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Title

Does increased core temperature alter cognitive performance during exercise-induced heat strain? A narrative review

Abbreviated Title:

Influence of core temperature on cognitive performance

Authors

Meg A Doohan[1,2], Jessica T Watzek[3], Neil King[1,2], Melanie J White[1,4] Ian B Stewart[1,2]

Affiliations

[1]Queensland University of Technology, Brisbane, Australia.

[2]School of Exercise and Nutrition Sciences, Queensland University of Technology, Brisbane, Australia.

[3]Menzies Health Institute Queensland, Griffith University, Brisbane, Australia.

[4]School of Psychology and Counselling, Queensland University of Technology, Brisbane, Australia.

Corresponding Author

Ms Meg Doohan

School of Exercise and Nutrition Sciences, Queensland University of Technology, Brisbane, Australia.

Address: 149 Victoria Park Rd, Kelvin Grove QLD 4059

Email: meg.doohan@hdr.qut.edu.au

Abstract

Introduction: Research to date, provides equivocal evidence regarding the influence of heat stress, heat strain, and more specifically, elevated exercise-induced core temperature on cognitive performance. This review sought to identify differences in how specific cognitive tasks were affected by increases in core body temperatures. *Methods:* Included papers (*N* = 31) measured cognitive performance and core temperature during exercise, while experiencing heightened thermal stress. Cognitive tasks were classified as: cognitive inhibition, working memory, or cognitive flexibility tasks. *Results:* Independently, core temperature changes were not sufficient predictors of cognitive performance. However, reaction time, memory recall, and Stroop tasks appeared to be most effective at identifying cognitive changes during heightened thermal strain. *Discussion:* Alterations in performance were more likely to arise under increased thermal loads, which were typically associated with cumulative physiological stressors, such as elevated core temperatures, occurring alongside dehydration, and prolonged exercise durations. Future experimental designs should consider the relevance, or futility of assessing cognitive performance in activities that do not elicit a considerable degree of heat strain, or physiological load.

Key Words: Cognitive Performance, Core Temperature, Exercise, Heat Strain, Heat Stress.

1. Introduction

The combined influences of physical activity and heat strain on cognitive performance have long been an area of interest in sporting, military, and occupational settings (1–9). Unfortunately, methodological discrepancies between individual research designs, and the lack of standardisation in the use of cognitive tasks, has produced inconsistent and often contradictory findings. Therefore, it has been challenging to ascertain whether the collective effects of heat strain and physical activity does (10–14), or does not (5,15–17), adversely influence cognitive performance.

Previous evidence has hypothesised that the observable influence of heat strain on cognitive performance is primarily dependent upon the complexity of the task (18). Using this explanation, simpler tasks (reaction time, attentional, inhibition) are more likely to demonstrate improvements, or plateaus in cognitive performance when experiencing elevated heat strain, which is typically identified as occurring at core body temperatures at around 38.5 - 38.7 °C (19). Therefore, the less complex the task is, the greater the likelihood of experiencing benefits from the acute demands placed on the body. Conversely, more complex cognitive tasks (decision making, cognitive flexibility, executive functioning), which require a greater degree of effort to complete, are anticipated to show notable performance decrements during thermal strain (18–20). This hypothesis proposes that an adverse influence of heat strain on cognitive performance is unlikely to be observed unless the difficulty of the task exceeds a pre-determined complexity threshold. However, the practicality of this theory has been questioned in studies incorporating exercise, and/or active heating protocols, given its development using predominantly passive heating procedures (6,21,22). Most noticeably, acute bouts of exercise have consistently been documented to facilitate information processing capacities (23), as has moderate exercise-induced hyperthermia (24). Passive models, therefore, cannot solely be used to dictate all cognitive functions during thermal strain. Further, this one-size-fits-all approach seemingly disregards a range of factors which have the potential to influence cognitive performance at varying rates and degrees, such as hydration, body temperature fluctuations, and ambient environmental conditions.

Alternative hypotheses have focused on the notion of cognitive load, where the capacity of brain functions are progressively exhausted by the introduction of heat strain (25). With increased thermal load, greater effort is required to maintain optimal cognitive performance (13,20). Using this hypothesis, only when the degree of heat strain is sufficiently intense, or, when the interaction between stressors is sufficiently high, will decrements in task performance be elicited. Therefore, cognitive performance may initially improve to compensate for an acute increase in stress, and be maintained for an extended period of time – if the overall cognitive load remains relatively stable. However, with increased effort and resources required to preserve these functions, and/or an elevation in the overall load, notable performance impairments are expected to occur (26). Similar to the Maximum Adaptability Model (26,27), this theory draws on the traditional principles of human stress responses, suggesting that a zone of compensable core temperature values may exist to protect against cognitive performance decrements (26–28). By this model, a slight increase in core temperature may initially provoke improvements in cognitive performance, and preserve performance during moderate, exercise-induced hyperthermia (26–28). Beyond this zone (~38.2–38.7 °C), however, where core temperature values progressively exceed compensability, impairments in cognitive task performance are more likely to be observed (27). While this theory does not discretely acknowledge the influence of additional stressors on cognitive performance, occurring alongside elevated core temperature, the notion of cognitive load does have the potential to highlight such extraneous variables.

The inclusion of several external variables, such as dehydration, physical activity, and extreme environmental conditions, may influence cognitive performance to a degree greater than the independent effects of elevated core temperature. Naturally, however, the interaction of such variables (dehydration, exercise, environmental conditions), makes it difficult to identify the true, and independent effects of elevated core temperature on cognitive performance. Adding to the complexities in determining the true effects of core temperature on cognitive performance, are the methodological inconsistencies prevalent across experimental designs (29–33). Common discrepancies include different environmental conditions, degrees and methods of producing heat strain, physical activity protocols, age, training status, sex, skill levels, and the number, complexity, duration and repetition of cognitive tasks (34–36). While such variables have been discussed in earlier reviews (19,27,36), more recent assessments have focused on changes in ambient conditions (32,33) and manipulation of hydration statuses (29,30) to explain variations in cognitive performance. The results of these reviews have emphasised the potential influence of increased perceptions of effort and decreased thermal comfort in hot environments, which have largely been neglected from the traditional models of physiological strain (i.e. Arousal Theory (inverted-u model), Environmental Determinism Theory (28,37).

Using a systematic approach, the purpose of this narrative review was to provide a greater understanding of the tasks and domains of cognitive function that are most impaired with exercise-induced heat strain. Emphasis was placed on determining the presence of task dependent changes in cognitive function, and whether distinct components of executive function were influenced by different levels of thermal strain (38). Drawing from the hypotheses described, the authors predicted that more complex tasks (cognitive flexibility) would experience the greatest decrements in performance, while simpler tasks (working memory and cognitive inhibition) were not predicted to show any statistically significant changes in cognitive performance. It was also predicted that the degree of heat strain –

demonstrated by changes in core temperature experienced during an exercise protocol – would be directly related to the observed variations in cognitive performance.

2. Methods

The review was conducted in alignment with the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) Guidelines (39) and registered on the international prospective register of systematic reviews (PROSPERO Reference: CRD42021226546).

Eligibility Criteria

Studies were considered eligible if they included the following criteria: 1) human participants, 2) adults (≥ 18 years), 3) measure of core temperature 4) control and experimental groups, 5) an active method of heat stress (i.e.: a physical activity protocol), and 6) measure of cognitive performance. Studies were required to include both a control and an experimental condition which elicited a change in core temperature at the time of cognitive assessment. Therefore, protocols in which core temperature returned to baseline prior to conducting cognitive assessments were excluded, and cognitive assessments were required to be completed within the relevant environmental condition. There was no limit on the time or type of exercise conducted. Studies were limited by availability in English, and being a peer reviewed, empirical experimental design. Studies that did not meet these criteria were excluded from the review.

Studies that included an internal or external method of cooling during an exercise protocol were included in the review, on the basis that all other criteria had been met. Acknowledging that these methods have the potential to significantly alter core temperature, the following three heat manipulation protocols were classified. Standard protocols were identified as designs where cold, or thermoneutral environments acted as the control, and hot environments as the experimental condition. Internal cooling mechanisms incorporated a form of menthol, ice or liquid ingestion to alter core temperature, either prior to or during exposure to heat strain. In these studies, the cooling conditions were used as the control, due to the reduced core temperature values, and the non-cooling trials as the experimental conditions. Finally, external mechanisms of inducing heat strain included wearing some form of personal protective equipment (PPE), where the control condition was the trial in which the PPE was not donned. In this same category, tasks which used external cooling vests were also permitted, wherein the conditions were reversed; control conditions occurred when participants were wearing the cooling apparatus.

Search Strategy

Three online databases were used for the search: Cumulative Index of Nursing and Allied Health Literature (CINAHL), Embase, and PubMed. The search consisted of three major themes: i) physical activity, ii) core temperature, and iii) cognitive performance. Terms were adjusted for each database by applying mesh terms and filters. Pilot searches occurred in October 2021 to ensure robustness of the search strategy, and the final search was conducted on May 11, 2022.

Data Extraction

All studies were imported into *Endnote* (version X9, 2013), before being uploaded onto *Covidence* (v2715, 2021) to complete the extraction. After removing duplicates, studies, titles and abstracts, followed by full texts, were screened independently by two reviewers (MD, JW) using standardised criteria. Disagreements were solved through discussions between reviewers, and if necessary, a third reviewer (IS) was introduced to resolve conflicts. Where possible, extracted data included: participant demographics (age, maximal oxygen consumption ($\dot{V}O_{2max}$), sex, sample size, training status, hydration manipulation, acclimatisation status, fuel intake, external weight bearing), experimental design, exercise protocol (type, intensity, and time), environmental manipulation, mean (M) and standard deviation values (SD) of cognitive assessments, and core temperature values from matched time points. To assess changes in core temperature across studies, the time point and experimental condition at which the peak core temperature change occurred, when compared to the control condition, were extracted. Any required data points that were only displayed graphically were digitised using *WebPlotDigitiser* (version 4.4).

Quality Assessment

Quality assessment analyses were conducted by two reviewers (MD, IS) using the Cochrane Risk of Bias Tool (40) and appropriate templates for parallel and crossover trials. The assessment aided in quantifying potential risks in allocating participants to conditions, standardising experimental protocols, missing data, condition blinding, and statistical analyses.

Statistical Analysis

Qualitative analyses aimed to identify similarities between research designs and results of specific tasks or domains, and to provide a foundation of which to inform future design methodologies. Tasks were categorised under three discrete domains, derived from Diamond (2013): cognitive inhibition, working memory, and cognitive flexibility (41). Studies were further identified as being either a between-groups or repeated measures design. Modes of heat strain were classified as: external (cooling vests, heat pads, clothing), internal (fluid, ice consumption), or standard (thermoneutral/cold, versus hot environments). Each task was categorised into the relevant domain, based on previous literature, or author classifications (41). Cognitive outcomes such as: reaction time (milliseconds; ms), accuracy (percentage; %), and errors (number, %), as well as the unit of measure (ms, % of in/correct responses), were extracted for analyses. Hydration and nutrition, acclimatisation status, load carriage, training status, and clothing were also considered as potentially influential variables. Using the time point and condition at which the peak difference in core temperature occurred between control and experimental groups, and the associated cognitive outcome, effect size was calculated using Hedge's g (42) – identifying the influence of heat strain on performance of a cognitive task, using $p \leq .05$ significance. A meaningful change in cognitive performance was determined where the 95% confidence intervals around the Hedge's g value did not cross zero. Where a meaningful change was observed, this implied that there was a statistical difference between conditions. While it is difficult to conclude whether this would transfer to a meaningful effect on cognitive performance in the field; within competitive athletic, or life-death contexts, any detrimental impact could be considered meaningful, and so statistical difference provided some assurance that this would be a reliable impact in such situations.

3. Results

Search Results

The final search produced 866 results; 751 when duplicates were removed. Of these, 671 studies were removed after title and abstract screening. Full text reviews were conducted on the remaining 80 studies, plus an additional five studies derived from grey literature (n = 85). Fifty-four studies were removed due to not having control conditions, not measuring cognitive performance when core temperature was different between conditions, or not incorporating an exercise protocol. From the remaining 31 studies, there were six incomplete datasets (43–49). However, changes in core temperature were able to be extracted from two of these studies (45,48) and so 27 studies were incorporated in the quantitative analyses of core temperature. The PRISMA diagram in Figure 1 describes the process of record selection.

Quality Analysis Assessment

Using the Cochrane Risk of Bias Tool (40), reviewers identified that despite some differences between categories, all studies returned a moderate risk of bias result. The adherence to protocol intervention and reporting of results were the two domains that were most subject to bias. Given the typical inability to blind participants to experimental conditions in thermoregulatory research, and as many of the studies included multiple time points and methods of calculation and analysis for cognitive tasks, these results are not surprising. Nevertheless, it is imperative to acknowledge such risks when analysing and interpreting the results of each study. Table 1 displays the results of the quality assessment analysis.

Study Characteristics

There were a total of 499 participants within the 31 studies (M = ~16), including 41 females in eight studies. Using available data, participant demographics were: Age: M = 24.03, SD = 3.18 years, $\dot{V}O_{2max}$: M = 52.8, SD = 5.6 $ml^{-1} \cdot kg^{-1} \cdot min$. Repeated measures designs were used in 25 studies, while five used a between-groups design (2,43,50–52), and in one, an intervention design (53). Training status was unknown in two studies (46,50) with participants either recreationally (*n* = 18) or well-trained (*n* = 11) in the remaining studies.

Acclimatisation status was unidentified in 15 studies. In 14 studies, participants were unacclimatized, and two included acclimatized participants (2,53). External loading was not manipulated in 26 studies. In the remainder, participants wore 20-kilogram backpacks (2,54), lifted 22.7-kilogram sandbags (45), carried 20% of body mass (50) or walked with a 22.7-kilogram backpack (52). Similarly, 26 studies did not manipulate food intake; one study incorporated scopolamine consumption (43), two included sports drinks (electrolytes) (47,52), and two examined carbohydrate consumption (55,56). Clothing was not identified in 12 studies; eight studies used personal protective gear, in ten, athletic clothing, and in one, long pants and shirts were worn (52). Hydration status was not manipulated in 18 studies. One study allowed ad lib consumption of fluid throughout the experimental procedures (52), while the remaining 12 studies used various forms of water provision and/or restriction to alter hydration statuses between control and experimental groups (6,15,21,24,46,49,54,57–61).

Walking protocols were used in 14 studies, while cycling and running were used in six each, and team sports in five. Eleven studies used standard environments to manipulate core temperature, five used internal methods, and two employed external mechanisms (3,58). Five studies used a combination of internal and standard mechanisms, four included external and standard methods (17,44,62,63), and four used internal and external protocols (21,49,56,59). Table 2 presents the descriptive characteristics of all studies.

Cognitive Performance

Cognitive tasks were categorised into one of the three aforementioned domains: cognitive inhibition, working memory, and cognitive flexibility (41). Cognitive inhibition was the most popular domain, being used in 24 of the 31 studies. Tasks of working memory were used in 11 different studies, while cognitive flexibility was assessed within 14 separate experimental procedures. Cognitive data was not available for comparison in six of the 31 studies (43–48). There were also three incomplete datasets (58,61,62); only the available data in these studies were analysed. Given the large range of cognitive tasks used, results between, and within studies, and tasks, were mixed.

Core Temperature Changes

Effect sizes (Hedges's *g*) were generated for each cognitive task at the time point in the study that elicited the peak difference in core temperature between the control and experimental conditions (Table 3), using the *dplyr* package in *R Studio* (version 1.3.1056). Despite attempts to contact authors, restrictions on data sharing meant that four of the 31 studies could not have their peak changes in core temperature identified (43,44,46,47). From the 27 studies where core temperature values were extracted, 18 evoked small core temperature changes (between 0 °C and 1.0 °C) (3,6,15,17,21,22,45,48–50,56,58,59,61,63–66), seven induced moderate changes (between 1.0 and 2.0 °C (52–55,57,60,62), and two produced large body temperature changes, greater than 2.0 °C (2,51).

Tables 3 and 4 provide preliminary evidence of the influence individual experimental protocols had on cognitive performance – as reflected by the effect sizes, and the respective confidence intervals around the effect sizes not encompassing zero. Categorisation by core temperature change orders studies from those that showed the smallest core temperature changes, to those with moderate to large core temperature changes between conditions. Table 3 portrays response outcomes as measured by accuracy, while Table 4 depicts reaction time outcomes. Both tables also categorise specific tasks into the separate cognitive domains (cognitive inhibition, working memory, cognitive flexibility).

4. Discussion

The initial hypothesis predicted that more complex tasks (cognitive flexibility) would show the greatest decrements in performance, compared to simpler tasks (working memory, cognitive inhibition), with elevations in core temperature. This review, however, was unable to support the hypothesis. Confounding issues included a large number of inconsistencies between research designs, methodologies, and task outcome measures. Preliminary evidence did indicate that moderate levels of core temperature change (> 1 °C) were at least required to influence cognitive performance across reaction time, motor screening, information processing, recognition, altered go/no-go, standard memory, list recall, vigilance, classic and numerical Stroop, and three-term reasoning tasks. Further, while the greatest performance decrements typically occurred when core temperatures reached ≥ 39 °C, of the outcome measures evaluated, irrespective of cognitive domain, task accuracy was more detrimentally affected compared with task response time.

In support of a recent review (27) of the Maximum Adaptability Model, in studies in which the maximum core temperatures of the examined conditions did not exceed 39 °C (23 of the 31 articles reviewed) and/or the difference in core temperature between studies was less than 1 °C (18 articles), predominantly no differences in cognitive performance were observed. Impairments were more likely to be observed when heat strain was combined with additional physiological stressors, such as prolonged bouts of exercise, extended periods of time spent at elevated core temperatures, and increased levels of dehydration. For example, of the two studies that elicited greater than 2 °C change in core temperature combined with 90-minutes of exercise, both produced observably negative changes in performance (2,51).

Cognitive Inhibition

Tasks of cognitive inhibition require a series of attentional control and inhibitory processes to override impulsive behaviours and produce the most desirable responses. Among the simplest of the three domains examined, such assessments typically include response and reaction time, vigilance, and target detection tasks (41). Within the current review, 17 distinct tasks of cognitive inhibition were included across 20 experimental designs. Of these tasks, no changes in either performance outcome was identified within any choice reaction time (15,21,49), numerical vigilance (48), dual task tracking (48), visual vigilance (54,64), time perception (60), shape recognition (58,62)¸ response time (66), perceptual processing (57), virtual environment (55), and standard go/no-go (3,17,22,57,63) tasks. A debilitating effect of heat was observed in a rapid visual information processing task (2), while a positive influence of heat was noted within a single shape and shade recognition task (62). Contradictory evidence was documented in standard vigilance (57), modified go/no-go (60), psychomotor vigilance (50), motor screening (2,51), and reaction time (2,51,58,62) tasks.

Accuracy responses were more detrimentally affected than response time outcomes in tasks of cognitive inhibition. In interventions that elicited > 1 °C, only 12% of tasks showed decrements in response time, compared with 28% for accuracy responses. whereas designs that evoked < 1 °C change resulted in only 5% of tasks showing significant effects of heat in cognitive outcomes. However, caution should be observed in dismissing tasks that have only been investigated once or where minimal physiological stress has been induced.

A detrimental effect of heat on both accuracy and response time outcomes was observed after 90-minutes of walking that provided a large core temperature change (> 2 °C), in a rapid visual information processing task, alongside an appropriately powered design (n = 40) (2). Within the same study, a negative influence of heat was also observed in motor screening and reaction time tasks for accuracy, but not response time outcomes. Using an identical experimental design (51), or an extended walking bout (58), similar results were observed for a reaction time task. These large changes in core temperature and/or extended exercise durations produce significant physiological load, and so are potentially more likely to demonstrate noticeable changes in performance in tasks of cognitive inhibition. On the contrary, in a single study (57), a negative effect on a vigilance task in response time, but not accuracy responses. However, this was in only one of seven outcomes within the study. Using a passive pre-heating protocol to elevate core temperature prior to the exercise bout, the results of this study highlight the importance of identifying the true, and combined effects that heat and exercise have on cognitive performance. Nevertheless, not all outcomes demonstrated negative effects of heat on cognitive inhibition. The following studies (50,60,62), while documenting some positive changes of heat and exercise on cognitive inhibition performance, did not induce core temperature elevations beyond 38.5 °C.

In summary, the standard reaction time task produced the most consistent performance decrements in terms of accuracy, across several experimental designs. While the go/no-go task appears to be the least influenced, this was predominantly utilised in studies that induced only small-to-moderate changes in core temperature. Consistent negative results of heat on accuracy performance were produced across multiple cognitive inhibition tasks when large changes in core temperature were combined with extended exercise bouts. Such results highlight how imperative it is to acknowledge the influence of cumulative stressors on cognitive performance, and overall stress loads experienced by participants, when designing, and analysing experiments.

Working Memory

Working memory performance is reliant on an individual's ability to hold information, and manipulate it, as is prominent in tasks requiring delayed recall and recognition, visual searches, and object and numeral spans (41). Typically, working memory tasks require an increased degree of complexity from simple inhibitory tasks. In the present analysis, 12 discrete tasks were used across eight studies. Of these tasks, only two showed any changes in accuracy, but not response time performance – a memory (57) and word list recall (52) task. No significant changes were observed for visual search (6), mathematical pairs (56), digit span (57), pattern recognition (51), match-to-sample visual search (51), serial sevens (15,59), Sternberg (6), letter-digit recognition (61), complex span (OSPAN) (59) or pattern comparison (61) tasks.

There were no significant changes in response time performance for any working memory tasks (6,51,61). The Sternberg (6), match to sample visual search (51), and pattern recognition (visual and spatial) memory (51) tasks, also documented no significant changes in accuracy responses at the examined time point. However, only one of these studies documented a large body temperature change, and extended exercise duration, resulting in absolute core temperature values exceeding 39 °C (51). While noting that these results only occur within a single study, the cumulative physiological load experienced in this design potentially indicates that the tasks used in this study are less susceptible to exercise-induced heat strain.

Accuracy remained unchanged in two serial sevens tasks (15,59), and single visual search (at both baseline and complex levels) (6), mathematical pairs (56), OSPAN (59) and digit span (57) tasks, also indicating that these tasks may be less susceptible to exercise-induced heat strain. Specifically, while the digit span task did not show any changes in accuracy performance, a memory task (involving recall of information about a previously presented map) used in the same study was shown to be negatively affected by heat. However, singular uses of the remaining three tasks prevents definitive conclusions being reached, as the experimental designs only induced small changes in core temperature (6,15,56,59).

The two tasks that identified decrements in working memory accuracy were a standard memory task (57), and a word list recall task (52). Both studies produced moderate changes in core temperature, and so further investigation of these working memory tasks is required to confirm the validity and reliability of these outcomes.

Cognitive Flexibility

Cognitive flexibility is arguably the most complex of the three domains, requiring an individual to continually alter their perspective – either spatially, interpersonally, or in response to continually altering rules (41). Tasks of cognitive flexibility typically include those of grammatical reasoning and rule switching. Within the current review, seven discrete tasks were used across ten studies. Performance in both classical, and modified versions of a trail making task (49,57,61,65) remained consistently unaffected across multiple designs. Contradictory results were identified within classical Stroop (6,52,64) and Wisconsin card sorting tests (50). Singular uses of three term reasoning (57), numerical Stroop (57) and colour multi-source interference (15) tasks prohibits any definitive conclusion being drawn about these tasks.

In the only use of the Wisconsin card sorting task (50), the accuracy of correct perseverative responses was detrimentally affected, while a beneficial effect of heat was identified for fewer perseverative errors. While this study employed a large sample size (n = 40), as noted in the original study, differences in cognitive performance between the control and experimental groups at baseline, questions the validity of these outcomes.

There were no significant changes in the response time (49,57), accuracy, or error count (57,61) outcomes, across multiple uses of both classical, and modified versions of a trail making task (65). Despite ideal experimental conditions of core temperature > 39 °C (49), long exercise duration (49,61,65), and moderate increases in core temperature (57), all studies consisted of relatively small sample sizes ($n \leq 12$) and so appropriate power may not have been reached, potentially limiting the observation of any meaningful performance changes.

Classical Stroop task results were inconsistent. In two studies, there were no changes in congruent or incongruent accuracy (6,52), or response time performance (6), when both studies incorporated a manipulation of hydration status. However, a positive effect of heat on both congruent and incongruent response times was observed in a standard heat manipulation design (64). Whereas a negative effect of heat on congruent (but not incongruent) response times (52) was identified with a two-fold greater change in core temperature, and three times as long in exercise duration. The small to moderate temperature changes across tasks of cognitive flexibility potentially prevents observation of any notable changes in performance. Given the evidence to date, further assessments of Stroop and Wisconsin card sorting tasks is warranted.

5. Limitations and Future Directions

This review is not without limitations. For instance, the relatively small sample sizes (~16 participants per study), alongside the modest number of studies (n = 27) the authors were able to retrieve data from, and the limited number of cognitive tasks and time points from which to extract discrete data points from, meant it would have been inappropriate to perform a meta-analysis or meta-regression alongside the review (67). While a meta-analysis may have produced statistically significant changes in cognitive performance, in the absence of a larger number of studies, the authors decided to avoid conducting a potentially misleading analysis through double-counting of studies, cognitive tasks, and raw data points, or reporting of a grouped effect size across multiple cognitive outcomes within any singular study (67–69). In addition, where cognitive performance is assessed during exercise interventions, often participants are asked to cease the activity, and in some instances, are moved to a thermoneutral room to perform the cognitive task. Subsequently, this can reduce both skin and core temperatures, which may affect the ability to accurately determine core temperature thresholds, when dropping during the assessment. Therefore, future studies may seek to abstain from moving participants to cooler environments during cognitive testing, as well as employing short-duration cognitive batteries, to help maintain elevated core temperatures if the exercise has to be ceased to perform the tasks. Finally, while this review focussed on the objective changes in core temperature in relation to cognitive performance changes, future research could seek to examine how such differences in cognitive assessments may correspond to subjective perceptions of exertion, and thermal strain.

6. Conclusion

The current review sought to examine the influence of exercise-induced heat strain on cognitive performance. Preliminary evidence did indicate that (1) at least moderate levels of core temperature change (> 1 °C) were required to influence cognitive performance across all three domains of cognitive performance (cognitive inhibition, working memory, cognitive flexibility), and (2) of the outcome measures evaluated, irrespective of cognitive domain, task accuracy was more detrimentally affected compared with task response time. However, of the utilised tasks, reaction time (cognitive inhibition), memory recall (working memory), and Stroop tasks (cognitive flexibility) appeared to be most likely to identify cognitive performance changes during heightened thermal strain.

A range of methodological discrepancies existed across research designs, including using multiple cognitive tasks of varying difficulties to manipulate cognitive load and experimental protocols, but there are also a range of extraneous factors which have the potential to confound the results. The present review has provided further evidence for the interplay of core temperature, physical activity, the external environment, and hydration status, on cognitive performance. Most notably, this review identified how changes in core temperature alone, are potentially not influential enough to produce consistent changes in cognitive performance, regardless of task complexity. Rather, a combination of factors is likely to heighten cognitive load beyond what core temperature alone would, and therefore, the cumulative influence of such factors – including exercise and dehydration – should be considered when analysing the effect of heat strain on cognitive performance.

The present review highlighted how experimental designs that employ short duration, intermittent protocols, commonly seen in team sports that allow recovery periods, re-hydration, and where high core temperatures are not sustained for extended periods of time, may be unlikely to provoke significant decrements in cognitive performance. However, activities of a longer duration which do not allow as frequent rehydration strategies, and which drive core temperatures beyond 39 °C, or require participants to function at an elevated core temperature for extended periods of time (> 60- minutes), may be more likely to demonstrate a negative effect on cognitive performance, and, more specifically, impair the executive network function. The continual use of small sample sizes and inadequately powered experiments within the literature potentially prevents the statistical observance of small but meaningful changes in cognitive performance. Appropriate cognitive task selection and reduction of methodological discrepancies, encouragement of larger sample sizes, and promotion of consistent assessments and definitions of cognitive tasks and domains is essential for future studies to determine the true influence of exercise-induced heat strain on cognitive performance.

7. Conflicts of Interest

The authors have no conflicts of interest to declare.

8. References

1. Zhang F, de Dear R, Hancock P. Effects of moderate thermal environments on cognitive performance: A multidisciplinary review. Appl Energy. 2019;236:760–77.

2. Radakovic SS, Maric J, Surbatovic M, Radjen S, Stefanova E, Stankovic N, et al. Effects of acclimation on cognitive performance in soldiers during exertional heat stress. Mil Med. 2007;172(2):133–6.

3. Coehoorn CJ, Stuart-Hill LA, Abimbola W, Neary JP, Krigolson OE. Firefighter neural function and decision-making following rapid heat stress. Fire Saf J. 2020 Nov 3;103240.

4. Li J, Yinsheng T, Li D, Huijuan Z, Zhaosheng R, Liyong S, et al. Simulating extreme environments: Ergonomic evaluation of Chinese pilot performance and heat stress tolerance. Work. 2015 Jul;51(2):215–22.

5. Amos D. Physiological and cognitive performance of soldiers conducting routine patrol and reconnaissance operations in the tropics. Mil Med. 2000;165(12):961–6.

6. MacLeod H, Cooper S, Bandelow S, Malcolm R, Sunderland C. Effects of heat stress and dehydration on cognitive function in elite female field hockey players. BMC Sports Sci Med Rehabil [Internet]. 2018;10(1). Available from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85061036530&doi=10.1186%2fs13102-018-0101-9&partnerID=40&md5=04c9c5577013fa16d935de3dca11b7ca

7. Buchheit M, Cholley Y, Lambert P. Psychometric and physiological responses to a preseason competitive camp in the heat with a 6-hour time difference in elite soccer players. Int J Sports Physiol Perform. 2016 Mar;11(2):176–81.

8. Coull NA, Watkins SL, Aldous JWF, Warren LK, Chrismas BCR, Dascombe B, et al. Effect of tyrosine ingestion on cognitive and physical performance utilising an intermittent soccer performance test (iSPT) in a warm environment. Eur J Appl Physiol. 2015;115(2):373–86.

9. Jiménez-Pavón D, Romeo J, Cervantes-Borunda M, Ortega FB, Ruiz JR, España-Romero V, et al. Effects of a running bout in the heat on cognitive performance. J Exerc Sci Fit. 2011 Apr;9(1):58–64.

10. Piil JF, Lundbye-Jensen J, Trangmar SJ, Nybo L. Performance in complex motor tasks deteriorates in hyperthermic humans. Temperature. 2017;4(4):420–8.

11. Piil JF, Christiansen L, Morris NB, Mikkelsen CJ, Ioannou LG, Flouris AD, et al. Direct exposure of the head to solar heat radiation impairs motor-cognitive performance. Sci Rep. 2020 Dec;10(1):7812.

12. Cian C, Barraud PA, Melin B, Raphel C. Effects of fluid ingestion on cognitive function after heat stress or exercise-induced dehydration. Int J Psychophysiol. 2001;42(3):243–51.

13. Hocking C, Silberstein RB, Lau WM, Stough C, Roberts W. Evaluation of cognitive performance in the heat by functional brain imaging and psychometric testing. Comp Biochem Physiol Part A. 2001;128(4):719–34.

14. Nunneley SA, Reader DC, Maldonado RJ. Head-temperature effects on physiology, comfort, and performance during hyperthermia. Aviat Space Environ Med. 1982;53(7):623–8.

15. Saldaris JM, Landers GJ, Lay BS. Physical and perceptual cooling: Improving cognitive function, mood disturbance and time to fatigue in the heat. Scand J Med Sci Sports. 2020 Apr;30(4):801–11.

16. Wright Beatty HE, Keillor JM, Hardcastle SG, Boulay P, Kenny GP. Preservation of cognitive performance with age during exertional heat stress under low and high air velocity. BioMed Res Int [Internet]. 2015;2015. Available from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84927126823&doi=10.1155%2f2015%2f619103&partnerID=40&md5=e1e2f38ae41a1883e04785cae3f18f24

17. Clarke ND, Duncan MJ, Smith M, Hankey J. Pre-cooling moderately enhances visual discrimination during exercise in the heat. J Sports Sci. 2017 Feb 15;35(4):355–60.

18. Liu K, Sun G, Li B, Jiang Q, Yang X, Li M, et al. The impact of passive hyperthermia on human attention networks: An fMRI study. Behav Brain Res. 2013 Apr 15;243:220–30.

19. Gaoua N, Racinais S, Grantham J, El Massioui F. Alterations in cognitive performance during passive hyperthermia are task dependent. Int J Hyperthermia. 2011;27(1):1–9.

20. Hancock PA, Vasmatzidis I. Effects of heat stress on cognitive performance: The current state of knowledge. Int J Hyperth Off J Eur Soc Hyperthermic Oncol North Am Hyperth Group. 2003 Jun;19(3):355–72.

21. Saldaris JM, Landers GJ, Lay BS, Zimmermann MR. Internal precooling decreases forehead and core temperature but does not alter choice reaction time during steady state exercise in hot, humid conditions. J Therm Biol. 2019 Apr;81:66–72.

22. Shibasaki M, Namba M, Kamijo YI, Ito T, Kakigi R, Nakata H. Effects of repetitive exercise and thermal stress on human cognitive processing. Physiol Rep [Internet]. 2019;7(4). Available from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85062167460&doi=10.14814%2fphy2.14003&partnerID=40&md5=8f0897fc41ea989d0d9db51829225b5f

23. Tomporowski PD. Effects of acute bouts of exercise on cognition. Acta Psychol (Amst). 2003 Mar 1;112(3):297–324.

24. Bandelow S, Maughan R, Shirreffs S, Ozgünen K, Kurdak S, Ersöz G, et al. The effects of exercise, heat, cooling and rehydration strategies on cognitive function in football players. Scand J Med Sci Sports. 2010;20(3):148–60.

25. Fischer M, Tamariz-Ellemann A, Gliemann L. Hyperthermia: The hotter the body, the hungrier the brain? J Physiol. 2020;598(11):2053–4.

26. Hancock PA, Warm JS. A Dynamic Model of Stress and Sustained Attention. Hum Factors. 1989 Oct 1;31(5):519–37.

27. Schmit C, Hausswirth C, Le Meur Y, Duffield R. Cognitive functioning and heat strain: Performance responses and protective strategies. Sports Med. 2017 Jul 1;47(7):1289–302.

28. Yerkes RM, Dodson JD. The relation of strength of stimulus to rapidity of habit-formation. J Comp Neurol Psychol. 1908;18(5):459–82.

29. Wittbrodt MT, Millard-Stafford M. Dehydration impairs cognitive performance: A meta-analysis. Med Sci Sports Exerc. 2018;

30. Goodman SPJ, Moreland AT, Marino FE. The effect of active hypohydration on cognitive function: A systematic review and meta-analysis. Physiol Behav. 2019 May 15;204:297–308.

31. Katz B, Airaghi K, Davy B. Does hydration status influence executive function? A systematic review. J Acad Nutr Diet. 2021 Jul;121(7):1284-1305.e1.

32. Robin N, Coudevylle GR, Hue O. Attentional processes and performance in hot humid or dry environments: Review, applied recommendation and new research directions. Mov Sport Sci. 2021;(112):41–51.

33. Donnan K, Williams EL, Morris JL, Stanger N. The effects of exercise at different temperatures on cognitive function: A systematic review. Psychol Sport Exerc. 2021 May 1;54:101908.

34. Gaoua N. Cognitive function in hot environments: A question of methodology. Scand J Med Sci Sports. 2010;20(SUPPL. 3):60–70.

35. Martin K, McLeod E, Périard J, Rattray B, Keegan R, Pyne DB. The impact of environmental stress on cognitive performance: A systematic review: Hum Factors [Internet]. 2019 Apr 19 [cited 2020 Nov 24]; Available from: http://journals.sagepub.com/doi/10.1177/0018720819839817

36. Ramsey JD. Task performance in heat: a review. Ergonomics. 1995 Jan;38(1):154–65.

37. Keighren IM. Environmental determinism. In: Int Encycl Soc Behav Sci. 2nd ed. Oxford: Elsevier; 2015. p. 720–5.

38. McCabe DP, Roediger HL, McDaniel MA, Balota DA, Hambrick DZ. The relationship between working memory capacity and executive functioning: evidence for a common executive attention construct. Neuropsychology. 2010 Mar;24(2):222–43.

39. Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. Br Med J. 2009 Jul 21;339:b2535.

40. ROB2 Development Group. Cochrane risk of bias tools [Internet]. 2019 [cited 2021 May 28]. Report No.: ROB 2. Available from: https://sites.google.com/site/riskofbiastool/welcome/rob-2-0-tool/current-version-of-rob-2

41. Diamond A. Executive Functions. Annu Rev Psychol. 2013;64:135–68.

42. Hedges LV, Vevea JL. Estimating effect size under publication bias: Small sample properties and robustness of a random effects selection model. J Educ Behav Stat. 1996 Dec 1;21(4):299–332.

43. Safer DJ. The effect of heat, cold, and work on the central actions of scopolamine. Clin Pharmacol Ther. 1969;

44. Benor D, Shvartz E. Effect of body cooling on vigilance in hot environments. Aerosp Med. 1971;42(7):727–30.

45. Gerhart HD, Fiorentini AB, Storti KL, Alman R, Bayles MP, Pesci L, et al. Psychophysiological responses in emergency medical technician students during simulated work activities in a hot environment. Int J Environ Res Public Health. 2020 May 15;17(10):E3443.

46. Ganio MS, Armstrong LE, Casa DJ, McDermott BP, Lee EC, Yamamoto LM, et al. Mild dehydration impairs cognitive performance and mood of men. Br J Nutr. 2011 Nov;106(10):1535–43.

47. Bandelow S, Maughan R, Shirreffs S, Ozgünen K, Kurdak S, Ersöz G, et al. The effects of exercise, heat, cooling and rehydration strategies on cognitive function in football players. Scand J Med Sci Sports. 2010 Oct;20 Suppl 3:148–60.

48. Watkins SL, Castle P, Mauger AR, Sculthorpe N, Fitch N, Aldous J, et al. The effect of different environmental conditions on the decision-making performance of soccer goal line officials. Res Sports Med. 2014 Oct 2;22(4):425–37.

49. Benjamin CL, Sekiguchi Y, Morrissey MC, Butler CR, Filep EM, Stearns RL, et al. The effects of hydration status and ice-water dousing on physiological and performance indices during a simulated soccer match in the heat. J Sci Med Sport. 2021 Aug 1;24(8):723–8.

50. Parker SM, Erin JR, Pryor RR, Khorana P, Suyama J, Guyette FX, et al. The effect of prolonged light intensity exercise in the heat on executive function. Wilderness Environ Med. 2013 Sep;24(3):203–10.

51. Maric J, Marjanovic M, Jovanovic D, Stojanovic F, Vukmirovic D, Jakovljevic V. Simple and complex cognitive functions under exertional heat stress. Serbian J Exp Clin Res. 2015;16(1):21–5.

52. Deming NJ, Anna JL, Colon-Bonet BM, Dinenno FA, Richards JC. Carbohydrate ingestion attenuates cognitive dysfunction following long-duration exercise in the heat in humans. J Therm Biol. 2021 Aug 1;100:103026.

53. Tamm M, Jakobson A, Havik M, Timpmann S, Burk A, Ööpik V, et al. Effects of heat acclimation on time perception. Int J Psychophysiol Off J Int Organ Psychophysiol. 2015 Mar;95(3):261–9.

54. Adams EL, Casa DJ, Huggins RA, Demartini-Nolan JK, Stearns RL, Kennedy RM, et al. Heat exposure and hypohydration exacerbate physiological strain during loading carrying. J Strength Cond Res. 2019 Mar;33(3):727–35.

55. Bailey SP, Holt C, Pfluger KC, La Budde Z, Afergan D, Stripling R, et al. Impact of prolonged exercise in the heat and carbohydrate supplementation on performance of a virtual environment task. Mil Med. 2008 Feb;173(2):187–92.

56. Clarke ND, Maclaren DPM, Reilly T, Drust B. Carbohydrate ingestion and pre-cooling improves exercise capacity following soccer-specific intermittent exercise performed in the heat. Eur J Appl Physiol. 2011 Jul;111(7):1447–55.

57. Ashworth ET, Cotter JD, Kilding AE. Impact of elevated core temperature on cognition in hot environments within a military context. Eur J Appl Physiol. 2021 Apr 1;121(4):1061–71.

58. Caldwell JN, Engelen L, van der Henst C, Patterson MJ, Taylor NJ, Engelen L, et al. The interaction of body armor, low-intensity exercise, and hot-humid conditions on physiological strain and cognitive function. Mil Med. 2011 May;176(5):488–93.

59. Mazalan NS, Landers GJ, Wallman KE, Ecker U. Head cooling prior to exercise in the heat does not improve cognitive performance. J Sports Sci Med. 2021 Mar 1;20(1):69–76.

60. Tikuisis P, Keefe AA. Heat strain at high levels does not degrade target detection and rifle marksmanship. Aviat Space Environ Med. 2005;76(10):963–9.

61. Wittbrodt MT, Millard-Stafford M, Sherman RA, Cheatham CC. Fluid replacement attenuates physiological strain resulting from mild hypohydration without impacting cognitive performance. Int J Sport Nutr Exerc Metab. 2015;25(5):439–47.

62. Caldwell JN, Patterson MJ, Taylor NAS. Exertional thermal strain, protective clothing and auxiliary cooling in dry heat: Evidence for physiological but not cognitive impairment. Eur J Appl Physiol. 2012 Oct 1;112(10):3597–606.

63. Aljaroudi AM, Kadis DS, Bhattacharya A, Strauch A, Quinn TD, Williams WJ. Effect of continuous cooling on inhibition and attention while wearing firefighter's PPE in a hot environment. J Occup Environ Hyg. 2020;17(5):243–52.

64. Donnan K, Williams EL, Stanger N. The effects of heat exposure during intermittent exercise on physical and cognitive performance among team sport athletes. Percept Mot Skills. 2021 Feb 1;128(1):439–66.

65. Edwards AM, Mann ME, Marfell-Jones MJ, Rankin DM, Noakes TD, Shillington DP. Influence of moderate dehydration on soccer performance: Physiological responses to 45 min of outdoor match-play and the immediate subsequent performance of sport-specific and mental concentration tests. Br J Sports Med. 2007;41(6):385–91.

66. Malan M, Dawson B, Goodman C, Peeling P. Effect of heat exposure on thermoregulation and hockey-specific response time in field hockey goalkeepers. J Sci Med Sport. 2010 May;13(3):371–5.

67. Senn SJ. Overstating the evidence – double counting in meta-analysis and related problems. BMC Med Res Methodol. 2009 Feb 13;9(1):10.

68. Thompson SG, Higgins JPT. How should meta-regression analyses be undertaken and interpreted? Stat Med. 2001;

69. Harrer M, Cuijpers P, Furukawa T A, Ebert D D. Doing Meta-Analysis in R: A Hands-On Guide [Internet]. Routledge: Taylor and Francis Group; 2021 [cited 2021 Oct 12]. Available from: https://bookdown.org/MathiasHarrer/Doing_Meta_Analysis_in_R/

9. Appendix

Figure Headings

Figure 1. PRISMA diagram representing the process of study screening for eligibility of qualitative review and effect size analysis.

Table Headings and Notes

Table 1. *Cochrane Risk of Bias Assessment* for *n = 31 studies*.

Note: Tick = Low Risk of Bias. Question Mark = Some Concerns of Bias. Cross = High Risk of Bias.

Table 2. *Descriptive results of all (N = 31) studies extracted.*

Note: - : unavailable data. *: Peak $\dot{V}O_2$ measure. GI: Gastrointestinal Temperature. M/F: Male/Female. RH: Relative Humidity. T_{core}: Core Temperature. Max: Maximal effort. Min: Minutes. Sec: Seconds. MHR: Maximal Heart Rate. WI: Water Immersion. TTF: Time to fatigue. (C): Control condition. (E): Experimental Condition. $\dot{V}o_{2max}$: Maximal Oxygen Consumption. $\dot{V}o_{2peak}$: Peak Oxygen Consumption. Peak T_{core} recorded at time of cognitive measurement. Conditions and studies in bold are those used within the quantitative analyses of effect sizes and experimental groups used for these analyses. Studies in italics indicate there is missing cognitive data.

Table 3. *Cognitive Task Results and Core Temperature Changes for Accuracy Response (displayed in ascending core temperature difference, for each cognitive domain).*

Notes: For significant results, the influence of heat column indicates direction (negative is detrimental).

Notes. '-': No available response. T_{core}: Core Temperature. Conditions at which peak changes in T_{core} occurred (between control and experimental) match the bolded conditions in Table 2. Hedges' g Effect Sizes: For incorrect (*) responses: Negative (-) indicates a performance benefit in experimental condition. For all other responses (i.e.: percentage or number correct), a negative (-) indicates performance decline in experimental condition (less correct responses).

Table 4. *Cognitive Task Results and Core Temperature Changes for Response Times (displayed in ascending core temperature difference, for each cognitive domain).*

Notes: For significant results, the influence of heat column indicates direction (negative is detrimental).

Notes. '-': No available response. T_{core}: Core Temperature. Conditions at which peak changes in T_{core} occurred (between control and experimental) match the bolded conditions in Table 2. Hedges' g Effect Sizes: Negative (-) indicates a performance benefit in experimental condition. For significant results, the direction of the effect of heat conditions is dictated by the 'effect of heat' column.

10. Supplementary Materials

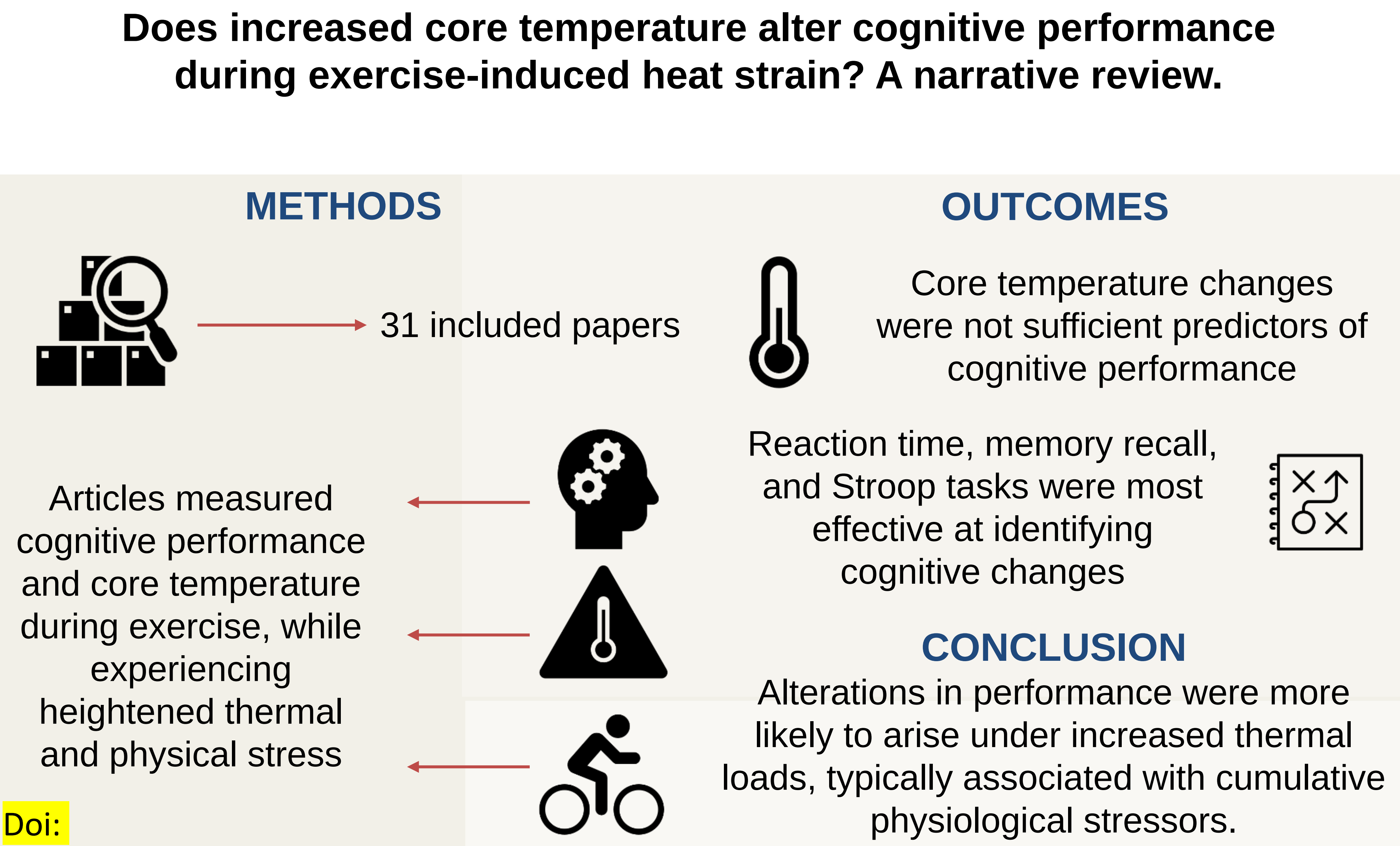
Search terms are available as supplementary materials in the Figshare repository.

Doi:

https://doi.org/10.6084/m9.figshare.22010063

URL:

https://figshare.com/articles/journal_contribution/Supplementary_Materials_Search_Terms_docx/22010063


Does increased core temperature alter cognitive performance during exercise-induced heat strain? A narrative review.
METHODS
31 included papers
Articles measured cognitive performance and core temperature during exercise, while experiencing heightened thermal and physical stress
Doi:
OUTCOMES
Core temperature changes were not sufficient predictors of cognitive performance
Reaction time, memory recall, and Stroop tasks were most effective at identifying cognitive changes
CONCLUSION
Alterations in performance were more likely to arise under increased thermal loads, typically associated with cumulative physiological stressors.

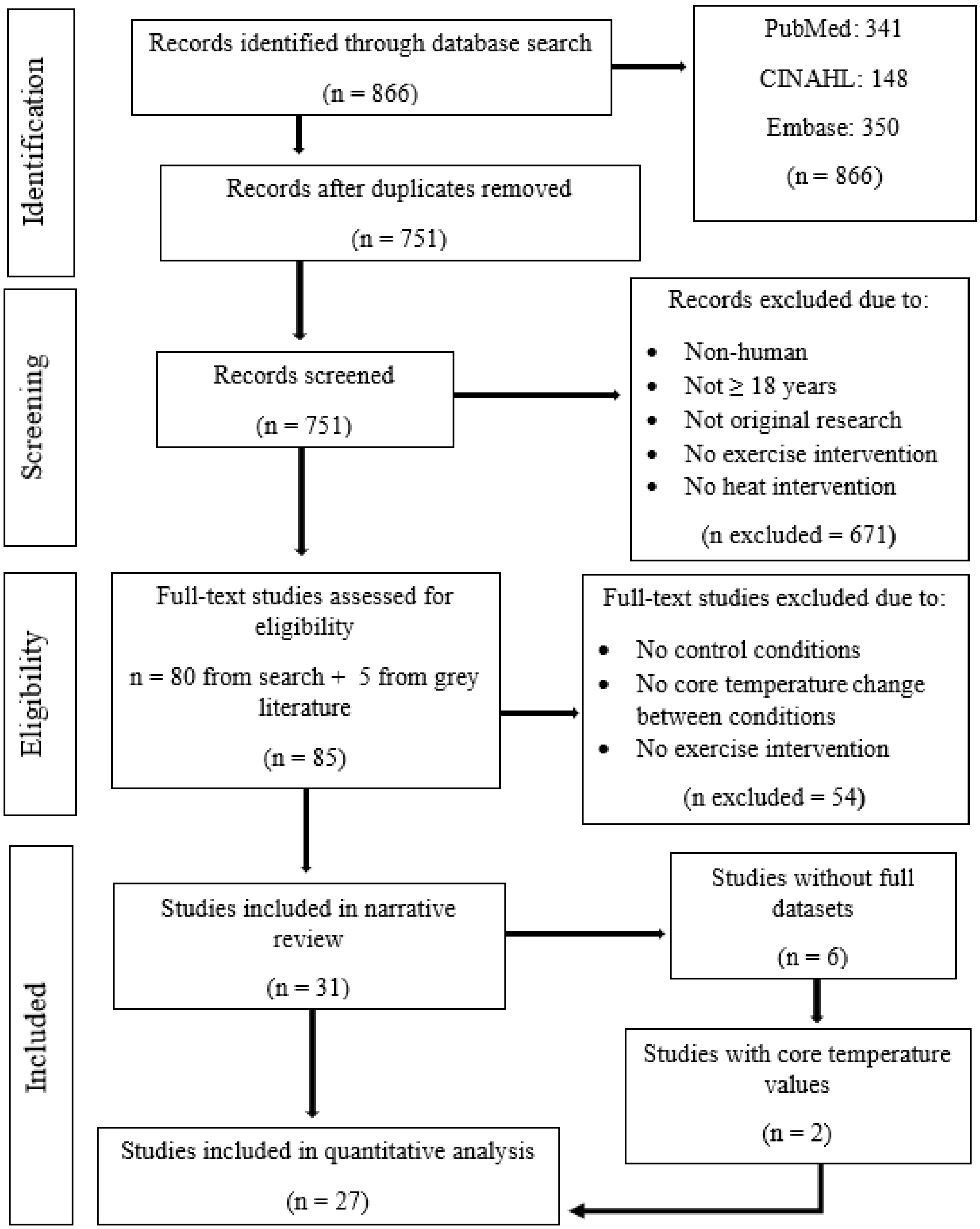


Figure 1. PRISMA diagram representing the process of study screening for eligibility of qualitative review and effect size analysis.

Table 1.

Between-Groups Studies						
Reference	**Domain 1:** Randomisation process	**Domain 2:** Deviations from intended interventions	**Domain 3:** Missing outcome data	**Domain 4:** Measurement of outcome	**Domain 5:** Selection of reported result	**Overall risk of bias**
Deming, 2021	?	?	?	✗	?	?
Maric, 2014	✓	?	✓	✓	?	?
Parker, 2013	?	?	✓	✓	?	?
Radakovic, 2007	?	?	✓	✓	?	?
Safer, 1969	?	✗	?	?	?	?

Within-Groups Studies							
Reference	**Domain 1:** Randomisation process	**Domain S:** Period & carryover effects	**Domain 2:** Deviations from intended interventions	**Domain 3:** Missing outcome data	**Domain 4:** Measurement of outcome	**Domain 5:** Selection of reported result	**Overall risk of bias**
Adams, 2019	✗	✓	✗	✓	?	✗	?
Aljaroudi, 2020	✓	?	?	✓	?	✗	?
Ashworth, 2020	✓	✓	?	✓	?	?	?
Bailey, 2008	✓	?	?	✓	✓	?	?
Bandelow, 2010	✗	✓	?	✗	?	✗	?
Benjamin, 2021	?	?	✗	✗	✗	✗	?
Benor, 1971	?	?	✗	✗	?	✗	?
Caldwell, 2011	✗	?	✗	✗	?	✗	?
Caldwell, 2012	✗	✓	✗	?	?	✗	?
Clarke, 2011	?	?	?	✓	?	✗	?
Clarke, 2017	?	?	✗	✓	?	✗	?
Coehoorn, 2020	?	?	✗	✓	?	✗	?
Donnan, 2021 (b)	✓	✓	?	✓	?	?	?
Edwards, 2007	?	✓	✗	?	?	?	?
Ganio, 2011	✓	✓	?	✗	✓	✗	?
Gerhart, 2020	✗	✓	?	?	?	✗	?
Macleod, 2018	✓	✓	✗	✗	?	✗	?
Malan, 2010	?	?	?	✓	?	?	?
Mazalan, 2022	✗	✗	?	✗	?	?	?
Saldaris, 2019	?	✓	?	?	?	?	?
Saldaris, 2020	?	?	?	✓	?	?	?
Shibasaki, 2019	?	✓	?	✓	?	✗	?
Tamm, 2015	✗	✓	✗	✓	✗	✗	?
Tikuisis, 2005	✗	✓	?	✓	?	✗	?
Watkins, 2014	?	✓	✗	✗	?	?	?
Wittbrodt, 2015	?	✓	?	✓	?	?	?

Cochrane Risk of Bias Assessment for *n = 31 studies*.

Note: Tick = Low Risk of Bias. Question Mark = Some Concerns of Bias. Cross = High Risk of Bias

Table 2.

Descriptive results of all (N = 31) studies extracted.

Reference	N (M/F)	Age *M* (SD)	$\dot{V}O_{2max}$ *M* (SD)	Groups	T_{core} Measure	Peak T_{core} (°C)	Peak T_{core} (°C) Change (Time)	Exercise Protocol	Environment °C(% RH)
Adams, 2019	12 (12/0)	*20* (2)	*57* (6)	**Euhydrated Temperate (C)** Euhydrated Hot Hypohydrated Temperate **Hypohydrated Hot (E)**	Rectal	37.86 38.25 38.22 39.32	1.46 (90 min)	90 min walk @ 50% $\dot{V}O_{2max}$	**TEMP**: *18.0*(50) **HOT**: *34.0*(45)
Aljaroudi, 2020	12 (12/0)	*24* (3.2)	*56.3* (7.4)	**Cooling (C)** **No Cooling (E)**	Rectal	37.80 38.30	0.50 (40 min)	40 min running @ 40% $\dot{V}O_{2max}$	*30*(70)
Ashworth, 2020	8 (3/5)	*28.13* (4.82)	-	**Control (C)** Menthol **Hot (E)**	Rectal	37.61 38.64 38.68	1.08 (15 min)	30 min steady state walking	**CONT:** 36(75), 33 °C WI **HOT:** *40*(75), 33 °C WI
Bailey, 2008	10 (10/0)	*23* (1)	*49.3* (1.4)	**Temperate Placebo (C)** Temperate CHO Hot Placebo **Hot CHO (E)**	GI	37.91 37.95 38.52 38.59	1.04 (> 101 min)	Cycling @ 80% $\dot{V}O_{2max}$ until fatigue (between 101 & 169 min)	**TEMP:** *22*(50) **HOT:** *35*(70)
Bandelow, 2010	20 (20/0)	*20.2* (2)	-	Match 1 – Ad lib Match 2 – Hydration Match 3 – Cooling	GI	- - -	-	90 min football game	**1:** *34.3*(64) **2:** *34.4*(65) **3:** *33.8*(62)
Benjamin, 2021	12 (12/0)	*20* (1)	*53.9* (7.3)	Euhydrated (No dousing) **Euhydrated (Dousing) (C)** **Hypohydrated (No dousing) (E)** Hypohydrated (Dousing)	Rectal	38.47 38.36 39.28 39.01	0.92 (75 min)	5 x 15 min treadmill run	*34.7*(46)
Benor, 1971	7 (7/0)	-	-	Temperature Only (x5) Cooling Garment (x5)	GI	- -	-	120 min continuous walking	**TEMP + COOLING:** *30, 35, 40, 45, 50*
Caldwell, 2011	9 (9/0)	*27.3* (5.43)	-	**Control (C)** Torso Armour **Full Armour (E)**	Tympanic	37.85 38.00 38.27	0.43 (150 min)	150 min steady state walking at varied intensity	*36*(60)
Caldwell, 2012	8 (8/0)	*27.1* (6.2)	-	**Control (C)** **Experimental (E)** Auxiliary Cooling	Tympanic and Rectal	36.92 38.36 37.28	1.43 (75 min)	8 x 13 min cycling @ ~30W, 2 min rest bouts	**CONT:** *20*(30) **HOT:** *48*(20)
Clarke, 2011	12 (12/0)	*25* (1)	*61.3* (1.4)	**Pre-Cooling Placebo (C)** Pre-Cooling CHO **Heat Placebo (E)** Heat CHO	GI	38.96 38.63 39.06 39.05	0.53 (15 min)	2x 45min walk, jog, sprint intervals	*30.5*(0.2)

Clarke, 2017	8 (8/0)	*28* (6)	*53* (6)	**Pre-Cooling (C)** **No cooling (E)**	Rectal	37.14 37.86	0.71 (30 min)	2 x 45min steady state running	*32.4*(6.4)
Coehoorn, 2020	15 (15/0)	*32.7* (12.2)	*51.3* (6.7)	**No Gear (C)** **Gear (E)**	GI	38.45 39.10	0.65 (> 50 min)	120 min graded intensity walking	*25-56*
Deming, 2021	24 (18/6)	*29* (3)	*51.8* (1.8)	**Normothermic Water (C)** Heat Water Heat Electrolytes **Heat Electrolytes + CHO (E)**	GI	37.66 38.73 38.56 38.79	1.13 (120 min)	120 min walking @ 4.8km/hr, 7% grade	*21* *33*(10)
Donnan, 2021 (b)	12 (12/0)	*21.4* (3.3)	*53*	**Control (C)** **Heat (E)**	GI	37.91 38.39	0.48 (40 min)	2x 20 x 2 min cycle: 5 sec max, 105 sec ~35% $\dot{V}O_{2max}$, 10 sec rest	**CONT:** *18.0*(51.9) **HEAT:** *31.6*(49.3)
Edwards, 2007	11 (11/0)	*24.4* (3)	*50.91* (2)	**Fluid Intake (C)** **No Fluid (E)** Mouth Rinse	GI	38.67 39.01 38.91	0.43 (95 min)	45 min cycle, 45 min team game	*24-25*(47-55)
Gerhart, 2020	10 (8/2)	*24* (2.5)	*49.7* (15.8)	**Thermoneutral (C)** **Heat (E)**	GI	37.92 38.02	0.10 (30 min)	2x 10 min walk @ 70-75% MHR, w/ 2x 15 22.7kg lifts	**THER:** *25*(40) **HEAT:** *37.8*(60)
Ganio, 2011	26 (26/0)	*20* (0.3)	-	Exercise + Diuretic Exercise + Placebo Euhydration + Placebo	GI	- - -	-	3 x40 min walking bouts	*27.7*(42)
Macleod, 2018	8 (0/8)	*22* (3)	*53.4* (2.2)	**Thermoneutral Fluid (C)** Thermoneutral No Fluid **Hot Fluid (E)** Hot No Fluid	Rectal	38.01 38.32 38.53 38.51	0.52 (50 min)	2 x 25 min running bouts	**THER:** *16*(53) **HOT:** *33*(59)
Malan, 2010	4 (2/2)	*22* (3)	-	**Cool (C)** **Hot (E)**	GI	37.51 37.76	0.25 (70 min)	Mimic goal keeper. 2x 35 min, 10 min rest	**COOL:** *20*(40) **HOT:** *35*(40)
Maric, 2014	40 (40/0)	*20* (0.9)	*53.4* (8.28)	**Hot (E)** **Control (C)**	Tympanic	39.50 36.78	2.72 (90 min)	90 min walking @ 5.5km/hr	**HOT:** *40*, 39°C WBGT **CON:** *20*, 16°C WBGT
Mazalan, 2022	10 (10/0)	*26.1* (1.9)	*53.9** (4.3)	**Head Cooling (HC) (E)** **Head Cooling + Ice Ingestion (C)** Room Temp Water Ingestion	GI	39.57 39.13 39.54	0.46 (60 min)	2x 30 min running bouts @ 70% of $\dot{V}O_{2peak}$	*35*(70)
Parker, 2013	40 (24/16)	*27.75*	-	**Temperate (C)** **Hot (E)**	GI	37.7 38.2	0.50 (90 min)	90 min walk @ 40-45% $\dot{V}O_{2max}$	**TEMP:** *22-24* **HOT:** *35-38*
Radakovic, 2007	40 (40/0)	*20.1* (0.9)	*58.17* (7.2)	**Unacclimated Cold (C)** **Unacclimated Hot (E)** Passively Acclimated Hot Actively Acclimated Hot	Tympanic	37.80 39.40 39.20 38.59	2.61 (90 min)	90 min walking @ 5.5km/hr	**COLD:** *20*, 16°C WBGT **HOT:** *40*, 29°C WBGT

Safer, 1969	48 (48/0)	-	-	Cold Drug + Work Cold Drug Cold Work Thermoneutral Drug + Work Thermoneutral Drug Thermoneutral Work Moderate Drug + Work Moderate Drug Moderate Work Hot Drug + Work Hot Drug Hot Work Severe Drug Severe Temp Only	-	- - - - - - - - - - - - - -	-	10 min walk per half hour for 6 hours	**COLD:** *4.44*(40) **THER:** *21.11*(40) **MOD:** *29.44*(40) **HOT:** *35*(40) **SEVERE:** *40.56*(40)
Saldaris, 2019	10 (10/0)	*23.1* (2.4)	*48.5* (3.6)	**ICE (C)** **Water (E)**	GI	37.73 37.93	0.33 (15 min)	60 min cycling @ 55% of $\dot{V}O_{2peak}$	*35*(50.2)
Saldaris, 2020	12 (12/0)	*25.3* (4.2)	*61.3** (4.3)	**Crushed Ice + Menth (C)** Water + Menthol **Water (E)**	GI	38.17 38.38 38.37	0.20 (30 min)	3x 30 min run @ 65% $\dot{V}O_{2peak}$ TTF run @ 100%	*35.3*(59.2)
Shibasaki, 2019	15 (15/0)	*20.8* (0.9)	-	**Temperate (C)** **Hot (E)**	Tympanic	37.19 37.86	0.67 (60 min)	4x 15min cycling bouts @ 67% $\dot{V}O_{2max}$	**TEMP:** *20*(30-40) **HOT:** *35*(30-40)
Tamm, 2015	20 (20/0)	*24.9* (3.7)	*53.8* (7.1)	**Thermoneutral (C)** **Heat, Pre-HA (E)** Heat, Post HA	Rectal	38.20 39.70 39.70	1.50 (90 min)	Walking @ 60% $\dot{V}O_{2max}$ until fatigue (between 85 and 158 min)	**THER:** *22*(35) **HEAT:** *42*(18)
Tikuisis, 2005	11 (9/2)	*28.9* (6)	-	**Control (C)** Heat Hydration **Heat Dehydration (E)**	Rectal	37.35 38.41 38.47	1.12 (180 min)	30 min walking bouts for max 240 min	**CONT:** *22* **HOT:** *28-30* (42 °C water perfused)
Watkins, 2014	13 (13/0)	*19.6* (3)	-	**Cold (C)** Thermoneutral **Heat (E)**	Rectal	37.15 37.16 37.19	0.36 (90 min)	2x 45 min football simulation	**COLD:** *-5*(50) **THER:** *18*(50) **HOT:** *30*(50)
Wittbrodt, 2015	12 (12/0)	*22.2* (2.4)	*42.8* (4.8)	**Fluid Replacement (C)** **No Fluid (E)** Ad Libitum	Rectal	37.76 38.22 37.86	0.46 (50 min)	50 min cycling @ 60% of $\dot{V}O_{2peak}$	32 °C, 65% RH

Note: - : unavailable data. *: Peak $\dot{V}O_2$ measure. GI: Gastrointestinal Temperature. M/F: Male/Female. RH: Relative Humidity. T_{core}: Core Temperature. Max: Maximal effort. Min: Minutes. Sec: Seconds. MHR: Maximal Heart Rate. WI: Water Immersion. TTF: Time to fatigue. (C): Control condition. (E): Experimental Condition. $\dot{V}o_{2max}$: Maximal Oxygen Consumption. $\dot{V}o_{2peak}$: Peak Oxygen Consumption. Peak T_{core} recorded at time of cognitive measurement. Conditions and studies in bold are those used within the quantitative analyses of effect sizes and experimental groups used for these analyses. Studies in italics indicate there is missing cognitive data.

Table 3.

Cognitive Task Results and Core Temperature Changes for Accuracy Responses (displayed in ascending core temperature difference, for each cognitive domain).

Notes: For significant results, the influence of heat column indicates direction (negative is detrimental).

Reference	Peak T_{core} Difference (°C)	Time Point	Cognitive Task	Performance Measure	Unit of Measure	Influence of Heat	Hedges' *g*	Lower CI	Upper CI
				COGNITIVE INHIBITION					
Saldaris, 2020	0.20	30	Choice Reaction Time	Accuracy	Percentage Correct		0.25	-0.55	1.05
Watkins, 2014	0.36	90	Numerical Vigilance	Targets Hit	Number Correct		-	-	-
				Missed Targets	*Number Incorrect		-	-	-
				False Targets	*Number Incorrect		-	-	-
			Dual Task Tracking	Accuracy	Percentage Correct		-	-	-
				Missed Targets	*Number Incorrect		-	-	-
				False Targets	*Number Incorrect		-	-	-
Caldwell, 2011	0.43	150	**Reaction Time**	**Accuracy**	**Number Correct**	**Negative**	**-1.70**	**-2.82**	**-0.58**
Donnan, 2021 (b)	0.48	40	Visual Vigilance	Accuracy	Percentage Correct		-0.31	-1.12	0.49
Aljaroudi, 2020	0.50	40	Go/No-Go	Accuracy	*Number Incorrect		0.13	-0.67	0.93
Parker, 2013	0.50	90	Psychomotor Vigilance Test	Minor Attention Lapse	*Number Incorrect		-0.3	-0.93	0.32
				False Starts	*Number Incorrect		-0.27	-0.89	0.35
Coehoorn, 2020	0.65	> 50	Go/No-Go	Accuracy	*Number Incorrect		3.83	2.57	5.09
Shibasaki, 2019	0.67	60	Go/No-Go	Accuracy	Percentage Correct		0.01	-0.71	0.72
Clarke, 2017	0.71	30	Go/No-Go	Accuracy	Percentage Correct		0.2	-0.78	1.19
Bailey, 2008	1.04	> 101	Virtual Environment	Kills	Number Correct		0.59	-0.31	1.49
				Failures	*Number Incorrect		0	-0.88	0.88
Ashworth, 2020	1.08	15	Go/No-Go	Accuracy	Percentage Correct		-0.19	-1.17	0.8
			Perceptual Processing	Accuracy	Percentage Correct		-0.84	-1.86	0.21
			Vigilance	Maximum Span	Levels		-0.55	-1.55	0.46

				Digit Span 1st Error	Percentage Correct		-0.32	-1.3	0.67
Tikuisis, 2005	1.12	180	**Friendly-Foe Target Detection & Marksmanship**	**Foe Identification (Go)**	**Percentage Correct**	**Positive**	**0.95**	**0.06**	**1.84**
				Friendly Identification (No-Go)	**Percentage Correct**	**Negative**	**-1.33**	**-2.27**	**-0.39**
Caldwell, 2012	1.43	75	Shape Recognition	Accuracy	Percentage Correct		0.60	-0.41	1.6
			Shape + Shade Recognition	**Accuracy**	**Percentage Correct**	**Positive**	**2.37**	**1.01**	**3.73**
			Reaction Time	**Accuracy**	**Percentage Correct**	**Positive**	**2.49**	**1.09**	**3.88**
Tamm, 2015	1.50	90	Time Perception	Slope	-		-0.29	-0.92	0.33
				Intercept	-		0	-0.62	0.62
Radakovic, 2007	2.61	90	**Motor Screening**	**Number of Errors**	***Number Incorrect**	**Negative**	**1.5**	**0.49**	**2.52**
			Reaction Time	**Correct Responses**	**Percentage Correct**	**Negative**	**-2.25**	**-3.42**	**-1.08**
			Rapid Visual Information Processing	**Correct Responses**	**Percentage Correct**	**Negative**	**-1.00**	**-1.94**	**-0.06**
Maric, 2014	2.72	90	Motor Screening	Accuracy	Number Correct		0.10	-0.52	0.72
			Reaction Time	**Accuracy**	**Percentage Correct**	**Negative**	**-0.89**	**-1.54**	**-0.23**
WORKING MEMORY									
Saldaris, 2020	0.20	30	Serial Sevens	Response Rate	Count		0.17	-0.63	0.98
				Accuracy	Percentage Correct		0.08	-0.72	0.88
Mazalan, 2022 (56)	0.46	60	Complex Span Task (OSPAN)	Accuracy	Number Correct		-0.62	-1.53	0.28
			Serial Sevens Task	Accuracy	Number Correct		-0.43	-1.32	0.46
Macleod, 2018	0.52	50	Sternberg 1 Item	Accuracy	Percentage Correct		0.17	-0.81	1.15
			Sternberg 3 Item	Accuracy	Percentage Correct		0	-0.98	0.98
			Sternberg 5 Item	Accuracy	Percentage Correct		-0.21	-1.19	0.78
			Visual Search Baseline	Accuracy	Percentage Correct		0	0	0
			Visual Search Complex	Accuracy	Percentage Correct		0	-0.98	0.98
Clarke, 2011	0.53	15	Mathematical Pairs	Accuracy	Percentage Correct		-0.65	-1.48	0.17
Ashworth, 2020	1.08	15	**Memory**	**Accuracy**	**Number Correct**	**Negative**	**-1.55**	**-2.71**	**-0.39**
			Digit Span	Maximum Span	Levels		-0.55	-1.55	0.46

				Digit Span 1st Error	Percentage Correct		-0.32	-1.3	0.67
Deming, 2021	1.13	120	**Word List Recall**	**Accuracy**	**Number Correct**	**Negative**	**-1.27**	**-2.21**	**-0.34**
Maric, 2014	2.72	90	Matching to Sample Visual Search	Accuracy	Percentage Correct		-0.55	-1.18	0.09
			Pattern Recognition memory (Spatial)	Accuracy	Percentage Correct		-0.4	-1.03	0.23
			Pattern Recognition memory (Visual)	Accuracy	Percentage Correct		-0.35	-0.97	0.28
				COGNITIVE FLEXIBILITY					
Gerhart, 2020	0.10	30	Classical Stroop	Word Correct Responses	Number Correct		-	-	-
				Colour Correct Responses	Number Correct		-	-	-
Saldaris, 2020	0.20	30	Colour Multi-Source Interference	Accuracy	Percentage Correct		-0.07	-0.87	0.73
Edwards, 2007	0.43	95	Modified Trail Making	Digits per minute	Number Correct		-0.27	-1.12	0.57
Wittbrodt, 2015	0.46	50	Trail Making	Accuracy	Percentage Correct		-0.18	-0.99	0.62
Donnan, 2021 (b)	0.48	40	Classical Stroop (Incongruent)	Accuracy	Percentage Correct		-0.30	-1.10	0.51
			Classical Stroop (Congruent)	Accuracy	Percentage Correct		-0.43	-1.24	0.38
Parker, 2013	0.50	90	**Wisconsin Card Sorting Test**	**Perseverative Response**	**Number Correct**	**Negative**	**-0.88**	**-1.53**	**-0.23**
				Conceptual Response	Number Correct		0.44	-0.19	1.07
				Perseverative Error	***Number Incorrect**	**Positive**	**-1.01**	**-1.67**	**-0.35**
				Non-Perseverative Error	*Number Incorrect		0.13	-0.49	0.75
Macleod, 2018	0.52	50	Classical Stroop (Incongruent)	Accuracy	Percentage Correct		0.31	-0.67	1.3
			Classical Stroop (Congruent)	Accuracy	Percentage Correct		0	-0.98	0.98
Ashworth, 2020	1.08	15	Trail Making	Trail Errors	*Number Incorrect		0.46	-0.53	1.46
			Numerical Stroop	**Accuracy**	**Percentage Correct**	**Negative**	**-2.07**	**-3.36**	**-0.79**
			Three-Term Reasoning	**Accuracy**	**Percentage Correct**	**Positive**	**1.8**	**0.58**	**3.01**

Notes. '-': No available response. T_{core}: Core Temperature. Conditions at which peak changes in T_{core} occurred (between control and experimental) match the bolded conditions in Table 2. Hedges' *g* Effect Sizes: For incorrect (*) responses: Negative (-) indicates a performance benefit in experimental condition. For all other responses (i.e.: percentage or number correct), a negative (-) indicates performance decline in experimental condition (less correct responses).

Table 4.

Cognitive Task Results and Core Temperature Changes for Response Times (displayed in ascending core temperature difference, for each cognitive domain).

Notes: For significant results, the influence of heat column indicates direction (negative is detrimental).

Reference	Peak T_{core} Difference (°C)	Time Point	Cognitive Task	Performance Measure	Unit of Measure	Influence of Heat	Hedges' *g*	Lower CI	Upper CI
				COGNITIVE INHIBITION					
Saldaris, 2020	0.20	30	Choice Reaction Time	Latency	Milliseconds		0.16	-0.64	0.96
Malan, 2010	0.25	70	Response Time Test	Response Time	Milliseconds		0.70	-0.77	2.16
Saldaris-Zimmerman, 2019	0.33	15	Choice Reaction Time	Reaction Time	Milliseconds		-0.10	-0.98	0.78
				Movement Time	Milliseconds		0	-0.88	0.88
Caldwell, 2011	0.43	150	Shape Recognition	Response Time	Milliseconds		0.79	-0.18	1.76
Donnan, 2021 (b)	0.48	40	Visual Vigilance	Reaction Time	Milliseconds		-0.09	-0.89	0.79
Aljaroudi, 2020	0.50	40	Go/No-Go	Reaction Time (Go)	Milliseconds		0.08	-0.72	0.88
				Reaction Time (No-Go)	Milliseconds		0.20	-0.60	1.01
Parker, 2013	0.50	90	**Psychomotor Vigilance Test**	**Mean Reaction Time**	**Milliseconds**	**Positive**	**-4.92**	**-6.21**	**-3.61**
Shibasaki, 2019	0.67	60	Go/No-Go	Reaction Time	Milliseconds		0.02	-0.70	0.73
Clarke, 2017	0.71	30	Go/No-Go	Response Time	Milliseconds		-0.11	-1.09	0.87
Benjamin, 2021	0.92	75	Choice Reaction Time	Reaction Time	Milliseconds		0	-0.80	0.80
Ashworth, 2020	1.08	15	Go/No-Go	Cued Reaction Time	Milliseconds		-0.22	-1.20	0.76
				Un-cued Reaction Time	Milliseconds		-0.22	-1.20	0.77
			Perceptual Processing	Global Reaction Time	Milliseconds		-0.33	-1.32	0.66
				Local Reaction Time	Milliseconds		-0.01	-0.99	0.97
				None, Reaction Time	Milliseconds		-0.42	-1.41	0.58
			Vigilance	**False Starts**	**Milliseconds**	**Negative**	**1.12**	**0.04**	**2.19**
				Correct Reaction Time	Milliseconds		0.55	-0.45	1.55

Tikuisis, 2005	1.12	180	Friendly-Foe Target Detection & Marksmanship	Foe Detection (Go)	Milliseconds		-0.52	-1.37	0.33
				Friendly Detection (No-Go)	Milliseconds		-0.36	-1.2	0.48
Adams, 2019	1.46	90	Visual Vigilance	Reaction Time	Milliseconds		0	-0.80	0.80
Radakovic, 2007	2.61	90	Motor Screening	Latency	Milliseconds		0.82	-0.1	1.74
			Reaction Time	Reaction Time	Milliseconds		0.18	-0.7	1.06
				Movement Time	Milliseconds		0.23	-0.65	1.11
			Rapid Visual Information Processing	**Latency**	**Milliseconds**	**Negative**	**0.63**	**0.27**	**1.53**
Maric, 2014	2.72	90	Motor Screening	Latency	Milliseconds		0	-0.62	0.62
			Reaction Time	Reaction Time	Milliseconds		0.17	-0.45	0.79
				Movement Time	Milliseconds		-0.17	-0.79	0.45
				WORKING MEMORY					
Wittbrodt, 2015	0.46	50	Pattern Comparison	Reaction Time	Milliseconds		0.33	-0.47	1.14
			Letter-Digit Recognition	Reaction Time	Milliseconds		0.21	-0.59	1.01
Macleod, 2018	0.52	50	Sternberg 1 Item	Response Time	Milliseconds		-0.19	-1.17	0.79
			Sternberg 3 Item	Response Time	Milliseconds		-0.65	-1.66	0.37
			Sternberg 5 Item	Response Time	Milliseconds		-0.09	-1.07	0.89
Maric, 2014	2.72	90	Matching to Sample Visual Search	Latency	Milliseconds		0.22	-0.41	0.84
			Pattern Recognition memory (Spatial)	Latency	Milliseconds		0.41	-0.22	1.03
			Pattern Recognition memory (Visual)	Latency	Milliseconds		0.16	-0.46	0.78
				COGNITIVE FLEXIBILITY					
Saldaris, 2020	0.20	30	Colour Multi-Source Interference	Latency	Milliseconds		0.05	-0.75	0.85
Donnan, 2021 (b)	0.48	40	**Classical Stroop (Incongruent)**	**Reaction Time**	**Milliseconds**	**Positive**	**-0.35**	**-1.15**	**-0.23**
			Classical Stroop (Congruent)	**Reaction Time**	**Milliseconds**	**Positive**	**-0.97**	**-1.82**	**-0.11**
Macleod, 2018	0.52	50	Classical Stroop (Incongruent)	Response Time	Milliseconds		-0.01	-0.99	0.97
			Classical Stroop (Congruent)	Response Time	Milliseconds		0.07	-0.91	1.05
Benjamin, 2021	0.92	75	Trail Making A	Time to Completion	Seconds		-0.25	-1.05	0.56

			Trail Making B	Time to Completion	Seconds		0.12	-0.69	0.92
Ashworth, 2020	1.08	15	Trail Making A	Response Time	Minutes		0	-0.98	0.98
			Trail Making B	Response Time	Minutes		0	-0.98	0.98
Deming, 2021	1.13	120	Classical Stroop (Incongruent)	Reaction Time	Milliseconds		0.78	-0.1	1.66
			Classical Stroop (Congruent)	**Reaction Time**	**Milliseconds**	**Negative**	**1.08**	**0.17**	**1.99**

Notes. '-': No available response. T_{core}: Core Temperature. Conditions at which peak changes in T_{core} occurred (between control and experimental) match the bolded conditions in Table 2. Hedges' g Effect Sizes: Negative (-) indicates a performance benefit in experimental condition. For significant results, the direction of the effect of heat conditions is dictated by the 'effect of heat' column.