carbohydrate availability [95,96]; here, caffeine may support performance when training a carbohydrate-depleted state [97,98].

As the athlete gets closer to the competition period, they may begin restricting energy intake as a means of reducing body fat and enhancing power-to-weight ratio [95]; during this period, caffeine ingestion may again alleviate feelings of fatigue [18], and, when consumed before a meal, may suppress acute energy intake [99]. Middle-distance runners may also utilise periods of altitude exposure to drive favourable physiological adaptations. Endurance performance is acutely harmed upon altitude exposure; here, acute caffeine ingestion prior to training may support performance [100] and hence drive positive training adaptations. Depending on their home base, athletes may have to travel across multiple time zones for both training camps and competitions, becoming subjected to both travel fatigue and jet lag. Caffeine has been demonstrated to be effective in mitigating daytime sleepiness following trans-meridian travel [101], and so its use may support subsequent performance in athletes following travel. During this phase of training, the athlete may wish to undergo some caffeine strategy self-experimentation prior to sessions that most mimic the competitive demands, varying caffeine dose, timing, and source to optimise performance [42,102,103].

During the competition period, athletes will primarily be utilising caffeine as a means of enhancing their competition performance. The use of caffeine in this way is subject to nuance, including consideration of:

a) Whether the dose of caffeine is sufficient to both mitigate any negative effects of habituation and deliver an optimised performance benefit [20, 104]; from a pragmatic perspective, during competition the athlete should utilise a caffeine dose that provides the greatest ergogenic effect whilst simultaneously being tolerable in terms of side-effects.
b) The state of arousal and/or anxiety of the athlete, with caffeine having the potential to increase both [41], potentially harming performance.
c) The contexts of the current competition; does the athlete have a more important competition or competitive bout in the coming hours/days in which acute caffeine ingestion may harm the preparation for, either by increasing workload—and hence fatigue and/or muscle damage in the current competitive bout—or harming post-exercise recovery by reducing sleep quality and quantity.
d) Whether caffeine is being consumed alongside other ergogenic aids that may enhance or ameliorate its ergogenic effects [45,105,106].

4.1 Caffeine Source

There are a variety of ways by which athletes could consume caffeine before and during both training and competition, including through caffeine anhydrous, sports drinks, energy drinks, carbohydrate bars and gels, gum, and coffee [103,107]. Coffee is likely a poor way to obtain caffeine pre-exercise; it exhibits substantial variation in caffeine concentrations both between brands/brews, but also within the same brand/brew across time [108-110]. As such, it can be difficult to accurately quantify the dose of caffeine consumed, which, given the potential for under- and over-dosing, increases the risk of making an error. Additionally, coffee tends to be consumed hot [107], which may harm performance in hot environments, and coffee also has the potential to be a gastric irritant [111]. Furthermore, a large volume of coffee may be required to deliver an ergogenic dose of caffeine, which may increase feelings of fullness and discomfort [107]. Due to these limitations, coffee might be an option for caffeine supplementation in the accumulation and intensification phases. However, given the importance of competition, athletes should seek to ensure that, during the competition phase, caffeine is obtained through a medium with limited dose variability, such as caffeine anhydrous, although other forms of caffeine supplementation, including with additional ergogenic substances such as carbohydrates, may be useful [103]. Caffeine sources and supplements with limited dose variability may also be useful during the regular training phases as a way of tightly monitoring caffeine intake.

5. Conclusion

As outlined within this manuscript, caffeine is a potent and well-established ergogenic substance [11], used regularly by athletes around both training [50] and competition [12]. Caffeine has a broad mechanism of action, and elicits its ergogenic effects through a variety of supplementation approaches; knowledge of these approaches can lead to a more nuanced use of caffeine to support specific outcomes across the sporting year. Maintenance of caffeine's ergogenic effects during competition is crucial [20], and so caffeine should be utilised in training in a way that maintains those benefits, possibly through limiting the habitual intake of caffeine to around 3 mg/kg per day, and utilising larger doses prior to competition [20]. During training phases, more moderate caffeine doses (1-3 mg/kg) can be used to acutely support performance during key sessions, and minimise attenuation of caffeine's ergogenic effects associated with chronic caffeine ingestion. Hypothetically, this approach would maximise performance benefits from acute caffeine ingestion at the competition.

The use of caffeine always comes at a cost, be that a gradual reduction in ergogenic response to a given dose [21], increased muscle damage and soreness due to enhanced workload [47], or reduced recovery due to sleep disturbances [15], or, in some cases, attenuated effectiveness of other consumed supplements [112]. In contrast, by not utilising caffeine, athlete performance may be lower than what is possible in both competition and training, and, in the latter case, this may reduce the magnitude of adaptations accumulated during a training phrase. As a result, the pragmatic use of caffeine across the sporting year in a way that supports the necessary performance whilst reducing any negative outcomes associated with its use—commonly termed "nutritional periodization"—represents perhaps the best approach to caffeine use over time. As we better understand some of the nuance around regular caffeine use, including the question of habituation, the effect on repeated competitive bouts, and training adaptations [20,44,45], we will be better able to provide more tailored advice. In the meantime, we encourage coaches, athletes, and their support staff to consider three key questions:

a) What am I hoping to achieve in this particular session or competition?
b) How might the use of caffeine support me in achieving these goals?
c) What are the potential costs of utilising caffeine during this session or competition, and how can I mitigate these side-effects?

In doing so, we hope that caffeine's ergogenic effects can be optimized by all, supporting the athlete in their performance goals.

Compliance with Ethical Standards

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Conflicts of Interest

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Author Contributions

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