**Cognitive functioning and heat strain: performance declines and protection.**

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**Abstract**

Despite the predominance of research on physical performance in the heat, many activities require high cognitive functioning for optimal performance (i.e., decision making) and/or health purposes (i.e., injury risk). Prolonged periods of demanding cognitive activity or exercise-induced fatigue will incur altered cognitive functioning. The addition of hot environmental conditions will exacerbate poor cognitive functioning and negatively affect performance outcomes. The present paper attempts to extract consistent themes from the heat-cognition literature to explore cognitive performance as a function of the level of heat stress encountered. More specifically, experimental studies investigating cognitive performance in conditions of hyperthermia, often via the completion of computerised tasks (i.e., cognitive tests), are used to better understand the relationship between endogenous thermal load and cognitive performance. The existence of an inverted U-shaped relationship between hyperthermia development and cognitive performance is suggested, and highlights core temperatures of ~38.5°C as potential ‘threshold’ for hyperthermia-induced negative cognitive performance. From this perspective, interventions to slow or blunt thermal loads and protect both task- and hyperthermia-related changes in task performances (e.g., cooling strategies) could be used to great benefit and potentially preserve cognitive performance during heat strain.

**1. Introduction: cognitive performance in the heat**

The interaction between exercise in the heat and performance decrement (as compared to temperate conditions) is often presented in a dose-response fashion, with greater heat exposure further limiting exercise duration [1, 2, 3, 4]. This relationship is classically explained by the progressive exacerbation of cardiovascular, thermoregulatory, metabolic and perceptual functioning [5]. Briefly, the augmented skin blood flow accompanying elevated skin (Tskin) and core (Tcore) temperatures poses additional challenges to cardiac strain and working muscles while amplifying perceived exertion [6]. Increased ventilation accompanying Tcore elevation may also decrease cerebral blood flow and incur inadequate substrate delivery to and heat removal from the brain [7]. Alongside these exacerbated perceptual and physiological responses from exercising in hot conditions, increased cognitive strain (i.e., the challenge of operating cognitive operations) is present [8].

Despite predominant research focussing on physical performance in the heat, many prolonged exercise events require maintenance of high cognitive functioning for performance (i.e., decision making [9]) and/or health purposes (i.e., injury risk [10, 11]). Indeed, in circumstances of goal-directed actions, outcome-based consequences rely on the ability to repeatedly and accurately regulate behaviour according to this goal. For example, athletes may be required to initiate immediate behavioural adjustments in response to a direct opponent (e.g., in duel sports), alter a pacing strategy (e.g., in prolonged efforts), encode and attend to a steady target (e.g., in shooting actions), interpret specific proprioceptive information (e.g., in natural outdoor settings), or distinguish unfair from fair moves (e.g., referee decision making). Such a collection of circumstances shows the direct need for optimal cognitive functioning during any athletic endeavour. Prolonged periods of demanding cognitive activity (i.e., mental fatigue) or exercise-induced fatigue will result in impaired cognitive functioning [12, 13]. The addition of hot environmental conditions (i.e., heat stress) will exacerbate poor cognitive functioning and negatively affect performance outcomes [14]. Accordingly, a further understanding of the effect of environmental-induced heat strain (i.e., the heat-related personal constraint) on cognitive functioning is of importance to discriminate and potentially protect the ability to adopt optimal goal-directed behaviour during exercise.

Cognitive performance reflects the accuracy and efficiency of sub-cortical and cortical processes allowing external stimuli detection and identification, response selection, preparation and activation [15]. Therefore, specific to sports performance, cognitive functioning refers to the ability to remain lucid during the strain of exercise. Behavioural response speed (i.e., reaction time) and accuracy (i.e., error rate) from test batteries are most commonly used as measures of information processing efficiency, whilst test specificity then allows inferences about specific cognitive operations (e.g., working memory - keep information in a quickly retrievable state; selective inhibition - deliberately inhibit an impulsive response when necessary). Of the cognitive operations assumed to be tested, working memory and vigilance tasks are considered the most demanding (i.e., relative to effort, and glucose and oxygen consumption), more so than dual tasks or tracking, perceptual motor and simple reaction time tests, respectively [16, 17]. Thus, task selectivity and measures enable access to behavioural outcomes whose changes in performance level then allow inferences about changes in cognitive functioning (e.g., improved cognitive control, increased impulsivity, impaired attentional focus). Accordingly, the use of behavioural outcomes during cognitive tasks is useful to i) provide an inexpensive, easy-to-use outcome to complement neuroimagery techniques (e.g., electroencephalography – EEG), ii) allow distinction to be made between, and within, motor and upstream stages of response processes when combined with electromyography (EMG); and iii) allow observations of *functional* brain responses (as opposed to resting cognitive activity). The abovementioned outcomes make cognitive performance particularly pertinent to enable further consideration of processes leading to greater cognitive fatigue and impaired goal-directed behaviour in the heat.

In hyperthermic conditions i.e., when Tcore rises, a number of responses are evident, including i) cognitive functions slow before physiological variables reach critical limits; and ii) the most effortful/complex cognitive computations are impaired earlier [18]. Further, it has been suggested that both the magnitude of heat strain and cognitive task complexity interact to predict cognitive efficiency; such that the more stressful the combination of hyperthermia *and* cognitive demands, the larger the cognitive impairment [19. 20]. Although it is intuitive that this relationship (heat strain and cognitive function) parallels the aforementioned dose-dependent effect of heat stress on endurance performance decrement, it is yet to be conclusively shown [21]. For example, some studies have reported no effect or positive cognitive performance outcomes in varying conditions of hyperthermia [8, 22]. If this is the case, it potentially makes the exacerbated thermal load during exercise in the heat relevant not just to physical performance, but also to cognitive performance for athletes and precautionary behavioural applications become even more important.

To date, due to its multi-faceted dimensions (dynamic conception of cognitive and physiological strains in the heat), the maximum adaptability model [23] represents the most established rationale to explain the heat-cognition response relationship. Based on empirical reports, the model suggests cognitive improvement with initiation of hyperthermia, resulting from adaptive strategies to heat strain, such as increased attentional focus. However, as hyperthermia develops, heat strain-induced depletion of attentional resources (expressed in terms of dynamic body Tcore increase) leads to cognitive performance decrement as a function of cognitive task complexity [23]. Despite growing interest in understanding hyperthermia-related physiological changes [24], this model has not been updated to date [25]; yet the recent development of innovative technologies that enable better tracking of cognitive processes (e.g., functional magnetic resonance imaging – fMRI; EMG applied to stimulus-response tasks) could challenge initial empirical reports. For instance, in temperate conditions, Ando et al. [26] and Grego et al. [27] highlighted discrepancies between behavioural and near-infrared spectroscopy and EEG indices of cognitive performance, respectively. Therefore, such observation suggests that the recent deeper monitoring of brain activity could refine empirical reports from cognitive tasks in the understanding of brain activity under increased heat stress.

Within this context, the present paper aims at extracting consistent themes from the recent heat-cognition literature to understand – and ultimately provide guidance for – cognitive performance as a function of the level of heat stress encountered. A three-step rationale for this possible relationship, together with potential explanatory mechanisms is presented. Further, a summary model of cognitive efficiency under heat stress is then proposed, and finally the potential practical implications are outlined.

**2. Cognitive responses during hyperthermia**

*2.1. Initial increases in core temperature and related cognitive benefits*

Irrespective of task complexity, cognitive functions initially improve when body heat accumulation elevates Tcore. Indeed, simple reaction times are reported as faster once Tcore begins to increase in situations of heat stress, highlighting a speeding effect of increased heat load on low-demanding tasks [28]. Greater performances are also reported during complex computations performed when passive heating (heat exposure in a resting state) induces a small increase in Tcore (~38.2°C) [29]. Specifically, Simmons et al. [29] found faster responses on both simple reaction time, choice reaction time and complex (vigilance) cognitive tests, which suggest a rise in body temperature induces a *systematic* improvement in the capacity to intensively, but punctually, focus and respond to a stimulus. The possibility of an initial cognitive improvement has more recently been reinforced by reports of small increases in Tcore (~38.0°C) resulting in improved working memory task and psychomotor vigilance performances [8, 30]. Interestingly, in the study by Bandelow et al. [8], block-tapping test performance improved when Tcore was elevated to ~38.2°C, a temperature beyond which the heat induced-beneficial effect disappeared (see section 2.2 for further discussion). Schlader et al. [31] provided further evidence for this initial heat-related acceleration of central processing for both attention and executive control tasks when Tcore was passively elevated in the range of ~1°C. Thus it is evident that small increases in endogenous heat accumulation result in an improvement in a variety of cognitive task performances.

The mechanisms responsible for this cognitive improvement may be plural and intertwined. Firstly, they could relate to a decrease in thermal comfort (i.e., the sensation of pleasantness related to heat) leading individuals to perceive greater difficulty in interpreting and responding to a given demand, as compared to colder conditions [5]. As a consequence, the athlete may deliberately invest a greater amount of cognitive effort into task completion to compensate for (or even overcompensate) the increased perception of difficulty induced by environmental conditions [32]. In addition, the heat-related cognitive benefits could relate to the arousal effect derived from endogenous thermoregulatory control mechanisms occurring during heat exposure [33, 34]. In particular, the massive projections from the dopaminergic pathways to the limbic system and the prefrontal cortex (PFC) could benefit from changes in neurotransmitters and hormonal activity and accelerate the cognitive computations [35]. Of note, this arousing effect is also reported to account for exercise-related enhanced cognitive performance in colder conditions [15] and could therefore be argued to mediate hyperthermia-related improved performance during heat- and exercise-induced hyperthermia (i.e., active heating) [8]. Cognitive improvement during modest passively-induced hyperthermia seems a consistent finding, whilst post-exercise related cognitive responses differ depending on the type of cognitive task undertaken [36]. Thus, when moderate hyperthermia is induced through exercise, exercise-related arousal may only partially contribute to cognitive performance improvement. An additional explanation for the observed enhancement of cognitive processing following small increases in Tcore relates to the Van’t Hoff Q10 effect. Similar to its metabolic effect at the muscular level, the Q10 effect may account for the increased cerebral metabolic rate of oxygen (CMRO2, an index of the rate of brain oxygen consumption) [37] observed with Tcore elevation [24] and thus mediate cognitive functioning efficiency. This proposal is supported both by age- and exercise-cognition studies reporting parallel variations in CMRO2 and cognitive performances [38, 39]. Other potential candidates that could support the positive cognitive effect of a modest hyperthermia include changes in regional cerebral blood flow (CBF) and substrate availability (i.e., an increase in CBF augmenting brain glucose delivery [40]) as well as blood-brain barrier permeability and circulating brain-derived neurotrophic factor [30].

Regardless of the multiple, though speculative, explanatory mechanisms, it seems a slight increase in Tcore (~38.2°C) improves cognitive performance. Importantly, both simple and complex cognitive processes are enhanced with initial increases in Tcore – regardless of whether passive or active in nature – suggesting no harmful cognitive consequences for athletes under limited heat stress or from normal pre-exercise behaviours i.e., warm-up.

*2.2. A heat-induced threshold for the reduction in cognitive performance?*

Noticing this initial positive effect on cognitive function induced by a passive mild Tcore elevation, Gaoua et al. [22] remarked that cognitive performance enhancement ceased once Tcore reached ~38.7°C. This ‘threshold’ indeed denoted an absence of further benefit in attention-based performance (i.e., reaction time and accuracy of rapid visual information processing). The existence of this ’threshold’ has previously been highlighted by Bandelow et al. [8] for a range of psychomotor tasks, implying a Tcore of ~38.2°C represented a plateau in heat-induced cognitive improvements. Consistent with the same trend, performance of numerous functions (verbal learning, attention and concentration) has been reported as unchanged at Tcore of ~38.5°C, whereas the most demanding performances tended to start to deteriorate [41]. Together, these observations suggest the existence of a threshold following which the initial cognitive benefits of heat stress start to plateau, and task complexity discriminates whether cognitive performance is further impaired.

Intuitively, interpretations about the absence of changes in cognitive task performance when Tcore is ~38.5°C may rely on whether a thermal stress is sufficient to appropriately disturb homeostasis i.e., normal cognitive functioning. However, at these levels of hyperthermia, changes in brain functioning have been shown and, in contrast to the proposal of a ‘normal’ cognitive functioning, led to discussions about the presence of a heat-related cognitive ‘ceiling’ effect. More precisely, it has been proposed that the contribution of the two components of reaction time i.e., the central component (the time interval between the onset of the response signal and the onset of the EMG activity of the muscles involved in the response) *vs*. the peripheral component (the time interval from the onset of EMG activity to the onset of the required motor response), is altered in response to increased heat strain (~38.5±0.2°C), despite overall performance remaining stable [22, 42]. In particular, when Tcore values approach ­~38.7°C, Gaoua et al. [22] suggested that the central component slows to such an extent that it compensates the heat-induced accelerated peripheral component of reaction time. This phenomenon has also been suggested by Hocking et al. [41] within the same range of heat stress (~38.7±0.2°C), with observations that alterations within steady-state visually evoked potentials (SSVEP) remained noticeable, even though no clear changes in task performances were evident. In this study, greater brain activity, as measured via increased SSVEP magnitude and decreased latency, was indicative of a greater utilization of neural resources in order to preserve performance [41]. At higher Tcore however, the authors speculated that heat strain would overload cognitive capacities (i.e., the ability to deal with both heat and the task), making any trade-off and performance maintenance difficult. More recently, Liu et al. [43] reported findings consistent with this speculation when performing fMRI analysis during alerting and orienting cognitive tasks. The authors suggested such compensating processes might result from a greater activity of variant regional brain areas (i.e., a compensation from additional brain structures including frontal and temporal areas, respectively), rather than a greater specific cortical involvement (i.e., a hyper-activation of the brain area initially activated).

These findings obtained using different tools interestingly point towards a common phenomenon; that a heat-induced ‘threshold’ exists for cognitive performance. More specifically, as Tcore reaches ~38.5°C a plateau in cognitive functioning appears evident, made explicit through the greater cognitive activity observed while task performance remains stable. However, beyond this threshold the greater activation of frontal and temporal cortices does not compensate for heat-related constraints, and leads to a concomitant increased cortical activity and decreased cognitive performance [44].

*2.3. Cognitive impairment as a function of hyperthermia*

As Tcore values progressively exceed ~38.7°C, the extent of hyperthermia and task complexity seemingly interact to determine the type and magnitude of cognitive performance impairment [25, 45, 46, 47]. For instance, at a Tcore of ~39.0°C, both Racinais et al. [48] and Gaoua et al. [22] reported negative effects of passive hyperthermia on complex tasks i.e.,working memory capacity and recognition. Concomitantly, the delay before subjects started to be more impulsive became shorter as compared to colder conditions i.e., from 20 to 7 min [22] – which is considered an indicator of the depletion of ego resources [49]. In contrast, at this level of hyperthermia, simple tests (choice reaction time, visual processing) remained unaffected, demonstrating a task-dependent response to Tcore drift. A similar complexity-based discrimination between tasks has more recently been reported when assessing the three components of the attention network [43]. In particular, when Tcore was passively increased to ~38.8°C impairment of the efficiency of executive component of self-control was evident (i.e., resolving conflicting situations), whilst the orienting and alerting components (which are critically less demanding tasks) remained unaffected. This led the authors to suggest that “*tasks demanding lower attention are less vulnerable to the effect of hyperthermia than those requiring more attention*” [43]. However, when Tcore continues to increase towards higher values (>~39°C), this sparing effect of ‘less vulnerable’ tasks seems to dissipate and hyperthermia-induced cognitive impairment spreads to simple tasks. Indeed, in addition to impaired high demand performances (complex levels of visual processing, working memory) when Tcore reached up to ~40°C, Bandelow et al. [8] noticed a global, non-specific slowing effect of hyperthermia that appeared consistent on psychomotor responses speed, regardless of task complexity. Such extended cognitive deterioration suggests the existence of a subject’s maximal capacity to tolerate an *overall* cognitive strain (both heat- and task-mediated), beyond which performance level could not be maintained.

Reasons for these observed decrements may vary. In part, the heating of neurons, together with temperature-related endogenous feedback from baro- and chemoreceptors, and type III and IV afferents, may exert inhibitory influence on cognitive functioning [50]. This inhibition may operate through basal ganglia, which in response to thalamic and insular reaction to hyperthermia may act to preserve perceived effort by inhibiting output intensity towards the PFC [51, 52, 53]. Evidence in support of this basal forebrain-dependent hypothesis has previously been obtained in subjects undergoing physical effort [54] and is further corroborated by heat-related changes in EEG. In particular, a generalized reduction of cortical activity in the heat is reported after exercising participants reach Tcore between ~39.5°C and ~40.0°C [55, 56]. The decreased β activity observed in conditions of hyperthermia (from the occipital to the frontal lobe) is classically considered as symptomatic of a lower arousal [55], changes in brain connectivity and slowing computations [58]. Of note, this reduction in cortical activity does not seem to be metabolism-based; that is, during hyperthermia (>~39.5°C) neither a serotonin-fatigue hypothesis in humans nor the reduced cerebral blood flow (and the related reduction in substrates delivery) were found to support such cortical down-regulation [59, 60]. In contrast, a hormonal perspective has been proposed to account for the reduction in cognitive performance. Specifically, impaired performances on high loading working memory tasks were found to correlate with high cortisol values [61]. As a potential mechanistic explanation, it has then been proposed that cerebral resources could be redistributed from frontal to emotional centres of the brain in response to heat stress-induced cortisol [34].

Given the above responses, it is presumed that hyperthermia-induced cognitive impairment is not systematic, even at Tcore above ~38.5°C. Rather, task complexity plays a key role in cognitive outcomes at this level of heat stress and suggests practical implications for athletes before specific cognitive processes become altered.

*2.4. Summary: a U-shaped interpretation of cognitive responses?*

Collectively the aforementioned findings suggest cognitive performance to be a function of the extent of hyperthermia and task complexity and, more specifically, propose the existence of an inverted U-shaped response of cognitive performances as Tcore increases (Fig. 1). In particular, as hyperthermia develops, a Tcore of ~38.5±0.2°C could constitute the ’threshold’ where cognitive improvement ceases and beyond which heat-related detrimental cognitive effects accumulate depending on cognitive task complexity [22, 41, 43]. However, the timing of this decrement remains unclear and a plateau of steady performance seems to persist before performance declines. Therefore, from an ecological perspective, this plateau needs to be considered since i) the onset of performance decrement along the dynamics of increasing Tcore seems dependent on how complex the task is for the subject [62] and could therefore vary with expertise level; ii) cognitive task performance results from decontextualized, laboratory measures of cognitive functioning which only partly reflect field characteristics; iii) inter-individual variations in the response to heat stress will influence hyperthermia-related cognitive outcomes (e.g., sex difference [63]).

Interestingly, these results are coherent with the maximum adaptability model proposed earlier by Hancock [23]. Specifically, regardless of the underpinning mechanisms at play within this inverted U-shaped model, recent reports from the heat-cognition literature highlight an initial increase in cognitive performance before performance impairment becomes noticeable with hyperthermia development. Adding to Hancock’s proposal [23], recent studies using innovative technologies provide further explanations of the evolving effects of heat strain on cognitive functioning. Notably, the fact that a modest hyperthermia could induce cognitive benefit seems systematic rather than situational and, further, could happen regardless of participants’ willingness to increase attentional focus (e.g., improvement via hyperthermia-related arousal). In addition, before cognitive performance declines, the existence of a ‘plateau’ of performance seems to emerge and could actually relate to a compensating activity from additional brain areas to those already involved in the task [43]. Some recent experimental findings also demonstrate that despite Tcore values exceeding ~39.0°C, cognitive performance decrement could be slowed, thus suggesting a possible uncoupling between heat strain and cognitive functioning (discussed in section 3). With this in mind, future investigations should provide insights concerning some important questions in the context of sport performance e.g., whether the ‘plateau’ of cognitive performance could be anticipated and/or maintained before performance decline, or how long this plateau lasts depending on task complexity or exercise mode (passive vs. active) -related arousal. Indeed, the exercise-cognition relationship appears a dynamical pattern (with beneficial then/or detrimental effects depending on exercise intensity and duration, and participants’ fitness level [13, 15]) whose fluctuations could overlap and thus moderate the heat-cognition relationship.

Recently, the debilitative responses to heat stress (i.e., the downward part of the inverted U-shaped curve of the present model) have been theorized to exist within an overload paradigm related to human cognitive capacity [22, 64]. Accordingly, heat stress (considered as a stressor equivalent to task complexity) would place an additional attentional demand on the limited cognitive workspace, thereby reducing the amount of resources remaining available for concurrent cognitive tasks [65]. Either induced passively or through exercise, hyperthermia development would here progressively lead the cognitive strain to become overloaded, making parallel computational demands subservient to spontaneous impulses [22]. If this switch from a control to an automatic mode of cognitive response during progressive hyperthermia is confirmed, then the downward part of the inverted U-shaped curve could potentially be underlined by mental fatigue paradigms [49, 66]. These paradigms propose the hypothesis that self-control resources would empty as cognitive processes are implemented – somewhat akin to muscle strength decreases during exercise. In the present case, the emptying of the cognitive “reserve” would be both task and heat dependent. However, this proposition remains speculative and requires confirmation by concomitant behavioural and neuroimagery studies.

Regardless, a practical viewpoint of the possible inverted U-shaped relationship of hyperthermia and cognitive performance highlights the need to track Tcore during exercise to identify situations that may impair cognitive performance and to consider interventions that could moderate cognitive performance. Specifically, these moderators could promote heat-related improvements (i.e., the upward part of the inverted U-shaped curve, Fig. 1) while delaying or preventing the drift towards excessive hyperthermia (i.e., >~39.0°C) to maintain optimal cognitive processing alongside physical performance.

**3. Behavioural implications of cognitive performances under heat stress**

*3. 1. Cooling manoeuvres*

Exercise- and/or environment-induced increased Tcore is associated with a greater physiological strain e.g., sweating responses and hypovolemia, cardiac strain and perceived effort, thermal discomfort and sensations of faintness [24]. Regardless of the pre- and/or post-exercise cooling methods used, the aim is to slow endogenous heat accumulation and thus limit the increase in Tcore. Cooling methods are commonly classified as external or internal strategies [67]. Internal cooling strategies (e.g., ice slushy, slurry) and some external cooling manoeuvres (e.g., cold water immersion, combined methods) have been shown to be effective in reducing Tcore [68]. While this augments the core-to-skin gradient of temperature and delays thermal homeostasis disruption [69], some other external cooling methods modulate this gradient only by decreasing Tskin (e.g., cooling vest, ice towels, cool showers) [68]. Regardless of the specific intervention, an ergogenic effect of pre-cooling for endurance performance in the heat is commonly reported [68]. However, in relation to the proposed model of cognitive functioning during hyperthermia, evidence for the effect of cooling strategies on cognitive performance remains limited but seems appropriate depending on the timing of implementation.

Mechanisms by which cooling interventions could be ergogenic for cognitive performance are probably plural in nature and we refer the reader to Ross et al. [67] for detailed mechanisms of the effect of cooling on the reduction of physiological strain. In brief, by decreasing Tskin, external cooling will reduce skin blood flow and both cardiac and brain strain associated with cutaneous perfusion. Complementarily, by decreasing Tcore and/or Tskin, cooling will reduce afferent information arising via endogenous thermo-, chemo- and baroreceptors, and thereby reduce thermoregulatory responses (e.g., sweating leading to dehydration). Overall, these cooling-based physiological changes could be of interest in the theory of a limited cognitive workspace [65], whereby reducing heat strain would increase attentional resource availability that would subsequently be used for coping with the cognitive demand.

The aforementioned U-shaped model suggests a modest increase in Tcore benefits cognitive functioning. However, in environmental hot conditions, an increase in Tskin *per se* is always reported before any increase in Tcore and, of note, this has been found to induce detrimental cognitive performance through sensory discomfort and associated altered cortical activity [5, 70]. Therefore, increasing Tcore while concomitantly restricting the rise in Tskin may have use for athletes required to perform cognitively demanding tasks in hot conditions. To this end, ice vest and towels, or cool showers could promote skin cooling while not hindering Tcore elevation [67]; in contrast, internal cooling manoeuvre may be less advisable since it would inhibit hyperthermia initiation and therefore maintain cognitive performance at a non-optimal level.

Once Tcore increases beyond ~38.5°C, strategies delaying the rate of body heat accumulation and/or heat-related perceived cognitive loads could benefit cognitive performances in the heat. Indeed, according to an inverted U-shape representation of cognitive functioning during the development of hyperthermia, these strategies may determine how long cognitive performance could plateau before declining. Accordingly, if practically appropriate, cooling methods could protect cognitive functioning against excessive hyperthermia (i.e., >~39.0°C). This protective effect may especially be effective when performance requires heavy, complex mental computations (e.g., planning, updating memory, switching from one rule to another). For instance, ice slurries and cold-water ingestion or immersion are known to decrease Tcore [71, 72] and could therefore be implemented during resting periods of competitions – with specific doses and pre-testing by athletes. Similarly, mixing ice vest with cold packs has been found effective in decreasing Tcore [68] and could therefore temporarily protect athletes performing for prolonged periods in the heat from dizziness and detrimental cognitive performance. However, such a protective effect for field-based cognitive performance (e.g., decision making for referees) has yet to be tested experimentally and thus remains speculative in real-world scenario.

In support of the strategies described in this section, Clarke et al. [73] reported improved visual discrimination during hyperthermia (~39.0±0.5°C) induced while exercising in the heat when using cold-water immersion at 20.3±0.3°C for 60min as a precooling intervention, in comparison to without precooling. Further, cooling the head and the neck during hyperthermic conditions was found to eclipse the hyperthermia-related debilitative effect on short-term memory [22], and search and memory functions [30], such that performances returned to baseline levels. Although such a cooling method does not appear to reduce Tcore [29, 74-79], it appears effective in decreasing perceived exertion during exercise [5] – which may help athletes push themselves to greater mental effort. In particular, among different head surfaces cooled, forehead (front) cooling could provide the most beneficial effect to reduce thermoregulatory responses in hot environments [80]. When it is considered that brain temperature may become higher than Tcore in hyperthermic conditions [59], and that even a moderate hyperthermia (i.e., ~38.4°C) becomes increasingly debilitative as soon as cognitive effort has to be sustained over time [14, 21], these manoeuvres could feasibly become of primary importance for sport performance or medical assistance. To date, however, no experimental evidence has reported the effects of head/neck cooling in these practical contexts.

*3.2. Hydration*

Hydration usually refers to overall water intake over the course of the day; however, hydration is more precisely addressed in sports and laboratory settings i.e., in terms of drink quantity, content, temperature (or form: liquid or solid) and timing – each of which is of particular interest in the prevention of water deficit [81]. Indeed, water deficit and consumption are known to play a crucial role in both physical and mental performance [82]; however, body water loss (and the resultant dehydration) is markedly exacerbated in hot conditions as compared to temperate conditions [83]. Therefore, besides its direct debilitative effect on cognitive performance, body water loss could also indirectly modulate cognitive functioning through its impact on thermoregulatory mechanisms and hyperthermia.

The debilitative psychological effect of dehydration has been demonstrated using both passive (i.e., hyperthermia) and active (i.e., exercise) methods of induction [84]. Specifically, while body water loss systematically impairs mood states, in contrast cognitive functioning and sport skills appear less sensitive to dehydration – with evidence indicating that they are less sensitive in real-life tasks than in laboratory tasks [85]. Interestingly, when cognitive impairment is not reported following dehydration, this could relate to higher levels of frontal and temporal neuronal activities implemented to compensate for the water-deficit related stress and enabling maintenance of performance level [86], an effect similar to that observed during hyperthermia [41, 43]. In explanation, dehydration-induced cognitive performance decline could originate in increased levels of cortisol [87], monoamine-related changes in blood-brain barrier permeability and associated perturbations of central nervous system functioning [88]. Alternatively, subjective feelings of ‘difficulty in concentrating’ and ‘fatigue’ that reduce the will to invest mental effort are also proposed to explain these declines [89, 90]. With this in mind, hydration status appears an important component of hyperthermia that could potentially exacerbate the decline in cognitive performance in hot conditions.

Accordingly, the general guideline is to initiate drinking before attaining 1 to 2% of body mass loss i.e., before heat- and/or exercise-induced dehydration starts to markedly deteriorate cognition [91]. Beyond these values (i.e., near 3-5% of body weight loss), it is possible that the robustness of even simple processes may be weakened [65]. Therefore, when there is a need to maintain an ability to perform complex cognitive computations in the heat, ingestion of fluids at a temperature of ~4-5°C or ice slushies ~20-45 min prior to the event could be of particular utility for preventing excessive dehydration [92-94]. Specifically, providing the athlete simultaneously with water intake *and* cooling will promote i) cooling-related reduction in Tcore (direct effect via conduction); ii) drink-related reduction in Tcore (indirect effect via plasma volume restoration i.e., convection); ii) cooling-related reduction in sweating responses and skin blood flow; and iv) improved thermal comfort and thirst [95, 96]. In so far as each of these mechanisms acts to reduce heat strain, a cold drink may thus have the potential to promote cognitive performance in the heat. However, to our knowledge, the effect of internal cooling strategies on cognitive performance in the heat has not been tested yet.

As a complement to cool drink ingestion, additional cooling methods (e.g., ice vest, ice packs) should be employed as this combination may augment the reduction in Tcore. Indeed, cooling-based magnitude of changes in Tcore appears amplified when in a euhydrated state as compared to when dehydrated [97], thus providing support for the use mixed cooling methods to improve cognitive functioning. Butts et al. [97] assumed this amplified effect relates to rehydration-based increased blood volume, which could improve the heat carrying capacity of the blood and thus the ability to remove heat from the core. However, no cognitive performance measurements were reported from this study. An additional hydration strategy that could limit the effect of hyperthermia on cognitive functioning takes into consideration the components of the fluid consumed. In particular, supplementing the cold drink with electrolytes and carbohydrate (e.g., using sport drinks) will promote fluid absorption (via sodium) while meeting the heat-related higher cognitive load (via glucose) [98, 99]. For instance, Bandelow et al. [8] reported that the ingestion of drinks containing carbohydrates accelerated complex levels of visual processing and performance on memory tasks. In addition, the correlation found in this study between Tcore and plasma glucose level (Pearson’s *r* = 50%) suggested that glucose supplementation enabled participants to partly counteract the negative cognitive effect of hyperthermia [8]. Therefore, in the case of combined interventions, it is speculated that these strategies act to shift the level of Tcore from excessive hyperthermia back to ‘threshold’ levels and minimize the magnitude of hyperthermia-related cognitive performance decline. Of note, Lee et al. [30] reported that exercising in the heat while in a euhydrated state – and despite a Tcore value superior to ~39.5°C – improved memory performances. Such anecdotal observations could relate to interactions between body water maintenance *and* exercise-induced cognitive arousal [100]. This specific observation highlights the necessity for future research to discriminate the interacting effects of heat- vs. exercise-related arousal from those of heat- vs. exercise-related dehydration in cognitive performance changes.

**4. Conclusion**

Cognitive functioning as determined from consideration of performance on respective cognitive tasks is altered with increasing extent of hyperthermia. However, this heat-cognition relationship is initially ergogenic for cognitive performance, with accumulating heat stress consistently improving both simple and complex cognitive processes when Tcore <~38.5°C. Beyond this threshold, however, cognitive performance plateaus before declining at Tcore >~39°C, with the more effortful cognitive computations being the first impaired. Thus an inverted U-shaped relationship emerges between the level of hyperthermia and cognitive performance, and may reflect the difficulty for the brain to deal with accumulating stressors (i.e., cognitive demand and increasing heat strain). While the upwards part of the curve may be explained through heat-related arousal, the downwards component has been suggested to reflect the inability of the ‘cognitive reserve’ to process such accumulation of constraints [22]. Since it mainly relies on Tcore, this dynamical conceptualization also suggests cognitive performances are modifiable i.e., performance could be protected in so far as heat-related physiological strains can be counteracted.

Compliance with Ethical Standards

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Conflicts of Interest

Cyril Schmit, Christophe Hausswirth, Yann Le Meur and Rob Duffield declare that they have no

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*Figure Legend*

**Figure 1** Schematic representation of heat related-cognitive performance.

The direction of the triangles indicates the nature of the effect of core temperature (Tcore) on cognitive performance. This effect can be positive (triangles clearly pointing up), neutral (triangles pointing horizontally) or negative (triangles clearly pointing down). The vertical broken line corresponds to the cognitive ‘threshold’ i.e., the maximal cognitive load (100%) the subject can sustain before hyperthermia-induced cognitive benefits cease. This load could be attained at a Tcore of ~38.5±0.2°C, and modulated by factors potentially regulating Tcore and listed under the curve. As an example, an individual whose cognitive reserve reaches ~80% as a result of core temperature increase would situate on the left side of the vertical broken line (i.e. triangles pointing up) and thus would cognitively benefit from heat strain.

*Key points*

* An inverted U-shaped response exists for cognitive performance as related to increasing hyperthermia.
* Initial increases in core temperature up to ~38.5oC improve cognitive functioning, but after ~39.0°C impairments start to appear as a function of task complexity.
* The heat-cognition interaction may be explained as an inability to deal with concomitant heat- and task-related constraints.
* Nascent reports suggest this inverted U-shape pattern is modifiable using typical strategies (e.g., cooling, hydration) so as to promote heat-related cognitive enhancement and reduce the debilitative effect of heat strain on cognitive performance.