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COMPREHENSIVE REVIEW

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The effectiveness of heat preparation and alleviation strategies for cognitive performance: A systematic review

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ABSTRACT

A range of occupational and performance contexts (e.g. military personnel operations, emergency services, sport) require the critical maintenance of cognitive performance in environmentally challenging environments. Several reviews exist which evaluate the effectiveness of heat preparation strategies to facilitate physical performance. To date, no review has explored the usefulness of heat preparation strategies for cognitive performance. Therefore, this systematic review aimed to evaluate a range of interventions for the maintenance of cognitive performance, during or following active or passive heat exposure. Studies to be included were assessed by two authors reviewing title, abstract, and full-text. Forty articles were identified which met the inclusion criteria. Interventions were categorised into chronic (i.e. acclimation/acclimatisation) and acute strategies (i.e. hydration, cooling, supplementation, psychological). The results indicate that medium-term consecutive heat acclimation may mitigate some cognitive deficits under heat stress, although heat acclimation effectiveness could be influenced by age. Further, pre-cooling appears the most effective cooling method for maintaining cognitive performance under heat stress, although results were somewhat ambiguous. The hydration literature showed that the most effective hydration strategies were those which individualised electrolyte fortified fluid volumes to match for sweat loss. Limited research exploring psychological interventions indicates that motivational self-talk could be facilitative for maintaining cognitive skills following exercise in hot conditions. These findings can be used to help inform strategies for maintaining critical cognitive and decision-making skills in hot environments.

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KEYWORDS
Acclimation; cooling; heat stress; hydration; hyperthermia; self-talk; supplementation

Introduction

Global warming is causing our earth's surface temperature to rise significantly, increasing by 0.6°C–0.9°C from 1905 to 2005, with climate models predicting further rises of >2°C by the end of the 21st century [1,2]. Consequently, hotter days are becoming more frequent and intense [3], where it is anticipated that the frequency of heat waves or extreme heat events will also continue to increase [4,5]. Global warming, in addition to the increased globalisation of sport has increased the prevalence of service personnel and athletes having to perform in hot and humid environments of over 30°C and 70%rh [6,7]. This poses significant problems across several contexts, causing additional loads and exacerbating the onset of exercise-induced fatigue for those involved in a range of already physically and mentally demanding contexts (e.g. military personnel operations, emergency services, athletic performance), alongside making the completion of everyday tasks and occupational work more challenging for the wider population [8,9].

In hot conditions, during demanding activity, the magnitude of core temperature (T_C) and individual sweat responses are often significantly elevated [10]. This results in adverse consequences such as dehydration [11–13], hyperthermia [11,14], increased cardiovascular strain [15,16], muscular blood flow reduction [16,17], and reduced cerebral blood flow during exercise with hyperthermia [18]. Previous reviews have recognised the performance implications of heat exposure in warm to hot environments (~25 to >40°C), showing both physical and mental decrements under heat stress [7,19,20].

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In many pressured situations, the simultaneous execution of a range of physical and increasingly considered cognitive skills are fundamental for success [6,21,22]. These cognitive skills have been shown to be influenced by physiological arousal [23,24], altered psychological state [25,26] and environmental stress [27,28], making them challenging to maintain in hot conditions. A recent paper by Piil et al. [29] summarised the implications of hyperthermia across a range of sports for complex motor-cognitive performance. The predicted risk of hyperthermia-induced deficits was considered greater for sports where the "complexity" was deemed high, such as in field sports where performance relies heavily upon tactical decision-making in ever-changing situations. Research has shown that where complex cognitive and motor performance is impaired by hyperthermia, simple task performance is not [30,31]. Sports considered to be lower in risk of hyperthermia-induced deficits (low or moderate) were categorised due to factors such as the activity itself inducing a lower metabolic rate (e.g. golf), more opportunity to seek shade and to rehydrate (e.g. tennis), and where task complexity was considered to be lower (i.e. sports dominated by closed skills) [29]. Those involved in roles reliant on demanding physical activity, particularly when exposed to solar radiation, and which require the execution of complex motor-cognitive skills (e.g. athletes, emergency service and military personnel), are therefore particularly susceptible to heat-induced detriments [8]. Despite this, evidence in relation to facilitating performance within athletic and occupational contexts in hot conditions has predominantly focused on the maintenance of physical parameters [32–34]. Whilst this too is important to understand, there is little use in physically conditioning these populations to maintain high physical work rates if attention and decision-making is impaired, leading to critical consequences either in competitive or dangerous environments. Moreover, these decisions could be those relating to their physical capacities and limits, with extreme cases leading to increases in heat-related morbidity and mortality [9].

It is also important to address the impact of a rising environmental temperature for the wider population, as even passive exposure to hot climates can have negative implications for cognitively dominated performance (CP) [35,36]. CP can be described as the execution of objective tasks that require conscious mental effort [28]. Thus, task performance is determined primarily by measured cognitive indices (e.g. information processing, memory, problem solving), whilst tasks still require adequate motor activation to provide an output (e.g. written, or verbal response, fine motor reaction). The Global Workspace theory [37] suggests that the conscious workspace has a limited cognitive capacity due to a variety of external stimuli which compete for the limited conscious workspace available. The alliesthesial responses to heat exposure are considered an additional cognitive load, which place further stress on the limited workspace available, reducing the availability of neural resources for use in cognitively demanding tasks [38]. Thus, where heat exposure can be physically debilitating to the wider population such as making the execution of everyday tasks more difficult (e.g. daily travel) [39], it can also cause cognitive declines [35], relevant to educational, household and office settings, amongst others. As such, it has led to a Consortium of twenty European research institutions to provide recommendations for occupational safety in the heat [8].

Since 2016, the HEAT-SHIELD project has provided guidance on solutions to combat occupational heat stress and better protect European health and productivity in hot climates [8]. The project has taken an inter-sectoral approach to develop a heat action plan to combat occupational heat stress, with much of the research evidence drawn from athletic settings [8]. However, to date, research exploring heat preparation or alleviation strategies has focused primarily on the maintenance of physical performance [32–34]. Acclimation strategies have focused on enhancing sweat rate for losing heat storage through evaporation, increasing plasma volume, reducing the rate and extent of T_C rise, maintaining hydration levels, and enhancing tolerance to exercise in the heat [32,40]. Likewise, cooling and hydration-based research has emphasised the physical benefits, for example, enhancing exercise performance in athletes [41,42], and improving work tolerance in military personnel [43,44]. Limited research across contexts has focused on the cognitive implications of these strategies [45]. This is despite increased exposure as to the importance of optimising CP for human performance across contexts [46,47], and the known implications of heat strain for the execution of fundamental cognitive skills [20,48]. Therefore, there is a need to rigorously synthesise the evidence base as to how heat preparation and alleviation strategies, traditionally adopted for the facilitation of physical performance, affect CP across occupational, educational, and athletic contexts.

Several reviews have explored the effectiveness of heat preparation strategies for the maintenance of physical performance [32,49,50]. Despite CP being understood as a vital component of human performance in a range of occupational and athletic contexts [46,47], to our knowledge, no review has investigated the effectiveness of heat preparation strategies for improving CP and decision-making. Therefore, the first aim of this review was to identify whether traditional chronic heat preparation strategies (i.e. acclimation or acclimatisation) are beneficial for the maintenance of CP in hot environments. Secondly, this review aimed to explore the effectiveness of acute heat preparation strategies (e.g. cooling, hydration, supplementation, psychological) for the maintenance of CP during heat exposure.

Methods

This systematic review was undertaken in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) Guidelines [51] and has been registered on the international prospective register of systematic reviews (PROSPERO: Reference = CRD42021269442).

Eligibility criteria

Studies included in this review were required to: (a) involve healthy human adult participants; (b) include at least one hot condition, defined in this review as any temperature >25°C; c) include at least one heat preparation or alleviation strategy as an intervention; and (d) have included CP as an outcome measure. Laboratory and field-based studies were eligible for inclusion provided environmental conditions were specified. Eligible articles had to be published in peer-reviewed journals from January 2000 onwards and have the full-text article available in English language. Any studies that did not meet this eligibility criteria were excluded.

Information sources and search strategy

Online searches were conducted on August 10 2021 on six electronic databases: Medline, SPORTDiscus, Psych Articles, PsychINFO, The Cochrane Library and CINAHL. The search strategy stemmed from three themes (a) Heat (b) Preparation Strategy (c) Cognitive Function (See Table 1). The search strategy specified the articles were available in English language, and only included articles published after January 2000 due to a lack of environmental research incorporating cognitive measures before 2000. The search strategy was pilot tested to ensure a robust search strategy. Following the searching of databases, hand-searching of reference lists from eligible studies and relevant review articles were also conducted, the last hand-search was conducting on October 19 2022.

Data extraction

Extracted articles from the databases were exported into Excel. Following removal of duplicates, the title and abstract of each article, and then

Table 1. Search Terms.

Heat:
Heat OR Hot OR Warm OR Environmental Temperature OR Humid OR High Temperature OR Thermal
AND
Preparation Strategy:
Acclimation OR Acclimati*ation OR Preparation OR Strategy OR Training OR Hydration OR Supplement* OR Cooling
AND
Cognition terms:
Cognitive Function OR Cognition OR Decision Making OR Anticipation OR Perception OR Mental OR Anticipation OR Perception OR Mental OR Psycholog* OR Accuracy OR Reaction Time OR Vigilance OR Attention* OR Memory OR Information Processing OR Reasoning OR Intelligence OR Dual Task OR Executive Function* OR Interference Control

the full text of articles, were screened using a standardized template by the first author and a second author independently (KD and MB). Any discrepancies between eligibility of studies were subsequently identified and discussed. There were no instances where eligibility of articles could not be agreed. Figure 1 details the screening process highlighting the number of studies excluded, and the main reason for exclusion.

Where available, data extracted from each article included: participant demographics (sample size, gender, age, training status, and VO_2 max); experimental design; environmental conditions (environmental temperature and relative humidity [rh]); if applicable, exercise characteristics (mode, duration, and intensity); T_C changes; intervention type and timing; CP measures/tasks included, and results of CP pre- and during or post- intervention. For the purpose of this review, level of hyperthermia experienced was categorised within Tables 4–9, considering both the protocol and peak body temperatures reached; ≤38°C was deemed low, >38 to ≤39°C categorised as moderate and >39°C as high. Cognitive tasks were also categorised as simple or complex based off the original articles' descriptions or where this was not stated, using descriptions in Taylor et al. [28], where it is recognised that this categorisation is simplistic and should be interpreted with care.

Risk of bias

The two review authors independently assessed the risk of bias for included studies using a modified version of the Downs & Black [52] Checklist Criteria for randomised and non-randomised intervention trials (Table 2). This quality assessment method included questions on quality of reporting, internal validity, external validity, and power. The two review authors extracted all relevant data independently for assessment of study quality. Following quality assessment of each article, any discrepancies between authors' scores were identified and discussed. There were no instances where a score could not be agreed in the present study. Study quality ranged from 58% to 92%, with an average of 71%.

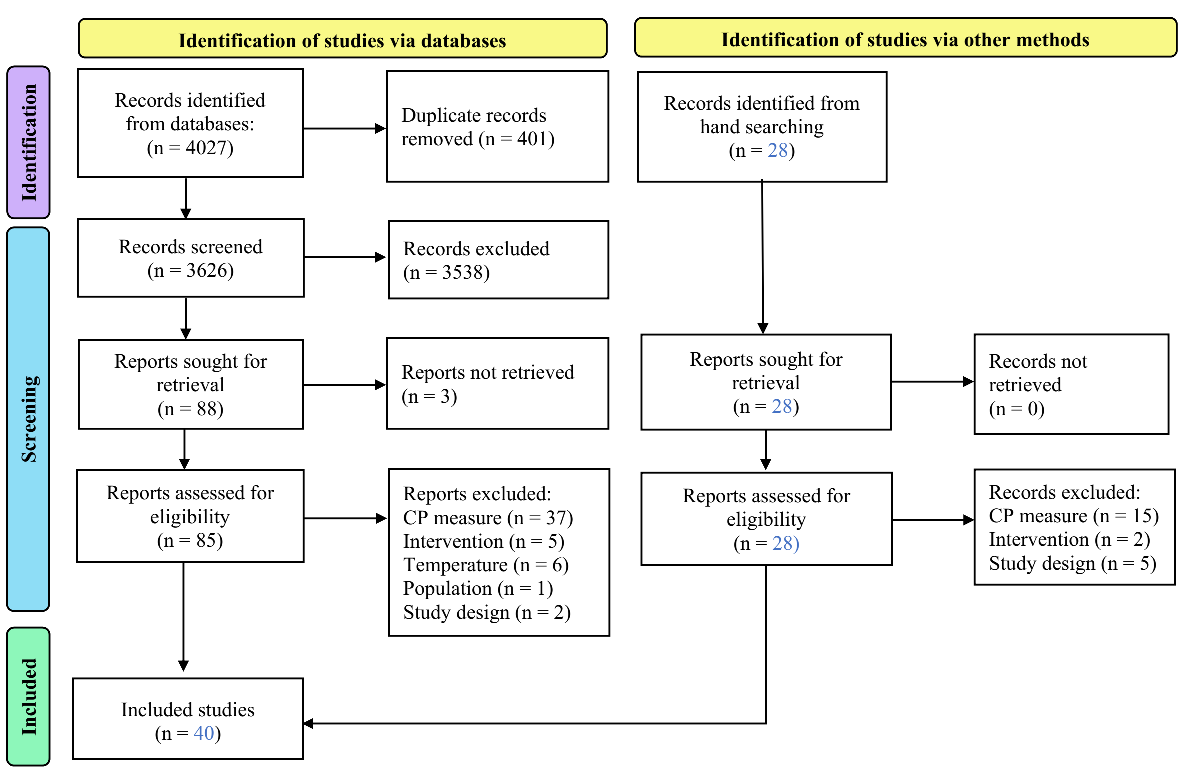

Figure 1. Prisma flowchart showing the screening protocol and exclusion of articles at each stage.

Table 2. Risk of bias quality assessment by downs and black checklist [40].

Study	Reporting (10)	External Validity (3)	Internal Validity: Bias (6)	Internal Validity: Confounding (6)	Power (1)	Total Score (26)	%
Aljaroudi et al. 2020	10	1	3	4	0	**18**	**69**
Ando et al. 2015	10	1	3	3	0	**17**	**65**
Ashworth et al. 2020	9	1	4	4	1	**19**	**73**
Bandelow et al. 2010	10	2	4	4	0	**20**	**77**
Benjamin et al. 2021	10	1	3	4	0	**18**	**69**
Caldwell et al. 2012	9	0	4	3	0	**16**	**62**
Caldwell et al. 2018	10	1	4	4	0	**19**	**73**
Cian et al. 2001	10	1	4	4	0	**19**	**73**
Clarke et al. 2011	10	1	3	4	0	**18**	**69**
Clarke et al. 2017	10	1	3	4	0	**18**	**69**
Coudevylle et al. 2020	8	1	4	4	0	**17**	**65**
Coull et al. 2015	10	1	6	5	0	**22**	**85**
Coull et al. 2016	10	1	6	6	1	**24**	**92**
Ely et al. 2013	8	1	4	4	1	**18**	**69**
Fujii et al. 2008	10	1	3	5	0	**19**	**73**
Gaoua et al. 2011	9	1	4	4	0	**18**	**69**
Hemmatjo et al. 2017	9	1	3	5	0	**18**	**69**
Lee et al. 2014	10	1	4	3	0	**18**	**69**
Lundgren-Kown et al. 2017	10	1	4	4	0	**19**	**73**
MacLeod et al. 2018	10	1	4	4	1	**20**	**77**
MacLeod & Sunderland 2012	10	1	4	4	0	**19**	**73**
Maroni et al. 2018	10	1	4	5	0	**20**	**77**
Maroni et al. 2019	10	1	4	5	1	**21**	**81**
Mazalan et al. 2021	10	1	4	4	1	**20**	**77**
O'Ne al & Bishop 2010	8	1	3	4	0	**16**	**62**
Piil et al. 2018	9	1	4	4	0	**18**	**69**
Piil et al. 2019	9	1	5	3	0	**18**	**69**
Racinais et al., 2017	10	1	4	5	0	**20**	**77**
Radakovic et al. 2007	9	1	4	5	0	**19**	**73**
Saldaris et al. 2020	10	1	5	4	0	**20**	**77**
Serwah & Marino 2006	10	1	4	4	0	**19**	**73**
Shibaski et al. 2017	8	0	4	3	0	**15**	**58**
Simmons et al. 2008	9	1	3	4	0	**17**	**65**
Tamm et al. 2015	9	1	4	3	0	**17**	**65**
Tikuisis et al. 2005	9	2	4	3	0	**18**	**69**
Tokizawa et al. 2015	9	1	3	4	0	**17**	**65**
Van Den Heuvel et al. 2017	10	1	4	4	0	**19**	**73**
Wallace et al. 2017	10	1	4	4	0	**19**	**73**
Wijayanto et al. 2017	9	1	4	4	0	**18**	**69**
Zhang et al. 2014	9	1	5	3	0	**18**	**69**

Green = >80; Blue = >70; Pink = >60; Orange = >50

Results

Search result

Initial searches returned 4027, plus 28 papers were identified through manual searches (Figure 1). Following removal of duplicates, 3626 papers were reviewed by title and abstract, leaving 113 to review at full-text, where 40 articles met the inclusion criteria and were included for qualitative analysis (Figure 1). Seven of the 39 articles were conducted in the UK, 7 in Australia, 6 in the USA, 5 in Japan, 2 in Denmark, 2 in Canada, 2 in France, 1 in Sweden, 1 in Turkey, 1 in Singapore, 1 in New Zealand, 1 in Iran, 1 in Estonia, 1 in Serbia and 2 in Qatar.

Of the 40 articles included, 5 examined heat acclimation/acclimatisation [53–57], 13 included a hydration strategy [58–70], 18 included cooling methods [35,58,59,71–85], 6 included a supplementation/mouth rinse intervention [45,74,83,86–88], and 2 involved psychological or "other" strategies [89,90]. Four articles explored the use of two intervention-types and are included in a mixed-methods section [58,59,74,83].

Sample sized ranged from 7 to 91, with an average of 15 participants. Only 91 participants were females, out of a total 601 (15.1%), included across 10 of the studies [35,45,60,62,64–66,69,77,85]. Nine studies focused on a healthy human population [35,56,57,63,70,72,84,85,89], 15 on trained/recreationally active individuals[1] [45, 55, 61, 62, 64, 67, 68, 71, 73, 75, 76, 78, 82, 87, 88], 12 on a well-trained/elite athletic population [53,58,59,65,66,74,79–81,83,86,90], two on military personnel [54,69], one on emergency service personnel [77] and one focused on obese compared to non-obese individuals [60] (See Table 3 for participant characteristics).

Characteristics of studies

An overview of study characteristics and findings exploring the effectiveness of strategies for maintaining CP in hot conditions is presented in Tables 4, 5 , 6 , 7 , 8 and 9. Heat stress was induced via different methods across studies, 33 out of 40 studies induced heat stress solely by using an environmental chamber, where the temperatures used as the hot condition ranged from 25°C-28°C ([61] [active trial], [86]), 29–34°C [64,66,68,71,74,75,77,78,82], 35–40°C [53,54,59,65,67,72,76,79–81,83,88–90], 41–45°C ([55], [61] [passive trial], [87]) >45°C [35,57,63,73,85]. One of the 40 studies was conducted in an air-conditioned room, controlled at ~32°C. One study was field based during match-play in conditions of ~34°C [58]. Two studies used temperature-controlled liquid suits to increase T_C; one was maintained at 42°C in a heat chamber (28 to 30°C) [69], with the other controlled at 50°C to induce a 1.1°C T_C rise in a laboratory held at ~26°C [84]. A further study used water-immersion in 40°C to increase T_C to 38.5°C prior to entering a chamber at 33°C [45]. One study used water-immersion to achieve moderate hyperthermia (T_C = 38.5°C) prior to entering a chamber at 48°C where they wore a water-perfusion suit to clamp T_C [70]. Thirty-five of the 40 articles reported relative humidity (rh), which ranged between 18 and 77.8%, five articles did not report rh [54,63,69,70,84].

Thirty out of the 40 studies used active heat stress, whereby participants exercised in hot conditions [53–55,58,59,63–69,71-83,86–90], whilst seven explored the effects of passive heat exposure [56,57,60,62,70,84,85]. One explored the effects of hydration status during either passive or active heat exposure on cognition [61]. One study used a light exercise protocol to initiate heat production prior to passive exposure [35], and one used passive heat exposure via hot water immersion (HWI) prior to implementing exercise [45]. Just nine articles included measures of CP *during* exercise [45,55,65,69,72–75,87]. The remaining 24 studies examined the effectiveness of the heat-based interventions on CP post-exercise.

Intervention effectiveness

Acclimation/acclimatisation

Three of the five studies which explored chronic heat-preparation strategies for CP, implemented acclimation protocols in an environmental chamber, using active protocols [53–55]. One study used a passive acclimation protocol [57], whilst the remaining study explored differences in an acclimatised population compared to non-acclimatised during passive heat stress [56] (See Table 4).

Acclimation for active heat stress

Of the three studies implementing active heat stress protocols, two found that 10-days of consecutive acclimation was beneficial for CP. Radakovic et al. [54], examined the CP of 40 male soldiers following 90-min treadmill walking at 5.5 km/h in combat uniform with 20 kg backpack (EHST), who were assigned to one of four conditions: (a) cool (20°C, 16°C WBGT); (b) unacclimated hot (40°C, 29°C WBGT); (c) 10-days passive acclimation or (d) 10-days active acclimation. For passive acclimation, participants sat for 3 h per day, whilst those assigned to active acclimation walked for 1 h at 5.5 km/h, both in 35°C, 40%rh. Only one soldier in the unacclimated hot group completed the EHST, the

Table 3. Participant characteristics across studies.

	Sample	Gender	Pop	Age (y)	Height (cm)	Weight (kg)	Body Fat %	$VO_{2\ max}$ (ml/kg/min)
Radakovic et al. (2007)	40	M	Military	20 ± 1	181 ± 4¶	75 ± 6¶	17 ± 3¶	58 ± 7¶
Tamm et al. (2015)	20	M	Healthy	25 ± 4				54 ± 7
Piil et al. (2019)	13	M	Trained	40 ± 2	185 ± 1	80 ± 0	14 ± 1	60 ± 1
Racinais et al. (2017)	14	M	Healthy	33 ± 8	177 ± 7	74 ± 7		
Wijayanto et al. (2017)	21	M	Southeast Asian students	26 ± 1	173 ± 2	63 ± 1		
			Japanese students	24 ± 1	171 ± 2	60 ± 3		
MacLeod et al. (2018)	8	F	Elite hockey players	22 ± 3	168 ± 5	63 ± 6		53 ± 2
Tikuisis & Keefe (2005)	11	9 M 2 F	Military	29 ± 6	177 ± 10	81 ± 19		
Piil et al. (2018)	8	M	Recreationally active	30 ± 2		85 ± 4		
Ely et al. (2013)	32	M	Healthy	22 ± 4	180 ± 0	85 ± 11		
MacLeod & Sunderland (2012)	8	F	Elite hockey players	22 ± 3	168 ± 5	63 ± 6		53 ± 2
Serwah & Marino (2006)	8	M	Trained	25 ± 1	180 ± 3	78 ± 5		
Lundgren-Kownacki et al. (2017)	12	6 M	Healthy	27 ± 3				57 ± 4
		6 F		24 ± 4				50 ± 5
Cian et al. (2001)	7	M	Healthy	25 ± 4	178 ± 4	74 ± 4		58 ± 7
Coudyvylle et al. (2020)	91	63 M	Physically active students	20 ± 2				
		28 F		20 ± 2				
Caldwell et al. (2018)	21	F	Obese	22 ± 2	161 ± 5	80 ± 18	44 ± 5	
			Non-obese	22 ± 2	165 ± 6	61 ± 6	25 ± 4	
Van den Heuvel et al. (2017)	8	M	Healthy	25 ± 7	179 ± 8	74 ± 9		
O'Neal & Bishop	10	M	Healthy	26 ± 3			13 ± 6	54 ± 9
Caldwell et al. (2012)	8	M	Physically active students	27 ± 6	179 ± 7	80 ± 8		
Fujii et al. (2008)	11	M	Physically active students	22 ± 2	171 ± 5	65 ± 6		
Aljaroudi et al. (2020)	12	M	Physically fit	24 ± 3	178 ± 9	78 ± 7		56 ± 7
Mazalan et al. (2021)	10	M	Trained endurance athletes	22 ± 7	178 ± 10	76 ± 16		52 ± 4
Lee et al., (2014)	12	M	Healthy	24 ± 2	172 ± 5	62 ± 8	12 ± 3	59 ± 5
Hemmatjo et al. (2017)	15	M	Firefighters	33 ± 6	179 ± 6	83 ± 15		
Ando et al. (2015)	8	M	Healthy	26 ± 3	175 ± 6	70 ± 8		46 ± 5
Maroni et al. (2018)	12	M	Team-sport athletes	22 ± 2	184 ± 11	80 ± 14		57 ± 7
Maroni et al. (2019)	10	M	Trained cyclists	21 ± 3	180 ± 8	74 ± 11		66 ± 11
Clarke et al. (2017)	8	M	Recreational runners	28 ± 6	176 ± 8	73 ± 13		53 ± 6
Gaoua et al. (2011)	16	11 M 5 F	Healthy	31 ± 1	175 ± 3	73 ± 3		
Simmons et al. (2008)	10	6 M	Healthy	32 ± 7				
		4 F		27 ± 5				
Shibaski et al. (2017)	15	M	Healthy	21 ± 1	172 ± 6	73 ± 14		
Coull et al. (2015)	8	M	Trained soccer players	21 ± 1	180 ± 6	75 ± 9	11 ± 5	
Coull et al. (2016)	8	M	Physically active	23 ± 1	176 ± 6	79 ± 13	13 ± 3	53 ± 6
Zhang et al. (2015)	10	M	Healthy	24 ± 4	179 ± 6	76 ± 15	8 ± 5	53 ± 5
Ashworth et al. (2020)	8	3 M 5 F	Physically active					
Bandelow et al. (2010)	20	M	Trained soccer players	20.2 ± 2	176 ± 5	68 ± 6		
Clarke et al. (2011)	12	M	Trained soccer players	25 ± 1	180 ± 2	74 ± 3		61 ± 1
Saldaris et al., (2019)	12	M	Long distance runners	25 ± 4	179 ± 6	75 ± 9	10 ± 3	61 ± 4
Benjamin et al. (2021)	12	M	Athletes	20 ± 1	174 ± 8	72 ± 11		54 ± 7
Tokizawa et al. (2015)	14	M	Healthy	34 ± 12	171 ± 6	63 ± 6		
Wallace et al. (2017)	18	14 M 4 F	Trained cyclists	39 ± 10¶	176 ± 7	74 ± 10	14 ± 4	60 ± 7

Notes: ¶ calculated from the breakdown provided between groups; population described in the table as per original authors descriptions, with some categorised in-text differently based on $VO_{2\ max/peak}$ values reported.

majority were withdrawn between 45–70 mins due to tympanic temperature reaching 39.5°C or subjective discomfort. With acclimation, most soldiers finished the EHST where tympanic temperature was lower compared to the unacclimatised group. Three were withdrawn with passive acclimation and one with active acclimation between 60–80 mins due to reaching 39.5°C, although they were willing to continue. For the unacclimated hot group, there was a significant decline in correct responses for a complex rapid visual processing test, before (79.4 ± 7.1%)

Table 4. The effectiveness of chronic heat strategies (i.e. acclimation or acclimatisation) for CP under heat stress.

	Heat (°C, %rh)	Protocol	Hyperthermia (°C)	Intervention and Comparison	Cognitive Outcomes
Radakovic et al. (2007)	**Chamber** 40°C	**Active – Treadmill** ● Walk at 5.5 km/h with 20 kg backpack (EHST) ● 90-min max	**Moderate** T_{TY} ~ 38.5°C post-acclimation# (~39°C pre)	**Acclimation** **P**: 10-day passive **A**: 10-day active **U**: Unacclimated **C**: Cool (20°C)	**Simple** P & A (+) Reaction time P & A (+) RVI processing P & A (0) Motor screening
Tamm et al. (2015)	**Chamber** 42°C, 18%	**Active – Treadmill** ● 2 × 50-min/10-min rest ● 1 = 50% $VO_{2\ peak}$ ● 2 = 60% $VO_{2\ peak}$	**Moderate** T_R = 38.2°C post- acclimation (39.7°C pre)	**Acclimation** ● 10-day active ● Pre-acclimation	**Simple** (+) Time production task
Piil et al. (2019)	**Chamber** 39 ± 0°C, 27 ± 1%	**Active – Cycle Erg** ● Cycle until maximal tolerable T_C	**High** T_R = 40.1 ± 0.1°C	**Acclimation** ● 28-day active, 5-days/week ● Pre-acclimation	**Simple** (0) Cognitive addition task (0) Motor task **Complex** (0) Motor-cognitive (0) Visuo-motor tracking
Racinais et al. (2017)	**Chamber** Trials: 44–50°C, 50% Acclimation: 48–50°C, 50%	**Passive** ● 30-min seated rest ● 3 × 5s MVC's ● 1 x 120s MVC.	**Moderate** T_R = 39°C	**Acclimation** ● 11-day passive ● Pre-acclimation	**Complex** (0) Any of the first 5 levels of the OTS (WM and spatial planning) (+) OTS- level 6 accuracy (+) OTS- level 6 latency
Wijayanto et al. (2017)	**Chamber-HWI** 28°C, 50% HWI at 42°C	**Passive** ● 40-min sat in chamber ● 60-min sat with lower-leg HWI	**Low** T_R = ~37.4–37.5°C	**Acclimatisation** ● Tropical native students ● Japanese students (non-acclimatised)	**Simple** (+) Two-column digit addition **Complex** (0) Corsi-block tapping (WM)

Notes: # = value approximated from figure; T_R = rectal temperature; T_{TY} = tympanic temperature; HWI = hot water immersion; ¶ = average calculated across groups reported; (+) = positive effect; (0) = no effect; (-) = negative effect. Intervention findings reported in comparison to control; therefore, positive effects may still reflect a decrement in heat, but to a lesser extent than controls.

compared to after exercise (69.7 ± 10.3%, $p < .05$). There was also a delay in movement in the reaction time (RT) task following (410 ± 80.7 ms, $p < .05$) compared to before exercise (368.4 ± 72.1 ms). No declines were observed in any of the other conditions (i.e. cool, or with passive, or active acclimation).

Similarly, Tamm et al. [55] found that 10-days heat acclimation (HA) improved the subjective perception of time in 20 healthy young males when walking at 60% VO_{2peak} in 42°C, 18%rh, compared to pre-acclimation. Participants were asked to produce target intervals of 0.5, 0.75, 1, 2, 3, 5 and 10-s, pre-exercise, at 60-min during and post-exercise. Following 10-days HA, T_C was significantly lower at 60-min exercise (38.6 ± 0.3°C) compared to pre- HA (39.2 ± 0.4°C). Pre- acclimation, exercising in the heat caused a significant reduction in the proportionality between subjective and objective time (a_1) at 60-min compared to pre-exercise ($p < .05$). Following acclimation, or in neutral conditions, there were no differences between pre-test, 60-min, and post-test measures ($p > .05$). This indicates a distorted perception of time, specifically, faster temporal processing during exercise in hot conditions when unacclimated, compared to when acclimated.

In comparison, Piil et al. [53] found no effects of a 28-day active HA protocol for 13 trained males (40 ± 2y) on CP post-exercise. Participants completed a battery of cognitive tasks at baseline and post-exercise, and then cycled until maximum tolerable T_C on day 1, before completing the cognitive tasks again. This was repeated on day 14 and 28, where participants cycled to the same T_C as day 1 (40.1 ± 0.1°C), but with significantly increased exercise endurance time ($p < .05$) following 14 and 28 days of acclimation, as a result of slower core temperature rise (day 0: 38.7 ± 2.4 min, day 14: 52.2 ± 1.1 min, and day 28: 64.3 ± 2.9 min). During the 28-day acclimation period, participants cycled 5 days a week for 1 h at 60% VO_{2max} in 39.4 ± 0.3°C (26.6 ± 1.2%). Neither medium (day 14) nor longer (day 28) HA affected performance on a simple cognitive addition task, simple motor task, more complex motor-cognitive task, or complex visuo-motor tracking task ($p > .05$). This was despite decrements being found post-exercise compared to baseline across all experimental days for the simple motor task and visuo-motor tracking task.

Acclimatisation for passive heat stress

Racinais et al. [57] examined the effects of 11-days consecutive passive HA, consisting of 1 h per day sat in 48–50°C (50%rh), on CP following 30-min sat in 44–50°C (50%rh), where temperature was manipulated to maintain T_R = 39°C on trial days. They found that accuracy on the highest level of the One Touch Stockings of Cambridge test (OTS-6) (a test of spatial planning and working-memory [WM]) was improved by acclimation, where pre-acclimation, OTS-6 accuracy declined in hyperthermic compared to control conditions (24°C, 40%rh) (−.786 [−1.543; −.029], $p = .043$). This was restored post-acclimation (+.214 [−.301; +.730], $p = .385$), showing improved accuracy from pre- to post- acclimation in hyperthermic conditions (1.143 [+.508; + 1.778], $p = .002$). Additionally, the latency of response was shorter with hyperthermia compared to the control pre-acclimation (−12.342 [−19.754; −4.930], $p = .003$), but not post-acclimation (−1.895 [−11.545; + 7.754], $p = .678$), reflecting a decrease in impulsivity.

Exploring the influence of acclimatisation for a tropical native student group from Southeast Asia and a non-acclimatised student group from Japan, Wijayanto et al. [56] implemented passive heat exposure where students sat for 40-min in a chamber at 28°C, 50%rh, followed by 60-min lower leg HWI at 42°C prior to completing cognitive tasks. When completing the control trial, participants continued to sit in 28°C, 50%rh but with no HWI. Whilst there were significant differences in T_C between the tropical native group (37.49 ± 0.09°C) and Japanese student group (37.43 ± 0.07°C) following passive heat exposure, these temperatures indicated low physiological heat stress experienced across groups. There were no differences between conditions for the acclimatised and non-acclimatised groups' short-term WM accuracy or RT on the Corsi block-tapping test ($p > .05$). However, correct answers for a two-column digit addition task were impaired by 7.2 ± 3.0% following passive heat stress compared to the control for the non-acclimatised group ($p < .05$, $d = -0.96$), where it was unaffected for the acclimatised group (2.8 ± 9.8%, $p > .05$, $d = 0.09$).

Hydration

Of the 11 articles exploring the effects of hydration on CP in hot conditions, seven studies implemented active heat protocols [63–69], three used passive heat exposure [60,62,70], and one explored the effectiveness of a fluid strategy during both passive and active heat stress [61] (See Table 5).

Fluid strategies for active heat stress

Two studies induced high levels of hyperthermia (body temperature ≥ 39°C), with differing results found as to the effectiveness of hydration strategies for simple and complex cognitive tasks under high levels of heat strain. Piil et al. [67] found that consuming the minimum volume of water needed to prevent dehydration (euhydrated) following the first of 3 × 30-min bouts of cycling at 100 W in 40°C, negated CP detriments when compared to dehydrated individuals, who could only consume fluid to maintain −2% BM. When dehydrated, complex cognitive-motor (math-pinch) performance declined by 9.0 ± 3.3% with hyperthermia (+2.0°C T_C), following the second and third cycling bouts, compared to baseline (p < .001). When euhydrated, no difference in performance was observed (p > .05). Additionally, when euhydrated, hyperthermia-induced declines appeared smaller for complex visuo-motor tracking performance (−10.5 ± 3.3%) compared to when dehydrated (−16.2 ± 3.9%), though non-significant (p > .05). Simple cognitive math performance was also reduced when dehydrated, with over two-fold more mistakes observed when hyperthermic compared to baseline (p < .001), where this did not change when euhydrated (p > .05). For simple motor performance (target pinch), performance was reduced with hyperthermia compared to baseline when dehydrated (−4.2 ± 1.0%, p < .001) and euhydrated (−2.5 ± 1.0%, p < .033). Conversely, Serwah & Marino [68] found no cognitive effects of 100% fluid replacement, in comparison to 0% fluid replacement (resulting in −1.7 ± 0.2% BM loss) following cycling at 70% of peak power for ~90-min in ~31°C, when employing a simple choice RT task (p > .05).

Four studies induced moderate levels of hyperthermia (body temperature ≥38°C to ≤39°C). MacLeod and Sunderland [65] found that replacing 150% sweat loss with a noncaloric electrolyte solution at 1 L/h improved hockey skill performance time (p = .029), penalty time (p = .024) and decision-making time (p = .008) compared to a hypohydrated control[2] (−2% BM induced by initial passive heat exposure), completed pre- and post-2 × 25-min field-hockey-specific treadmill exercise in ~40°C. Cian et al. [61] also found that fluid intake, (50 $g.l^{-1}$ glucose, 1.34 l^{-1} NaCl, and 1.5 $ml.l^{-1}$ in water) to match 100% of BM loss, improved long-term memory compared to no fluid following either active exposure, consisting of 2 h treadmill exercise at 65% VO_{2max} at 25–26°C inducing −2.8% BM (T_C ≤ 39°C), or 2 h passive heat exposure to 45°C-50°C (T_C ≤38°C). However, there were no fluid effects for simple tasks of RT or complex tasks of unstable tracking, perceptive discrimination, and short-term memory regardless of active or passive heat exposure (p > .20).

Employing an ad libitum fluid intake protocol, Macleod et al. [66] conversely found no benefits compared to no fluid intake (resulting in ~2% dehydration), for the complex Stroop test, simple visual search or complex Sternberg WM test following 2 × 25-min treadmill activity replicating the demands of field hockey in ~33°C when in moderate hyperthermic conditions (T_R = ~38.7°C). Likewise, Tikuisis & Keefe [69] found that the implementation of unlimited water breaks yielded no effects compared to a dehydrated (−3.27 ± 1.11% BM) condition, on a complex friend vs. foe detection task during cycles of 25-min walking at $3.km.h^{-1}$, whilst wearing a liquid suit at 42°C.

For those inducing low levels of hyperthermia (≤38°C) no hydration-induced benefits were observed. Ely et al. [63] found no cognitive effects of euhydration, where for every 1 g of mass lost at each weigh in, 1 ml of 0.05% NaCI was replaced, in comparison to hypohydration of −4% BM. No effects were found for simple tasks of psychomotor vigilance, 4-choice RT, match-to-sample or for a complex grammatical reasoning tasks, following a 90-min rest period in either 10, 20, 30 or 40°C

Table 5. The effectiveness of hydration strategies on CP under heat stress.

	Heat (°C, %rh)	Protocol	Hyperthermia (°C)	Intervention and Comparison	Cognitive Outcomes
Piil et al. (2018)	**Chamber** 40°C, 25%	**Active – Cycle Erg** 3 × ~30-min cycling bouts at 100 W, ~75 rpm (heat production of 400 W)	**High** Bout 1 T_R > ~1°C (38.5 ± 0.1°C) Bouts 2/3 T_R = >2°C (39.3 ± 0.1°C)	**Euhydration** ● 37°C water, ingestion to thirst with minimal volume to prevent DEH DEH (−2% BM)	**Simple** (+) Simple cognitive addition task (0) Simple motor task **Complex** (+) Motor-cognitive (+) Visuo-motor tracking
Serwah & Marino (2006)	**Chamber** 31°C, 63%	**Active – Cycle Erg** Cycling at ~70% of peak power for 90-min or to exhaustion	**High**Mean increase between 1.6 ± 0.2°C to 1.9 ± 0.1°C	**Fluid Intake** ● 100% water replaced ● 50% water replaced ● 0% water replaced (−1.7 ± .2% BM)	**Simple** (0) Choice RT
MacLeod & Sunderland (2012)	**Chamber** DEH: ~40°C, 75% Exercise: 33°C, 61%	**Active – Treadmill** 2 × 25-min/10-min rest field hockey protocol	**Moderate**[2]No T_R values reported.	**Euhydration** ● 150% sweat loss replaced with noncaloric, electrolyte fortified solution at 1 L/h post- DEH **DEH (−2% BM)**	**Complex** (+) Hockey skill performance time (+) Hockey skill penalty time (+) Hockey skill decision-making time
MacLeod et al. (2018)	**Chamber** Dehydrated: ~40°C, 75% (~28-min) Euhydrated: 19°C (~2 h) Exercise: 33°C, 60%	**Active – Treadmill** 2 × 25-min/10-min rest field hockey protocol	**Moderate**T_R = ~38.7°C[#]	**Fluid Intake** ● Ad libitum fluid intake (0.5 ± 0.5% DEH) ● No fluid (2.6 ± 0.6% DEH)	**Simple** (0) Visual search **Complex** (0) Stroop – selective attention/ inhibition (0) Sternberg WM
Tikuisis & Keefe (2005)	**Chamber-Suit** 28–30°C 42°C liquid suit	**Active – Treadmill** Cycles of 25-min walk at 3 $km.h^{-1}$/5-min seat rest (4 h-max)	**Moderate**T_R = 38.4–38.5°C	**Fluid Intake** ● Unlimited water in break (0.96 ± 0.69 DEH) ● No fluid (3.27 ± 1.11% DEH)	**Complex**(0) Friend vs. foe detection using combat simulator
Cian et al. (2001)	**Chamber** ● Thermal DEH (H^0 &H^1): 45°C-50°C, 20% – 70% ● Exercise-DEH ($E^0$and E^1): 25–26°C, 35–45%	**Passive OR Active** ● H^0 & H^1: 2 h passive hea-texposure −2.8% BM ● E^0 & E^1: Treadmill at 65% VO_{2max} for −2.8% BM (~2 h)	**Moderate** ● H^0 & H^1 = T_C maintained ≤38°C ● E^0 and E^1 = T_C maintained ≤39°C	**Fluid Intake** ● H^1 = thermal dehydration with 100% fluid replacement ● E^1 = exercise-dehydration with 100% fluid replacement (Fluid = 50 $g.l^{-1}$ glucose, 1.34 l^{-1} NaCl, 1.5 $ml.l^{-1}$ in water) ● DEH = −2.8% BM	**Simple** (0) Reaction-time **Complex** H^1 and E^1 (+) Long-term memory (0) Unstable tracking (0) Perceptive discrimination (0) Short-term memory

(*Continued*)

Table 5. (Continued).

	Heat (°C, %rh)	Protocol	Hyperthermia (°C)	Intervention and Comparison	Cognitive Outcomes
Ely et al. (2013)	**Chamber** 3 h at 50°C to dehydrate followed by cognitive testing in 10, 20, 30, or 40°C	**Active – Treadmill** ● 3 h work/rest cycle inc. 30-min walk at 1.34 m/s, 3.5% gradient, 30-min rest (× 3) 90-min rest	**Low** T_C = 37.1 ± 0.3°C – 37.9 ± 0.2°C	**Euhydration** ● 1 ml of 0.05% NaCI replaced every 1 g of body mass lost each weigh-in ● DEH (−4% BM)	**Simple** (0) Psychomotor vigilance (0) Choice RT **Complex** (0) Match-to-sample (0) Grammatical reasoning
Lundgren-Kownacki et al. (2017)	**Chamber** 34°C, 60%	**Active – Circuit** 3 h moderate work inc. brick loading, stepping, biking and arm crank in 20-min intervals	**Low** Average height of 38.0 ± .03°C	**Fluid Intake** ● 100 ml water every 20-min ● 100 ml buttermilk every 20-min (~<0.5% BM) ● No fluid (−1.5 ± 0.2% BM)	**Simple** (0) *1*-back **Complex** (0) *2*-back
Van den Heuvel et al. (2017)	**HWI-Chamber-Suit** ● HWI in 40–41°C ● 48°C chamber ● 50°C water-perfusion suit	**Passive** ● ~185-min intermittent whole body HWI, T_C = 38.5°C ● Sat in chamber at 48°C in 50°C water-perfusion suit to clamp T_C (<10-min)	**Moderate** Deep body temperature (calculated from T_A T_O and T_R) = 38.5°C	**Euhydration** ● Isotonic fluid ingestion every 15–20-min for full fluid replacement (−0.7 ± 0.4 BM) ● 3% DEH ● 5% DEH	**Simple** (0) "Simple" WM measuring response sensitivity, target distinction, response bias and RT **Simple and Complex (Levels)** (0) Visual perception measuring response sensitivity, target distinction, response bias and RT
Caldwell et al. (2018)	**Chamber-Suit** 35°C, 31% Water suit = 45°C	**Passive** Passive heat stress perfusing 45°C water through suit in the chamber until T_C ↑ by 1.0°C	**Low** T_C ↑ by 1.0°C, Post-heating T_R = ~37.7–37.9°C	**Euhydration** ● +950 ml water the night pre-trial, +475 ml ~2 h pre-trial, 37.5°C water during trial (−0.6 ± 0.5 kg BM) ● Hypohydration: 250 ml water only,no fluid during heat (−1.1 ± 0.5 BM)	**Simple** (0) Processing speed and RT **Complex** (+) Visual WM (0) Verbal WM
Coudevylle et al. (2020)	**Air-Con Room** 32°C, 78%	**Passive** 30-min passive rest	**Low** No measures of body temperature reported	**Fluid Intake** ● 330 ml cold water (4°C) ● 330 ml neutral water (24°C) **No fluid**	**Complex** (0) Attention D2 assessment processing speed, inattention, impulsivity, and concentration

Notes: # = value approximated from figure; T_{TY} = tympanic temperature; T_T = temporal temperature; T_A = auditory canal temperature; T_O = oesophageal temperature; T_R = rectal temperature; T_C = core temperature; WM = working-memory; RT = reaction time; WBGT = wet bulb globe temperature; BM = body mass; DEH = dehydration; (+) = positive effect; (0) = no effect; (-) = negative effect. Intervention findings reported in comparison to control; therefore, positive effects may still reflect a decrement in heat, but to a lesser extent than controls.

after completing 3 h work/rest cycle of 30-min treadmill walking followed by 30-min of rest, in 50°C. Similarly, Lundgren-Kownacki et al. [64] found no effects of consuming 100 ml of water or buttermilk every 20-min (total 700 ml) compared to no fluid intake (~-1.5% BM) for *1*-back or more complex *2*-back performance, during or following 3 h (or until T_C = 38.5°C) of moderate intermittent work (e.g. brick loading, and arm cranks) in 34°C.

Fluid strategies for passive heat stress

Three studies explored the effectiveness of hydration strategies during passive heat stress, with one inducing a moderate level of hyperthermia. Van den Heuvel et al. [70] investigated the effects of euhydration via isotonic fluid ingestion every 15 to 20-min for full fluid replacement compared to 3% dehydration following passive heat exposure on CP. Passive heat exposure was administered via HWI in 40–41°C to achieve a T_C of 38.5°C, followed by T_C clamping with 50°C water-perfusion garment in a 48°C chamber. No differences were found between fluid conditions for simple and complex visual perception and simple WM tasks.

Inducing low levels of hyperthermia, Caldwell et al. [60] compared CP following passive heat exposure induced via a water perfusion suit at 45°C in a 34°C chamber (until T_C = +1.0°C) when euhydrated or hypohydrated (−1.14 ± 0.48 kg BM) in obese compared to non-obese individuals. When euhydrated, participants consumed 1425 ml pre-trial (evening and morning), alongside consuming water to maintain euhydration during heat exposure, compared to when hypohydrated, where no water consumption was permitted during trials. Regardless of hydration status, complex verbal and visual memory-based cognition was impaired with hyperthermia (p < .05), though no effects were found for simple processing speed and RT. However, they did find a trend toward a multivariate effect of hydration status (p = .07, Wilks' Λ = 0.59) whereby visual WM was slightly reduced when hypohydrated compared to when euhydrated (−4.9 ± 1.8 arbitrary unit, p = .01). Similarly, Coudevylle et al. [62] found no effects of consuming 330 ml of cold or neutral water, compared to no fluid on a complex Attention D2 test following 30-min passive exposure to ~32°C.

Cooling

Of the 14 studies investigating just cooling on CP under heat stress, 11 articles explored cooling pre-, during or post- active heat stress [71–73,75-82], two articles investigated cooling for cognition under passive heat exposure [84,85] and one article explored pre-cooling following active exposure to initiate heat production before moving to 45-min passive exposure [35] (See Table 6).

Cooling for active heat stress

Eight of the active heat stress studies included cooling strategies implemented *during* exercise in the heat [71–73,76-78,81,82]. Under high levels of hyperthermia, Lee et al. [78] found that wearing a neck cooling collar, 5-mins into a 75-min running bout at 70% VO_{2peak}, reduced number of errors pre- to post- exercise on a search and memory test (level 3) from 0 ± 1 in the control, to −1 ± 2 (p < .05). However, they found no effects of cooling for simple psychomotor vigilance or digit matching tasks, whereby RT decreased similarly pre-post exercise across conditions (p < .05). No differences were observed pre- to post- exercise for simple choice RT across conditions. Interestingly, the use of a cooling collar appeared to inhibit the post-exercise improvement in digit span recall with no difference pre- to post- exercise (0 ± 1, p > .05), where in the control condition; no cooling, maximum span increased by 1 ± 2 post-exercise (p < .05). Under similar hyperthermic levels, Mazalan et al. [81] found no effects of cooling on the OSPAN WM test when exploring the use of a head-cooling cap during 2 × 30-mins running at 70% VO_{2peak}.

Cooling under moderate hyperthermia also yielded mixed results. Hemmatjo et al. [77], found that wearing a cooling vest alongside using a cooling gel containing menthol, during ~45 to 50-min firefighting activity, significantly increased participants' RT (389.53 ± 6.24 ms; 389.87 ± 6.12 ms, respectively) but improved accuracy on a (complex) continuous vigilance task (143.47 ± 1.18; 143.53 ± 1.24 correct responses, respectively) compared to the cooling gel, no cooling vest condition (385.73 ± 7.25 ms; 143.07 ± 0.88 correct responses) and the control (385.67 ± 7.19 ms; 143.00 ± 0.84 correct responses)

($p < .05$). Conversely, O'Neal & Bishop [82] found no effects of a cooling vest worn during activity on short-term memory, simple arithmetic or dual RT tracking task following cycles of bicep curls and walking at 3.0mph until volitional exhaustion or until T_C = 38.7°C. Likewise, Caldwell et al. [73] found no effects of wearing a liquid-cooling suit on vigilance, divided attention, verbal WM, problem-solving, perceptual or visual RT tasks, during 2-hours repeated light exercise in ~35°C. Similarly, Aljaroudi et al. [71] found no effects of a liquid-cooling suit worn during 40-min treadmill exercise at 40% max on Go/No-Go performance. Ando et al. [72] also found no effects of neck cooling with a wet towel and the use of a small fan during ~15-min of exercise at 160 bpm for Go/No-Go performance, or a spatial delayed response task. Finally, under low hyperthermic conditions, Fujii et al. [76] found no effects of 2 L cold water head pouring during 15-min rest periods in between 3 × 20-min cycling at 75 W on a simple visual RT task.

Three studies implementing active heat stress protocols explored the use of pre-cooling on CP, all inducing moderate levels of hyperthermia. Clarke et al. [75] found that 60-min pre-cooling by seated water immersion protected performance CP on a Go/No-Go task implemented at 30-min intervals during 90-min treadmill exercise at 65% VO_{2max} in 32°C. Visual discrimination was reported as more accurate (~+5-10%[3]) at 60- and 90-min exercise following pre-cooling (p = .067, η^2_p = 0.40) compared to control, despite non-significance. Gaoua et al. [35] also found that pre-cooling using head and neck cool packs was useful for mitigating against cognitive declines when implementing combined active-passive heat exposure. Participants walked for 10 to 15-min to initiate heat production before sitting passively for 45-min in a chamber at 50°C. Following passive exposure, complex spatial span WM (+0.6 spatial span, 95%CI 0.1–0.9, p = .027) and pattern recognition (−3.9 errors, 95%CI −9.2, 1.4, p = .023) were both improved with pre-cooling compared to no cooling. However, simple choice RT, rapid visual processing and match-to-sample visual search tasks were unaffected with cooling compared to no-cooling in hot ($p > .05$). Conversely, Maroni et al. [80] found no benefits of 20-min pre-cooling (+ 10-min during warm-up) via a cooling glove, cooling jacket, or combined use of cooling glove and jacket, before repeated sprint cycling sets, on post-exercise verbal series sevens performance (complex attention and WM) in 35°C. The final active heat stress study implemented post-exercise cooling under moderate hyperthermia but found no effects of 30-min of one-hand glove cooling, two-hand glove cooling or cooling jacket following cycling at 75% VO_{2max} until T_C = 39°C on performance in the Stroop test [79].

Cooling for Passive Heat Stress

Simmons et al. [85] found no effects of head and neck cooling implemented pre-, during- and post-passive heat exposure to 45°C, 50%rh until T_C rose by +1°C (moderate hyperthermia), for simple RT, digit vigilance, choice RT, rapid visual information processing or morse tapping task. Conversely, Shibaski et al. [84] found post- whole-body cooling using a water-perfused suit improved error rate on a more complex Go/No-Go task compared to during passive heat stress by ~2%[#] ($p < .05$) (low hyperthermia). They explored the use of various methods of post-cooling following 60-min passive heat exposure by a water-perfused suit at 50°C, first implementing a face fan and icepack cooling on the back of the head for 5-min, followed by whole-body cooling by 25°C water circulation in the suit. No differences were observed following face and head-cooling compared to during heat stress.

Supplementation/Mouth Rinses

All four articles including the use of supplements or mouth rinse on cognition during or following heat stress, implemented active protocols [45,86–88] and induced moderate levels of hyperthermia (See Table 7). Two studies [86,87] explored the use of tyrosine on cognition under heat stress, whilst Zhang et al. [88] included a menthol ingestion as an intervention, alongside caffeine supplementation. The remaining study first implemented passive HWI, followed by an active heat exposure protocol [45], which also explored the influence of a menthol mouth rinse.

Coull et al. [86] explored the use of 2 × 150 mg. $kg.bm^{-1}$ doses of tyrosine consumed 5 h and 1 h

Table 6. The effectiveness of cooling strategies on CP under heat stress.

	Heat (°C, %rh)	Protocol	Hyperthermia (°C)	Intervention and Comparison	Cognitive Outcomes
Lee et al. (2014)	**Chamber** 30°C, 71%	**Active – Treadmill** Running at 70% VO_{2peak} for 75-min or volitional exhaustion	**High** • No cooling post-exercise T_C = 39.5°C • Cooling post-exercise T_C = 39.6°C	**Cooling** • Neck cooling collar worn 5-min into exercise and post-exercise • No cooling	**Simple** (0) Choice RT (0) Psychomotor vigilance task **Complex** (+) Search and memory (-) Digit span (0) Digit matching (short-term WM)
Mazalan et al. (2021)	**Chamber** 35°C, 70%	**Active – Treadmill** 5-min warm-up at 50% of VO_{2peak}, 2 × 30-min running bouts at 70% VO_{2peak} interspersed with 10-min rest	**High** • No cooling peak T_C = 39.8°C • Cooling peak T_C = 39.6°C	**Cooling** • Head-cooling cap, (~0.01 ± 0.1°C) during activity • Head cap worn at ~22°C	**Complex** (0) OSPAN WM
Hemmatjo et al. (2017)	**Chamber** WBGT 28–30°C, 55%-60%	**Active – Circuit** ~45-50-min simulated firefighting activities inc. hose pulling, ladder handling and climbing, search and rescue operation	**Moderate** Post-exercise T_T: • CG = 38.1°C • CV = 37.9°C • CG + CV = 37.9°C • No cooling T_T = 38.1°C	**Cooling** • CG: Cooling gel containing menthol during activity • CV: Cooling vest during activity • CG+CV: Cooling gel and vest during activity • No cooling	**Complex** CV (+) Continuous vigilance accuracy CV + CG (+) Continuous vigilance accuracy CV (-) Continuous vigilance RT CV + CG (-) Continuous vigilance RT CG (0) Continuous vigilance accuracy and RT
O'Neal & Bishop (2010)	**Chamber** WBGT 30°C, 70–75%	**Active – Treadmill** 12 bicep curls and walk at 3.0mph, ~450kcal/h, until exhaustion, 90% HR_{max} or T_C = 38.7°C	**Moderate** • Mean T_R change = +0.8 to +1.0°C • Max permitted T_R = 8.7°C	**Cooling** • Cooling vest during activity • No cooling vest worn	**Simple** (0) Simple arithmetic (0) RT/tracking task (0) Short term memory
Caldwell et al. (2012)	**Chamber** 48°C, 20%	**Active – Cycle Erg** 2-h protocol inc. 8 × 13-min 30 W cycling bouts	**Moderate** • No cooling end T_C = 38.9°C • Cooling T_C = 37.3°C (Core temperature calculated from T_A, T_R)	**Cooling** • Liquid-cooling suit at 15°C worn throughout • Inactive cooling suit with temperate-warm water	**Simple** (0) Perceptual RT **Complex** (0) Verbal WM (0) Divided attention and filtering (0) Problem-solving (0) Vigilance

(*Continued*)

Table 6. (Continued).

	Heat (°C, %rh)	Protocol	Hyperthermia (°C)	Intervention and Comparison	Cognitive Outcomes
Aljaroudi et al. (2020)	**Chamber** 30°C, 70%	**Active – Treadmill** ● 15-min stabilisation sat in chamber ● 40-min exercise at 40% VO_{2max}	**Moderate** No cooling T_R = 38.3°C Cooling T_R = 37.9°C	**Cooling** ● Liquid cooling garment infused with 18°C water during activity ● No cooling garment worn	**Complex** (0) Go/No-Go (inhibition control)
Ando et al. (2015)	**Chamber** 35°C, 70%	**Active – Cycle Erg** ● 5-min ↑ at 30–32 W/min (ramp) ● ↑ then 20–21 W/min (step) until HR = 160 bpm 10-min at 160 bpm	**Moderate** Post-exercise T_{TY} 38.3–38.4°C with and without cooling	**Cooling** ● Neck cooling with a wet towel (~21°C water) 2-min post 160 bpm and fanning with a small fan ● No cooling	**Complex** (0) Spatial delayed response (WM) (0) Go/No-Go (inhibition)
Fujii et al. (2008)	**Chamber** 35°C, 60%	**Active – Cycle Erg** 10-min rest, 3 × 20-min cycling bouts at 75 W/15-min rest periods	**Low** ● Peak Tc <38°C with or without cooling[#]	**Cooling** ● 2 L of cold-water head pouring during rest ● No cold-water pouring	**Simple** (0) Visual RT
Clarke et al. (2017)	**Chamber** 32°C, 47%	**Active – Treadmill** 90-min running at 65% VO_{2max}	**Moderate** Peak T_R = between >38.5 – <39°C[#]	**Pre-cooling** ● 60-min pre-cooling by seated water immersion (20.3 ± 0.3°C) ● No cooling, seated in lab at ~20°C	**Complex** (+) Go/No-Go visual discrimination
Gaoua et al. (2011)	**Chamber** 50°C, 50%	**Active-Passive** ● 10 to 15-min walking at 3 to 5 $km.h^{-1}$ (fitness dependent) to initiate heat production 45-min sat in chamber	**Moderate** Peak T_C in hot = 38.6°C	**Pre-cooling** ● 3 × head and neck cool packs at C applied pre-heat exposure -14° **No cooling**	**Simple** (0) Choice RT (0) Visual information processing **Complex** (+) Spatial-span WM (+) Pattern recognition memory (0) Match to sample visual search

(*Continued*)

Table 6. (Continued).

	Heat (°C, %rh)	Protocol	Hyperthermia (°C)	Intervention and Comparison	Cognitive Outcomes
Maroni et al. (2019)	**Chamber** 35°C, 57%	**Active – Cycle Erg** ● 10-min warm-up inc. 3 × 5s sprints at 70, 80, 90% "perceived" intensity ● Simulated cycling race inc. 6 sets (4 sets of 6 × 15s sprints/varying recovery) ● 2 × 5-min max time trials ● Sets/by 3-min at 100 W	**Moderate** Peak T_C averaged 38.8°C	**Pre- Cooling** 20-min pre-trial and 10-min during warm up ● Cooling glove ● Cooling jacket ● Cooling glove and jacket ● No cooling	**Complex** (0) Verbal Serial Sevens measuring attention, concentration, and WM
Maroni et al. (2018)	**Chamber** 36°C, 49%	**Active – Cycle Erg** 75% VO_{2max} until T_C = ~39°C or volitional exhaustion	**Moderate** ● Peak T_{OE} between 38.7 –38.9°C across glove and no cooling conditions ● 39.1°C with cooling jacket	**Post- Cooling** 30-min post-exercise cooling ● One hand glove cooling ● Two hand glove cooling ● Cooling jacket ● No cooling	**Complex** (0) Stroop (selective attention, inhibition)
Simmons et al. (2008)	**Chamber** 45°C, 50%rh	**Passive** ● 30-min in 25°C, 50% ● ↑ to 45°C, 50%, remained seated until T_C = +1.0°C	**Moderate** Peak T_C = ~38.1°C	**Cooling** ● Head and neck cooling, 3°C in 25°C and 8°C during- and post- passive heat exposure ● No cooling	**Simple** (0) RT (0) Digit Vigilance (0) Choice RT (0) Visual information processing (0) Morse tapping
Shibaski et al. (2017)	**Lab–Suit** 26 ± 1°C Water-perfused suit at 50°C	**Passive** ● 30-min sat in water perfused suit at 33°C ● 60-min sat in water-perfused suit at 50°C for 1.1°C ↑ in T_{ES}	**Low** ● Peak T_{ES} = 38.0°C following heat stress	**Post- Cooling** ● 5-min face fan and head cooling packs post 60-min passive exposure ● Whole body cooling (WBC) by 25°C water circulation	**Complex** WBC (+) Go/No-Go

Notes: # = value approximated from figure; T_{TY} = tympanic temperature; T_T = temporal temperature; T_A = auditory canal temperature; T_O = oesophageal temperature; T_R = rectal temperature; T_C = core temperature; WM = working-memory; RT = reaction time; WBGT = wet bulb globe temperature; BM = body mass; DEH = dehydration; (+) = positive effect; (0) = no effect; (-) = negative effect. Intervention findings reported in comparison to control; therefore, positive effects may still reflect a decrement in heat, but to a lesser extent than controls.

pre-exercise in comparison to a placebo on CP, pre-, HT and following 2 × 45-min treadmill activity replicating the demands of a soccer match in a warm environment (25°C, 40%rh). They found a main effect of condition where tyrosine increased overall correct responses (12.6 ± 1.7 vs 11.5 ± 2.4, $p = .015$) and reduced missed responses (2.4 ± 1.8 vs 3.5 ± 2.4, $p = .013$) compared to placebo in a vigilance task. No effects were found for a dual-task. In a later study by Coull et al. [87], one dose of 150 $mg.kg.bm^{-1}$ tyrosine consumed 1 h pre-trial was found to be ineffective for enhancing vigilance, dual-task, or simple RT pre-, 30-min during, and post- 60-min load carriage treadmill protocol followed by a 2.4 km loaded time-trial.

Zhang et al. [88] also found no effects of 10 mg menthol lozenge ingestion, when comparing its effects to caffeine ingestion (400 mg capsule) and a placebo, on CP under active heat stress. The protocol implemented two bouts of 4 × 4-min of treadmill walking at a metabolic rate of 60% VO_{2max} followed by 1-min of arm curls, and a final bout including a 4 × 4-min step exercise protocol, followed by 1-min of arm curls. No effects for simple RT, short-term memory, retrieval memory or math tasks were found. Similarly, Ashworth et al. [45] found no effects of a 25 ml mouth-rinse with 0.1% menthol concentration compared to a water mouth-rinse on cognition under passive HWI (T_C = 38.5°C), or during active heat stress, walking for 30-min in military uniform in a 20 kg weighted vest. Implementing the mouth-rinse prior to each task, no effects were found for declarative memory, Go/No-Go RT, perceptual processing, WM, executive function and cognitive flexibility or vigilance.

Mixed Strategies

Four studies integrated a mixed-strategy approach, all combining the use of cooling strategies, but two with supplementation or mouth rinse approaches [74,83], and two with hydration strategies [58,59] (See Table 8). In field-based work, when under high levels of hyperthermia, Bandelow et al. [58] found that increasing fluid intake and using sports drinks in addition to players normal fluid intake across 3 football matches in ~34°C did not have any effects on visual sensitivity, Sternberg WM or the Corsi block-tapping test ($p > .05$) pre, half time (HT) and post- match-play. However, they did find that cooling via a tent pre-match and at HT improved complex level RT for the visual sensitivity test at HT and post-match (−84 ms when grouped) compared to no cooling ($p < .05$). Benjamin et al. [59] similarly integrated a cooling and hydration approach under moderate hyperthermia, exploring the impact of euhydration, replacing BM loss with water mid-trial, compared to hypohydration (4.39 ± 2.02% BM loss from baseline), and cooling via ice water dousing, during 5 × 15-minute intermittent treadmill bouts at 35°C. However, they found no effects of either euhydration or cooling compared to the hypohydrated, no-cooling condition, for a trail making test or choice RT implemented pre- and post-exercise ($p > .05$).

Also provoking moderate hyperthermia, Saldaris et al. [83] found that 30-min pre-cooling via crushed ice ingestion combined with menthol swilling enhanced selective attention following 90-min running and a subsequent time to fatigue protocol in 35°C. More errors on the Colour Multi-Source Interference task were present in control (9.00 ± 3.84; 8.50 ± 4.54) compared to crushed ice + menthol (6.08 ± 2.07, 5.33 ± 3.26, $p \leq .011$, $d = .80$ to .95). However, when exploring the effectiveness of the interventions independently, no effects were found in the absence of pre-cooling, suggesting that pre-cooling through crushed ice ingestion facilitated the protective effects of selective attention, and not the menthol intervention. The second study integrating a cooling and supplementation strategy, found that the combined use of a carbohydrate-electrolyte solution every 15-min during exercise and a cooling vest pre- and at half-time of a 2 × 45-min soccer specific treadmill protocol, improved performance on a simple mental concentration task compared to control ($p = .025$) [74]. Percentage of correct responses was significantly higher after 4-, 34- and 49-min of exercise with pre-cooling and carbohydrate-electrolyte solution compared with no-cooling, placebo. However, no effects were found for independent use of pre-cooling without the carbohydrate-electrolyte solution, alternatively suggesting that

Table 7. The effectiveness of supplementation and mouth-rinse methods on CP under heat stress.

	Heat (°C, % rh)	Protocol	Hyperthermia (°C)	Intervention and Comparison	Cognitive Outcomes
Coull et al. (2015)	**Chamber** 25°C, 40%rh	**Active – Treadmill** 2 × 45-min intermittent soccer performance test/15-min rest	**Moderate** End T_R = 38.7°C in tyrosine and 39°C in placebo	**Tyrosine** ● 150 mg.kg.bm^{-1} tyrosine powder × 2, 5 h and 1 h pre-exercise protocol ● 250 ml sugar free lemon squash (placebo)	**Simple** (+) Numerical vigilance **Complex** (0) Dual- tracking and attention task
Coull et al. (2016)	**Chamber** 40°C, 30%rh	**Active – Treadmill** ● 60-min walk at 6.5 km.h^{-1} with 25 kg backpack ● 2.4-km time trial with the 25 kg backpack	**Moderate** Highest T_R values observed post-time trial, 38.8°C in tyrosine and 38.8°C in placebo.	**Tyrosine** ● 150 mg.kg.bm^{-1} tyrosine powder, 1 h pre-exercise ● 250 ml sugar free lemon squash (placebo)	**Simple** (0) Numerical vigilance (0) Simple RT **Complex** (0) Dual- tracking and attention task
Zhang et al. (2015)	**Chamber** 35°C WBGT, wet: 31°C, dry: 45°C, globe: 43°C, 40%	**Active – Treadmill** ● 4 × 4-min walking at 60% VO_{2max} metabolic rate ● 1-min of 15 arm curls (4.5 kg bar) × **2** ● 4 × 4-min step exercise, 25 steps per min on a 40-cm platform, 1-min of 15 arm curls (4.5 kg) ● Bouts/15-min rest periods	**Moderate** End T_R = 39.0°C in placebo and menthol trials, and 39.1°C with caffeine	**Caffeine-Menthol** ● 400 mg caffeine capsule 10-min pre- bout 1 (+ placebo protocol) ● 10 mg menthol, 6 mg benzocaine menthol lozenges taken prior to bout 1, 2 and 3 ● 6 mg benzocaine placebo lozenges taken prior to bout 1, 2 and 3	**Simple** (0) Simple RT (0) Short-term memory (0) Math test **Complex** (0) Retrieval memory
Ashworth et al. (2020)	**HWI-Chamber** 40°C HWI Chamber: 33°C, 75%	**Passive-Active** ● 40°C water immersion until T_C = 38.5°C ● 30-min walk at 5 km.h^{-1}, 1% gradient in military uniform and 20 kg vest	**Moderate** Max T_R = ~38.3°C	**Menthol** ● 25 ml mouth-rinse with 0.1% menthol concentration prior to each task ● 25 ml water mouth-rinse prior to each task (placebo)	**Simple** (0) Visual perceptual processing **Complex** (0) Declarative memory (0) Go/No-Go RT (0) WM (0) Executive function and cognitive flexibility (0) Vigilance

Notes: T_R = rectal temperature; WM = working-memory; RT = reaction time; WBGT = wet bulb globe temperature; (+) = positive effect; (0) = no effect; (-) = negative effect. Intervention findings reported in comparison to control; therefore, positive effects may still reflect a decrement in heat, but to a lesser extent than controls.

the carbohydrate solution induced the protective benefits, and not the use of the cooling vest. There were no effects found for choice RT or a serial sevens WM task for either intervention.

Psychological

Just 2 articles explored psychological (or other) strategies for cognition following active heat exposure (See Table 9). Wallace et al. [90] explored the impact of a 2-week motivational self-talk (MST) training programme in comparison to a control group on CP across a variety of tasks, following inducing moderate hyperthermia by 25-min cycling at 60% peak power output, and a second bout at 80% peak power output to exhaustion in 35°C. They found no influence of MST on speed or accuracy for a detection and 2-back cognitive task. However, on the Groton Maze Learning Task, measuring short-term memory, they found that overall completion time reduced for the MST group at baseline and following the second bout of exercise, where there was no difference for the control group.

Inducing low levels of hyperthermia, Tokizawa et al. [89] included four conditions, a lunchtime nap vs. no nap condition following either a night of normal sleep (7–8 hours) or a night of partial sleep restriction (4 hours), on psychomotor vigilance following two 40-min walking bouts at 3.5 km/h in 35°C in the morning and afternoon. A reduction in vigilance lapses and mean RT was observed when a 30-min nap had been taken in comparison to no nap, following the first afternoon exercise session in the heat. No differences for psychomotor vigilance performance were found between conditions when participants had a normal night of sleep.

Discussion

Heat stress is understood to impair CP and decision-making [27–29], which can result in critical consequences either in competitive or dangerous environments. Impaired decisions relating to physical capabilities and limits could contribute to heightened heat-related morbidity and mortality risks [9]. Such impacts may also lead to economic damages through reduced working capacity and lower productivity [91,92]. Therefore, the aim of this review was to explore the effectiveness of chronic heat preparation strategies, alongside acute heat alleviation strategies for the maintenance of CP under heat stress across athletic and occupational contexts.

Chronic heat preparation strategies

The findings from this review highlight a lack of existing research exploring the effectiveness of widely used acclimation and acclimatisation strategies, for the maintenance of CP. From the five studies identified, the findings appear equivocal, perhaps due to the varied methodology and different cognitive measures employed across studies. Both studies which employed 10-days of consecutive active HA [54,55] found beneficial cognitive effects under active heat exposure with HA. However, in the only study to explore the use of a long-term active HA protocol, where participants cycled in ~39°C, 5 × week, across 28-days, no effects were found across simple cognitive and motor tasks [53]. There were also no effects observed for more complex combined motor-cognitive and visuo-motor tasks, despite declines being observed with hyperthermia compared to normothermia [53].

Compared to those who found protective benefits of HA, Piil et al. [53] employed a fixed T_C protocol, terminating exercise only when T_C had reached that of the first trial. Thus, compared to those employing fixed *time* protocols which resulted in lower final T_C [54,55], HA had instead enabled participants to work for longer until $T_C =$ 40.1°C [53]. However, as observed by Racinais et al. [57], long-term HA has been shown to be effective in protecting executive function, restoring accuracy, and reducing the likelihood of impulsive responses (returning latency to that of control) under hyperthermic conditions even when T_C is controlled to reach a fixed level, although markedly lower (39°C) and during passive exposure.

The differences observed in the effectiveness of HA across these studies could also be attributed to the successive nature of the included protocols. Heat acclimation has been found to induce greater adaptations when employed on consecutive days [93,94], therefore, the non-consecutive nature of

Table 8. The effectiveness of mixed-methods on CP under heat stress.

	Heat (°C, %rh)	Protocol	Hyperthermia (°C)	Intervention and Comparison	Cognitive Outcomes
Bandelow et al. (2010)	**Field-Based** Match 1: 34°C, 64% Match 2: 34°C, 65% Match 3: 34°C, 62%	**Active** Normal match-play	**High** After exercise, temperature range = 37.2–40.0°C	**Fluid Intake – Cooling** ● ↑ fluid intake and sports drink ● Cooling tent pre-match and HT ● Normal fluid intake/no cooling	**Simple** Fluid (0) Visual sensitivity Cooling (+) Visual sensitivity **Complex** Fluid (+) Sternberg WM Fluid (0) Corsi block-tapping (WM) Cooling (0) Sternberg WM Cooling (0) Corsi block-tapping (WM)
Benjamin et al. (2021)	**Chamber** 35°C, 46%	**Active – Treadmill** 5 × 15-min intermittent bouts/5- to 10-min breaks	**Moderate** EuD T_R = 38.3°C EuND T_R = 38.4°C HypoD T_R = 38.7°C HypoND T_R = 38.7°C	**Euhydration – Cooling** ● Euhydrated with ice water dousing post-exercise bouts (EuD) ● Euhydrated, no ice water dousing (EuND) ● Hypohydrated with ice water dousing post-exercise bouts (HypoD) ● Hypohydrated, no ice water dousing (HypoND)	**Simple** (0) Choice RT **Complex** (0) Trail making test (visual attention and task switching)
Saldaris et al. (2019)	**Chamber** 35°C, 59%	**Active – Treadmill** ● 3 × 30-min running at 65% VO_{2peak}/rest ● TTE run at 100% VO_{2peak}	**Moderate** Mean peak T_C = ~39°C#	**Cooling – Menthol** ● CI+M: 30-min ingesting crushed ice, and menthol swilling at start, 15-, 30-min into each running block ● W + M: 7 g·kg^{-1} of water (32.4 ± 0.9°C) ingested and menthol procedure ● No cooling or menthol, warm water swilled	**Simple** CI+M and W + M (0) Choice RT **Complex** CI+M (+) Colour multi-source interference W + M (0) Colour multi-source interference
Clarke et al. (2011)	**Chamber** 31°C, 42%	**Active – Treadmill** 2 × 45-min soccer specific protocol/ 15-min rest	**Moderate** End T_C range = 38.8 to 39.0°C#	**Pre- and HT- Cooling – Carbohydrate** ● Cooling vest with carbohydrate electrolyte (C-C) ● Cooling vest with placebo (C-PL) ● No cooling, carbohydrate-electrolyte (NC-C) ● No cooling, placebo (NC-PL) *Solutions consumed every 15-min during exercise*	**Simple** C-C (+) Mental concentration C-PL (0) Mental concentration NC-C (0) Mental concentration

Notes: # = value approximated from figure; T_R = rectal temperature; T_C = core temperature, WM = working-memory; RT = reaction time; TTE = time to exhaustion; (+) = positive effect; (0) = no effect; (-) = negative effect. Intervention findings reported in comparison to control; therefore, positive effects may still reflect a decrement in heat, but to a lesser extent than controls.

Piil et al.'s [53] protocol may have contributed to a lack of protective benefits observed. That said, participants only had two rest days per week for 28 days in this study [53], and a review by Daanen et al. [95] suggests that the average decay per rest day for T_C and HR is only around 2.5%, even less so when using long-term protocols, which induce more sustainable adaptations. However, the decay in cognitive adaptations is yet to be explored and it may be that the consecutive vs. non-consecutive nature of HA influences how effective HA is for maintaining CP which warrants further attention.

Additionally, conflicts could be attributed to the age of participants, where the average age range was 20–25y in the studies which employed 10-days HA and observed protective effects [54,55], compared to 40y in Piil et al. [53]. Larose et al. [96] observed a 4–11% reduction in heat dissipation in 40–44y and 45–49y olds in hot, humid conditions compared to 20–30y olds. Though the participants were highly trained in Piil et al. [53], which may positively influence the heat dissipation capacity of this sample [97,98], although this remains inconclusive [99]. Four of the five studies used participants with a mean age < 34y (most < 26y), thus more evidence is needed in relation to the effectiveness of HA on older populations to better inform preparation for individuals >40y who are required to perform in hot conditions [100], such as those in the military, those competing in high level masters' sports competitions (e.g. 2022 Masters Hockey World Cup: Cape Town), or simply those who want to be able to engage in physical activity safely in warmer temperatures.

Just one study investigated the effects of acclimatisation by comparing a group of naturally acclimatised tropical natives to a non-acclimatised group [56]. They found that the naturally acclimatised group performed better on a two-column digit addition test, following passive exposure (40-min in a 28°C chamber and 60-min HWI). This was despite both groups having resided in Japan for ≈ 12 months prior to the experiment, indicating that being raised in tropical countries may have long lasting effects for maintaining CP in hot environments. Indeed, previous research by Wijayanto et al. [101] showed that tropical natives have an enhanced sweating efficiency and improved heat dissipation capabilities during heat loading. Though interestingly, T_C was not markedly raised with heat exposure (between 37.4–37.5°C across groups) in Wijayanto et al [56], and it is suggested that these protective effects may have been more psychological, where the Japanese subjects reported more negative feelings than the tropical native group. Oxyhaemoglobin levels were also higher in the Japanese subjects when performing cognitive tasks, suggested by the authors to indicate overloaded neural resource and heightened arousal levels in response to heat exposure, where oxyhaemoglobin was lower for the tropical native group. However, due to exploring the effectiveness of acclimatisation by comparing tropical natives to non-tropical natives', the applicability of implementing acclimatisation as a strategy for those unaccustomed to heat exposure remains unanswered and future research should investigate the effectiveness of this with the use of a replicable protocol.

Acute heat-based strategies

Most studies included in this review explored an acute strategy (i.e. any short-term strategy implemented within 24-hours of the heat exposure) for enhancing cognitive (and sometimes physical) performance in the heat. These varied from hydration, cooling, supplementation, and psychological based strategies, with some exploring the combined effectiveness, or comparing the effects of, two types of strategy (e.g. cooling and hydration). During active heat exposure, mixed results were found in relation to the effectiveness of fluid intake on CP during or following exercise under heat stress, perhaps resultant of methodological differences in relation to the level of hyperthermia experienced, intervention administered, participant hydration status, and timing of the cognitive tasks.

Studies which found beneficial effects for indices such as simple cognitive addition, and complex motor-cognitive tasks and hockey penalty performance and decision-making time, generally administered a prescribed individualised volume of fluid (often electrolyte solutions) to ensure euhydration, compared to dehydration/

Table 9. The effectiveness of psychological or other strategies on CP under heat stress.

	Heat (°C, %rh)	Protocol	Hyperthermia (°C)	Intervention and Comparison	Cognitive Outcomes
Wallace et al. (2017)	**Chamber** 35°C, ~50%	**Active – Cycle Erg** ● 5-min at 100 W ● 25-min at 60% peak power ● 5-min at 125 W and 80% peak power to exhaustion ● 30-min rest periods post-exercise bouts	**Moderate** Peak T_R post-TTE = 38.8°C	**Self-Talk** ● 2-wk motivational self-talk training No self-talk	**Simple** (0) Detection RT **Complex** (+) Groton Maze Learning Task (0) *2*-back test
Tokizawa et al. (2015)	**Chamber** 35°C, 40%	**Active-Treadmill** ● 40-min walk at 3.5 km/h × **2**/20-min rest in 28°C ● Morning cycle repeated × **2** following 30-min lunch	**Low** Peak T_R = ~37.6°C#	**Sleep** ● 30-min lunchtime nap ● No nap	**Simple** (+) Psychomotor vigilance

Notes: T_R = rectal temperature;
T_C = core temperature, RT = reaction time; (+) = positive effect; (0) = no effect; (-) = negative effect. Intervention findings reported in comparison to control; therefore, positive effects may still reflect a decrement in heat, but to a lesser extent than controls.

hypohydration conditions (defined between −2 to −3% body weight for those observing protective benefits) [61,65,67]. This was in comparison to studies which used non-specific *ad libitum* or non-prescribed fluid intake volumes (and did not achieve full rehydration) in comparison to no fluid or dehydration conditions, which generally observed no cognitive effects for simple or complex cognitive tasks (e.g. 64, 66, 69). This was similar for studies involving passive heat exposure, relevant for occupational and educational settings, whereby when individualising fluid replacement to correspond to 100% of body mass lost, in comparison to dehydration (−2.8% body mass), protective benefits of fluid intake were found for long-term memory [61], where otherwise no effects were found within studies whereby 100% rehydration was not achieved [62,70], other than a trend for visual WM with *ad libitum* fluid intake [60].

Several studies explored the effectiveness of pre-, during, or post- cooling strategies on CP during or following active or passive heat stress. Pre-cooling appeared to be most consistent for protecting CP under heat stress across a variety of tasks. Visual sensitivity, visual discrimination and memory tasks were all improved with whole body or local cooling in comparison to no cooling during studies implementing active heat stress [35,58,75]. In one instance, cooling via a tent pre- match and at half-time of match-play, improved visual sensitivity in football players, where no protective effects were found from increased fluid ingestion or sports drink consumption [58]. In contrary, Clarke et al. [74] found that mental concentration was improved with the combined use of pre-cooling and a carbohydrate-electrolyte solution in football players, but no effects were found in the absence of the carbohydrate solution, suggesting that the carbohydrate-electrolyte solution is what drove the effects.

Most studies implementing cooling strategies during heat exposure, either whole body or local cooling, were found to be ineffective for facilitating simple or complex cognition during or following active or passive heat exposure. One of the only two studies which found protective effects, found that neck cooling 5-min into exercise, alongside post-exercise, protected performance on the highest level of a search and memory task [78]. However, they also found that cooling mitigated the benefits observed post-exercise in the control condition for a digit span WM task, suggesting that cooling may be facilitative only for the most complex tasks, but ineffective for others where it may interfere with the exercise-induced BDNF-mediated mechanisms shown to improve

WM [78,102]. Similarly, Hemmatjo et al. [77] found that the use of a cooling vest, and combined use of a vest with a cooling gel containing menthol during simulated firefighting activity, was found to be beneficial for accuracy on a continuous vigilance task but detrimental for RT, which slowed with cooling. Previous research has found that response speed can improve with increased T_C [66,103], perhaps due to a more accentuated catecholamine rise which has been shown to speed up processing time [104]. This can sometimes result in quicker, more impulsive but less accurate responses. Cooling in this instance, appears to have inhibited the speed of responses, but improved the accuracy of responses.

The use of menthol, as well as tyrosine and caffeine, as supplements to enhance CP during or following active heat exposure was explored across a few studies. Menthol swilling has been used as a perceptual cooling strategy, which has been shown to reduce perceived exertion, thirst, and thermal sensation, and enhance exercise performance in hot conditions [105,106], through stimulating feelings of coolness in the absence of T_C reductions [83]. The cooling sensation related to the use of menthol has also been reported to influence arousal and alertness levels [105,107], thus having potential to also influence CP under heat stress. However, menthol was generally ineffective for facilitating simple or complex indices of CP [45], even when combined with the use of caffeine ingestion [88]. The one study to find positive effects of menthol on CP following exercise in hot conditions, only found these when combined with crushed ice ingestion, implying that cooling by crushed ice facilitated the positive effects observed for executive function, and not the menthol supplementation itself [83]. Therefore, from the available literature, menthol appears ineffective for enhancing CP under heat stress.

Tyrosine supplementation was also explored in two studies and presented conflicting results. Tyrosine ingestion has been used to increase dopamine precursor availability, due to an increased synthesis rate expending these resources when performing under additional thermal strain [108,109], where dopamine is known to play an important role in exercise tolerance [110,111] and CP [112]. Coull et al. [86] found positive effects for post-exercise vigilance following ingestion of 2×150 mg•kg•bm^{-1} doses of tyrosine consumed 5 h and 1 h prior to soccer-specific treadmill activity in which subjects were instructed to follow a target work-output. However, within a military context, they later found no effects to cognitive indices following one 150 mg•kg•bm^{-1} dose of tyrosine consumed an hour prior to a self-paced load-carriage time-trial protocol in a much higher exposure of 40°C [87]. This was despite no differences being found in the extent of the serum tyrosine rise following 1 or 2 doses of 150 mg.kg.bm^{-1} in a preliminary part of the study [87]. Whilst there is limited evidence to draw conclusions upon the effectiveness of tyrosine for performing under heat stress, only very strenuous activity – for example, to exhaustion in extreme environments [113] or fixed-paced high-intensity intermittent running protocols [86] in comparison to self-paced [87,114], may provoke a need for additional tyrosine stores, perhaps due to the increased physical and psychological demand [115,116]. Further research is needed to better understand the circumstances where tyrosine may be facilitative for physical and CP under thermal strain.

It is well evidenced that heat exposure increases sensory displeasure and the perceptual demands of a situation, particularly during exercise [45,103], but also during passive heat exposure [38]. These perceptual responses to heat stress have been attributed to both simple and complex cognitive declines [38,117]. The Global Workspace theory [37] offers some support for this explaining that the alliesthesial responses to heat exposure place further demands where multiple external stimuli already compete for the limited conscious workspace available, reducing the availability of resources for cognitively demanding tasks [38]. The deterioration of CP is observed when the available cognitive resources are insufficient for meeting the demands of both the cognitive task and the interfering load (i.e. the additional thermal strain) imposed on the participant [118]. With this mechanistic perspective in mind, it is plausible to suggest that psychological-based interventions, could be more effective for the maintenance of CP under thermal strain than the more traditional physiological-based strategies (e.g. cooling, acclimation) which have previously been associated with a wide range of physical performance benefits under hot conditions.

There is currently limited research exploring the use of psychological strategies for improving human performance in the heat. Self-talk is a well-established cognitive technique used within sport to influence the thoughts, feelings, and behaviours of athletes [119,120], and it's acknowledged as one of the most effective strategies for enhancing sport performance [121]. Previous research has found that motivational self-talk can aid endurance performance [122], in thermoneutral environments [123] and in the heat [124], with participants experiencing similar levels of perceptual strain across conditions despite an increased work rate [124]. The only study to examine CP and heat, found that two weeks of motivational self-talk improved short-term memory following exercise to exhaustion [90]. Whilst there is little evidence to date, the initial findings provide fresh insights that motivational self-talk may be effective for enhancing physical and cognitive performance in the heat. Perhaps integrating more psychological based strategies such as self-talk with more traditional acclimation/acclimatisation methods, could offer more comprehensive protective effects for those having to perform in more strenuous conditions (e.g. military personnel, athletes).

Limitations and future directions

There is a lack of research exploring the effects of chronic heat-based strategies (i.e. acclimation and acclimatisation) on CP, making it difficult to draw conclusions on its effectiveness for mental performance. It is important that future research addresses this gap, where the maintenance of cognitive skills is essential across athletic and occupational contexts. Furthermore, whilst research has identified some psychological interventions which can benefit a wide range of cognitive and physical performance measures, limited research has explored the integration of psychological measures for maintaining performance under heat stress, which could offer additional insights than the traditionally explored physical strategies employed. It is also challenging to draw complete conclusions on the effectiveness of intervention types across studies, where a variety of different cognitive tasks and batteries have included within methodologies (e.g. CANTAB), often designed initially to test deficits for stroke and cerebrovascular disease and the effectiveness of treatments, rather than the performance implications of acute stressors. Additionally, as is found with much of the heat-based research, there is a lack of research including female participants [125], making it difficult to generalise the effectiveness of these strategies due to well-known differences such as menstrual cycle phase in females [126], affecting the physiological response to heat stress. Gender, age, and cultural factors also require greater consideration within the occupational settings as well as the athletic populations due to some specific categories; females, older populations and specific occupational roles in relation to their heat tolerance, risks of heat illness and optimisation of work rate during exertional heat stress [8]. Finally, future studies should look to simulate sunlight exposure where possible which was not integrated across most studies included in this review, as we know this influences the extent and likelihood of decrements [29].

Conclusions

The effectiveness of well-known physical heat preparation strategies for CP is conflicting, due in part, to the sparseness of research, and differences in methods implemented. The findings of this review suggest that HA may be an effective way for mitigating some cognitive deficits under heat stress. More research is required to understand if there are differences in the effectiveness of HA for the maintenance of CP between consecutive and non-consecutive protocols, or across different age groups, as the findings of this review show these factors may play a role.

If implementing hydration strategies for the maintenance of cognition in hot conditions, then electrolyte fortified fluid volumes should be prescribed to match for sweat loss. Strategies which encouraged participants to drink more or employed *ad libitum* procedures and did not rehydrate to match fluid losses, generally did not find protective effects for cognition. Further, cooling strategies appeared most beneficial for maintaining CP when employed pre- active or passive heat exposure, although research is still conflicted regarding the specific protective effects. There was limited evidence to suggest that cooling during heat exposure improved cognition, other than via ice slurry ingestion. Moreover, little is known in relation to psychological strategies for maintaining CP in hot conditions, which is surprising considering the known impact that psychological stress has on the execution of cognitive skills, which are fundamental across domains (e.g. military personnel, emergency services, athletes). The limited evidence exploring motivational self-talk as a strategy for enhancing human performance in hot conditions offers promising results that this may facilitate cognition (e.g. short-term memory), alongside exercise tolerance.

Future research should look to integrate effective physical preparation strategies, such as heat acclimation, with lesser known, psychological strategies to try to maximise the benefits of preparing humans to perform in hot conditions. These findings can be used by practitioners to help inform heat preparation strategies for maintaining critical cognitive and decision-making skills in strenuous environments, rather than focusing solely on the maintenance of physical functioning in occupational and athletic contexts.

Notes

1. Population determined as active based off $VO_{2\ max}$ values reported. The authors acknowledge the difference in the definitions of dehydration and hypohydration in that dehydration is the process of dynamic body water loss whereas hypohydration is the state of reduced total body water beyond normal. For the purpose of this review, hydration terminology has been kept consistent with that of the original authors descriptions.
2. Informed by temperatures reported in MacLeod et al. (2018) using the same protocol. No T_R values reported in MacLeod & Sunderland (2012).
3. Any results marked # have been estimated based off figures in the original articles.

Abbreviations

BM, Body mass; CP, Cognitively dominated performance; $T_{C,}$ Core temperature; HA, Heat acclimation; HWI, Hot water immersion; RT, Reaction time; T_R, Rectal temperature;T_{TY}, Tympanic temperature; WM, Working-memory. . .

Disclosure statement

No potential conflict of interest was reported by the authors.

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