The effects of exercise at different temperatures on cognitive function: A systematic review

Abstract

To date, no review has focused specifically on the potential modulating role of environmental temperature on the effects of exercise on cognitive function. Despite this, a range of occupations and performance contexts exist (e.g., military personnel, emergency services, sport) where the maintenance of cognitive function in environmentally challenging environments is crucial. Therefore, this systematic review aimed to evaluate the experimental research investigating how manipulating environmental temperature influenced the effects of acute bouts exercise on cognitive functioning from pre- to post- exercise, or during exercise. Studies to be included were assessed by two authors reviewing title, abstract, and then full-text. From the searches conducted, twenty articles were identified which met the inclusion criteria. For the purpose of this review, exercise involved in each study was categorised into low, moderate, and vigorous dosages (dependent on intensity and duration). The results indicate that moderate dosages of exercise help stimulate improved cognitive performance from pre-to-post exercise in temperate conditions, where cold exposure appears to blunt these effects. In addition, hot environments led to cognitive decrements during and post exercise which were often identified in studies that implemented prolonged moderate or vigorous exercise protocols. Therefore, suggesting a combination of heightened physiological strain from increased dose of exercise, alongside heat exposure, can be detrimental to optimal cognitive functioning, whereby executive functioning tasks appeared to be most affected. The findings from this systematic review highlight the potential modulating role of environmental temperature on the effects of exercise on cognitive function. Thus, highlighting the importance of considering the role of environmental temperature for individuals either exercising to elicit desired cognitive benefits or for those involved in physically demanding occupations or performance domains.

Keywords: cold, cognitive function, environmental temperature, exercise, hot

The effects of exercise at different temperatures on cognition: A systematic review

In occupations and performance contexts that have simultaneous physical and cognitive demands such as those undertaken by military personnel, emergency services (Perry, Sheik-Nainer, Segall, Ruigi & Kaber, 2008), and elite sport performers (Meeusen, Watson, & Dvorak, 2006), the sustainment of optimal cognitive functioning during (or immediately following) physical exertion that may also be undertaken in varying environmental temperatures are fundamental for successful performance. Cognition is a term that refers to a range of mental processes, for example, learning, attention, decision making, memory, and reasoning (Fisher, Chacon, & Chaffee, 2019), and is sensitive to changes in physical demand (Hogervorst, Riedel, Jeukendrup, & Jolles, 1996). For example, previous research has reported that acute moderate intensity exercise can enhance cognitive functioning post-exercise (McMorris & Hale, 2012; Rattray & Smee, 2016). However, extended (~45-60-min), or more intense bouts of exercise, could compromise some aspects of cognitive functioning post-exercise (McMorris, Turner, Hale, & Sproule, 2016; Rattray & Smee, 2016; Tomporowski, 2003) and during exercise in temperate conditions (e.g., Lambourne & Tomporoski, 2010; Schmit & Brisswalter, 2018). A number of reviews have provided crucial insights about the facilitative effects of chronic physical activity on cognitive functioning (long-term; e.g., Blondell, Hammersley-Mather, & Veerman, 2014), the varying effects of acute bouts of physical activity on cognitive functioning (e.g., Chang, Labban, Gapin, & Etnier, 2012; McMorris & Hale, 2012), as well as the debilitative effects of extreme environmental conditions (including hot and cold conditions) for complex cognitive tasks in the absence of physical activity (Martin, McLeod, Périard, Rattray, Keegan, & Pyne, 2019). However, such reviews have not considered the effects that environmental temperature may have on the effects of exercise on cognitive functioning, which is relevant to various occupational and performance contexts (e.g., military, elite sport). This review aims to address this gap in our understanding by considering how the physical demands of acute bouts of exercise under differing environmental temperatures can affect cognition.

The Role of Exercise on Cognition

In relation to the effects of acute bouts of exercise on cognition, several mechanisms have been applied to explain how these effects occur. One such mechanism focuses on how exercise can increase neurotransmitters that are understood to be important for effective cognitive function (e.g., working-memory, processing speed), such as the catecholamines epinephrine (EP), norepinephrine (NE) and dopamine (DA) (e.g., Cooper, 1973; McMorris & Hale, 2012). Research has shown that acute bouts of exercise can increase peripheral catecholamine plasma levels in humans (e.g., McMorris et al., 2009; Winter et al., 2007) and cerebral levels in animals (e.g., Meeusen & De Meirleir, 1995; Sutoo & Akiyama, 2003), as well as indicating exercise-induced catecholamine rises (i.e., increases in arousal) may induce cognitive benefits such as improved speed of processing (McMorris & Hale, 2012). That said, it has also been proposed that prolonged vigorous exercise could lead to excessive catecholamine rises reflecting over-arousal that impairs cognitive performance by weakening the ‘signal to noise’ ratio beyond catecholamine thresholds (McMorris, 2016).

The exercise intensity or physical demand dependent effects of exercise on cognition have been implied in a range of theories, such as the inverted-U and central fatigue hypotheses. In keeping with Yerkes & Dodson’s (1908) theory referring to a curvilinear relationship between arousal and performance, Davey (1973) proposed a curvilinear relationship between exercise intensity and cognition during or following exercise. Specifically, light and/or heavy exercise has been considered insufficient for cognitive facilitation, due to under-, or over-arousal, but moderate intensity exercise (of <~60-minutes) is suggested to optimise cognitive performance (Lambourne & Tomporowski, 2010; McMorris & Hale, 2012; Tomporowski, 2003). Moreover, prolonged bouts of exercise may compromise cognitive function (Tomporowski, 2003) in part due to the onset of dehydration and reduction of energy stores, which aligns to premises of the central fatigue hypothesis (Davis & Bailey, 1997). Based on this latter perspective, prolonged exercise may also increase the brain serotonin to dopamine ratio associated with feelings of lethargy, loss of motivation and arousal (Meeusen et al., 2006).

Evidence for the inverted-U hypothesis remains disputed; some meta-analyses and narrative reviews have reported facilitating effects of light and vigorous exercise on some aspects of cognitive performance (e.g., Brisswalter, Collardeau, & René, 2002; Chang et al., 2012). Cognitive tasks are typically categorised as either “simple” or “complex”, where simple tasks are explained to involve simple perceptual motor skills (e.g., reaction time) in comparison to complex tasks which require higher levels of attention and effort (e.g., dual-task, working-memory) (Taylor, Watkins, Marshall, Dascombe, & Foster, 2016). Specifically, it appears that exercise of short to moderate duration and of moderate intensity facilitates more complex central executive tasks (e.g., measures of executive functioning) more so than other lower-order cognitive function tasks (Basso & Suzuki, 2017; McMorris et al., 2016), perhaps due to their enhanced sensitivity to arousal and catecholamine alterations (McMorris et al., 2016). However, high-intensity exercise can facilitate simple cognitive functions, such as information processing speed (Chang & Etnier, 2009), but is unable to facilitate executive functioning (McMorris, Sproule, Turner, & Hale, 2011; McMorris et al., 2016). Therefore, the exercise-induced cognitive effects may also be dependent on the complexity of the cognitive task.

The Role of Environmental Temperature on Cognitive Functioning

In addition to the simultaneous physical and cognitive demands involved in many occupational and performance contexts, extreme environmental conditions in which people are often required to perform (e.g., military personnel, firefighters, athletes) can play a role in the maintenance of optimal cognitive function (Martin et al., 2019). Specifically, environmental temperature has been shown to influence cognition during exposure to both hot and cold environments, suggested to be driven by an alteration to psycho-physiological pathways, such as catecholamine availability, cerebral blood flow and sensory pleasure/displeasure within these environments (Taylor et al., 2016). Research has also suggested that varying environmental temperatures (including in the absence of physical activity) has been shown to impact simple and complex task performance differentially (Martin et al., 2019).

It is generally recognised that heat exposure in warm to hot environments (~25 to >40°C) can impair physical and mental performance (the latter in response to passive or active exposure) (Girard, Brocherie, & Bishop, 2015; Hancock, Ross, & Szalma, 2007). The onset of exercise-induced fatigue on both physical and cognitive performance is thought to accelerate in the heat due to thermal strain (such as increased core temperature) and exacerbated dehydration, thereby limiting the availability of oxygen to cerebral regions (Maughan, 2010). Relating to central fatigue, these factors have been reported to influence serotonergic and dopaminergic activity, and increase the release of stress hormones (e.g., cortisol), potentially leading to cognitive deficits (Masento, Golightly, Field, Butler, & van Reekum, 2014). In relation to core temperature, a review by Schmit, Hausswirth, Le Meur, & Duffield, (2017) concluded that increases in core temperature up to ~38.2°C may benefit some indices of cognitive performance (e.g., improved response speed), after which these benefits begin to disappear, with decrements to more complex cognitive functions beginning to be observed when core temperature reaches >38.5°C. When core temperature further surpasses 39°C, it is suggested that these deficits are less sparing and simple cognitive functions also begin to be adversely affected (Schmit et al., 2017).

Similarly, exposure to cold environments (~-20 to 10°C) has also been shown to induce cognitive decrements (Taylor et al., 2016), where performance on complex cognitive tasks are again thought be most affected (Martin et al., 2019). The early distraction hypothesis proposed that stress elicited from cold exposure shifts attention toward the environmental stressor and away from the cognitive task (Teichner, 1958). That said, findings from recent studies suggest that cognitive deficits may be attributed to catecholamine dysregulation in the cold (Muller et al., 2012). Although research surrounding the effects of cold stress is sparse in comparison to those in the heat (Taylor et al., 2016), no systematic review has examined the potential modulating effect of cold or hot environments in comparison to temperate conditions on the effects of acute physical activity on cognition.

Purpose of the Review

Although several systematic reviews and/or meta-analyses have been conducted on the effects of acute physical activity on cognition (e.g., Lambourne & Tomorowski, 2010; McMorris et al., 2011), as well as on the effects of environmental temperature on cognition (including in the absence of physical activity and/or in one temperature condition) (e.g., Martin et al., 2019), no review has specifically focused on the potential modulating role of environmental temperature on the effects of physical activity on cognitive function. Given the range of contexts by which the need to maintain cognitive functioning during or immediately following physical activity (e.g., elite sport, military operations; emergency services) in environmentally challenging environments is important for performance, this review aimed to systematically review the research evidence on the effects of exercise on cognition in studies where two or more temperature conditions were manipulated to determine directly how environmental temperature can influence the effect of exercise on cognitive function. Therefore, the aims of this review were to discuss: (a) the role of (manipulating) temperature on the effects of acute exercise on cognitive functioning from pre-exercise to during and/or post-exercise, or between different time-points during exercise and (b) the variances in the effects of different intensities and durations of acute exercise on cognitive function when environmental temperature has been manipulated.

Methods

This systematic review was undertaken in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) Guidelines (Moher, Liberati, Tetzlaff, & Altmans, 2009), and has been registered on the international prospective register of systematic reviews (PROSPERO: Reference = CRD42018090653).

Eligibility Criteria

Studies included in this review were required to meet the following selection criteria: The research needed to: (a) be a laboratory-based study so temperature (and humidity) was controlled in the research; (b) involve healthy human adult participants; (c) compare two or more environmental conditions where the temperature was manipulated and involved an acute bout of exercise, thereby studies with just one environmental condition or elicited mental fatigue pre-trial were excluded; and (d) have assessed some form of cognitive function from pre- to post- exercise, or at least two time-points with reference to during exercise (i.e., pre-exercise and during exercise; or a minimum of two time points during exercise). Field based or longitudinal studies were not included due to the purpose of the review being to investigate the effects of acute exercise in different temperatures on cognition and to ensure environmental conditions were controlled. Articles were also included if they were published in peer-reviewed journals from January 2000 and needed to be available in English. Studies that did not meet this eligibility criteria were thereby excluded. Three searches were conducted in total, the first was on 24th March (2018), with updated searches conducted on June 6th (2019) and October 8th (2020).

Information Sources and Search Strategy

The following electronic bibliographic databases were searched: Medline, SPORTDiscus, Psych Articles, PsychINFO, The Cochrane Library and CINAHL. The search strategy stemmed from three themes (1) Physical Activity (2) Hot or Cold Temperature Exposure (3) Cognitive Function. The search terms were adapted for each database, with their database-specific filters and MeSh terms (See Supplementary Material 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 controlled laboratory-based environmental research incorporating cognitive measures across two or more conditions before 2000. The search strategy was pilot tested to ensure a robust search strategy. Following the searching of databases, hand-searching of references lists from eligible studies and relevant review articles were also conducted.

Data Extraction

Extracted articles from the databases were exported into EndNote. Following removal of duplicates, the title and abstract of each article, and then the full-text of articles, were screened using a standardized template by the first author and a second author independently ([redacted] and [redacted]). Any disagreement between reviewers over eligibility of studies was resolved through discussions among these authors and if necessary, a third reviewer was included ([redacted]). Figure 1 details the screening process highlighting the number of studies excluded at each stage.

Where available, data extracted from each article included: participant demographics (sample size, gender, age, training status, and VO_2 max); experimental design; environmental manipulation (environmental temperature and relative humidity [rh]); exercise characteristics (mode, duration and intensity); core temperature changes; cognitive function measures/tasks included, and results of cognitive function with reference to pre-, during, and/or post-exercise. For the purpose of this review, physical activity/exercise was categorised as ‘light’, 'moderate' or 'vigorous' across studies, whereby these were aimed to align somewhat with the classification of exercise intensities from the American College of Sports Medicine (American College of Sports Medicine, 2000) and relevant reviews (Swain et al., 2005).[1] Specifically, in this review, where data was available, 'light' exercise was defined as <40% VO_2 max or heart rate reserve (HRR), or where heart rate was maintained <110bpm in temperate conditions (e.g., McMorris et al., 2005; Swain et al., 2005). 'Moderate' exercise was defined as between 40-60% VO_2max or HRR, or where heart rate was maintained between ˜110-140bpm throughout the temperate condition (e.g., Radakovic et al., 2007; Swain et al., 2005). 'Vigorous' exercise was defined as >60% VO_2 max or HRR, any protocols to exhaustion or where heart rate was >~140bpm in temperate conditions (Taylor et al., 2014; Swain et al., 2005). If VO_2 max, HRR, nor heart rate data were available ($n = 2$)[2], categorisation was based upon that implied by the authors.

Risk of Bias

The two review authors independently assessed the risk of bias for included studies using the Downs & Black (1998) Checklist Criteria for randomised and non-randomised intervention trials (Table 1). 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 articles, any discrepancies between authors' scores were identified and discussed, and

[1] ACSM thresholds are based off VO2 reserve % (VO2R), however VO2max was mostly reported in the studies included. Minimal differences were assumed between % VO2 max and % VO2R due to average resting VO2 being ~2.6 ml/kg/min (Byrne et al., 2005), therefore % VO2 max was deemed suitable for categorising dosage of exercise.

[2] Exercise included in Cvirn et al. (2019) was categorised as moderate for the purpose of this review due to the intermittent nature of the task, including lengthy rest periods between bouts, however no physiological data is provided to support the categorisation of the exercise dose, nor reference to the intensity of the tasks included. Physiological data was also not reported in Chandra et al (2010) and exercise dose was categorised as light based upon the authors description and seemingly non-taxing nature of the task. Therefore, classification of exercise dosage for these studies should be interpreted with these cautionary notes in mind.

where these were unable to be resolved, a third author ([redacted]) was consulted. Study quality ranged from 56-85%, with an average of 73%.

Results

Search Result

Initial searches returned 4004 papers, plus 37 papers identified through manual searches **(Figure 1).** After removing duplicates, 2914 papers were reviewed by title and abstract, 93 articles were then reviewed full-text, whereby 16 articles met the inclusion criteria (Figure 1 shows reasons for rejection at full paper stage).[3] The first updated search (June 2019) returned an additional 304 articles, after removing duplicates 255 articles were reviewed by title and abstract. Six full-text articles were then reviewed, where one article met the inclusion criteria. The final updated search (October 2020) returned a further 691 papers, plus 3 papers identified through manual searches. After removing duplicates, 605 articles were reviewed by title and abstract, 10 of these were reviewed by full-text and 3 met the inclusion criteria. From both searches, twenty articles were included for qualitative analysis. Five of the twenty studies were conducted in the UK, two in Australia, two in Estonia, three in the U.S., and one each in India, Poland, Republic of Korea, Belgium, Canada, China, Japan, and Serbia.

Of the twenty articles identified, thirteen investigated exercise and cognition in hot compared to temperate environmental conditions (28˚C to 48˚C vs. 15˚C to 25˚C; 20-75%rh), three examined effects in cold compared to temperate (2˚C to 10˚C vs. 20˚C to 25˚C; 50-70%rh), one study examined three different hot environmental conditions (from 28.6˚C to 33.2˚C), one study examined lower and higher temperate conditions (15˚C vs. 25˚C), and two investigated exercise and cognition in hot, temperate and cold environments (30˚C vs. 18˚C

[3] An article by Ferguson, Smith, Browne, & Rockloff, (2016) was excluded in the later stages of data analysis to avoid the influence of confounding variables (e.g., sleep duration), due to repeated bouts of PA continuing over a period of three days and cognitive function comparisons run only before, and after the three day intervention.

vs. -5˚C; 50%rh). For the purposes of this review, conditions ≤10˚C were classified as cold, 15˚C to 25˚C as temperate, and ≥28˚C as hot conditions. Across the twenty studies, sample sizes ranged from 8 to 73, with an average of 19 participants. Of the 366 participants in total, only 41 were females from 6 of the studies (Adam et al., 2008; Cvirn et al., 2019; Gerhart et al., 2020; Macleod, Cooper, Bandelow, Malcolm, & Sunderland, 2018; Parker et al., 2013; Tikuisis & Keefe, 2005). Eight studies focused on healthy, physically active individuals, seven on professional/well-trained athletes and/or referees, three on military personnel, and two on emergency service personnel. This review first examines the effects of exercise and cold exposure on cognition, followed by studies in the heat.

Cold Exposure

Characteristics of studies. An overview of studies and associated findings examining the effects of cold exposure on cognitive functioning are presented in Table 2**.** Two of the five studies induced cold exposure using an environmental temperature of -5°C (50%rh) (Watkins et al., 2014; Taylor et al., 2014), whereas temperatures of 2°C (50%rh) (Adam et al., 2008), 4°C (70%rh) (Kruk et al., 2001) or 10°C (50%rh) (Ji et al., 2017) were used to induce cold exposure in the other studies. Temperate conditions ranged between 18°C to 25°C (50-60%rh). One study also included a 60-min period of passive cold exposure prior to the commencement of exercise (Ji et al., 2017). One study also examined the effects of caffeine vs. placebo (Kruk et al., 2001), and another investigated cold vs temperate environments whilst euhydrated or hypohydrated (Adam et al., 2008). Four of the five studies measured cognitive function pre- and post-exercise, and one included cognitive measures pre- and during exercise (Kruk et al., 2001).

The effect of exercise on cognition in the cold.

Light exercise. Only one study examined light exercise on cognition pre-to-post exercise in cold and temperate conditions which found a main effect for condition on vigilance, whereby vigilance hit scores were significantly lower in -5°C compared to 18°C (Watkins et al., 2014). However, no condition × time interaction effect was identified for vigilance hit scores, nor were other effects found for added measures of cognitive performance across conditions (i.e., vigilance miss or false scores, dual-task tracking performance, dual-task visual scores).

Moderate exercise. Both studies investigating the effects of cold vs. temperate exposure on cognition following moderate exercise found some beneficial effects on cognition in temperate conditions (Adam et al, 2008; Ji et al, 2017). Specifically, Adam et al. (2008) identified a significant interaction whereby visual vigilance (i.e., total response latency) was faster in the temperate condition post-exercise compared to pre-exercise but did not differ pre-to-post exercise in the cold. Moreover, a main condition effect on visual vigilance (i.e., target detection latency) revealed slower responses in 2°C compared to 20°C. No other effects were identified for other indices of vigilance (e.g., scanning visual vigilance) or reaction time (RT). However, it is worth noting that friend-foe target accuracy (%) was found to improve from pre-to-post moderate exercise across both temperature conditions. Comparatively, Ji et al. (2017) found identification and 2-back working-memory RT decreased immediately after exercise across both cold and temperate conditions compared to pre-exercise. However, a condition × time interaction was found where 2-back working-memory RT remained quicker 30-minutes post-exercise compared to pre-exercise in the temperate condition, but not in the cold. Additionally, a main condition effect for identification RT and 2-back working-memory accuracy revealed that identification RT was slower and 2-back working-memory accuracy was lower in cold compared to the temperate condition. No other noteworthy effects were found.

Vigorous exercise. The one study (Taylor et al., 2014) examining the effect of cold exposure (-5˚C) on cognition post vigorous exercise found no main nor condition × time interaction effect on any measure of cognitive functioning (i.e., for dual-task visual-tracking or vigilance). Furthermore, the only study to examine the effect of exercise on cognition *during* exercise involved vigorous graded exercise to exhaustion and included a manipulation of caffeine intake, identified a main effect of time for choice RT (Kruk et al., 2001). Compared to baseline, RT was quicker during exercise between 100-200W stages in 22°C and during 200W in 4°C, but as work increased to 300W, RT was significantly slower compared to baseline across both conditions. Another key finding from this study was in relation to RT being significantly faster from caffeine supplementation compared to placebo at 22°C, but there were no differences at 4°C. Therefore, suggesting that potential ergogenic effects from caffeine supplementation may be more effective in temperate compared to cold conditions, or such ergogenic effects are suppressed in cold conditions.

Of relevance, one study manipulated two temperature conditions that reflected lower (15°C) and higher (25°C) temperate conditions, and also looked at the interaction between temperature and altitude (0 vs 3800m) on cognition (Van Cutsem et al., 2015). Specifically, a vigorous exercise protocol was implemented whereby participants completed a 30-minute cycling time-trial. No condition (temperature only) or condition × time (pre-to-post) interaction effects were noted for psychomotor vigilance RT scores.

In sum, the benefits of exercise on cognitive functioning from pre-to-post exercise were demonstrated following moderate exercise in temperate/ambient conditions, however such benefits seemed to be negated in cold conditions, or when exercise was vigorous.

Heat Exposure

Characteristics of studies. An overview of results for each study examining the effect of exercise on cognition (from pre-to-post and/or to during exercise) in the heat are presented in Table 2. Of the sixteen studies that included a hot condition fifteen included comparisons with a temperate condition, and one study included only a manipulation within hot conditions (Chandra, Ghosh, Barman, Iqbal, & Sadhu, 2010). Three studies looked at temperatures between 28°C and 30°C (Taylor et al., 2014; Tikuisis & Keefe, 2005; Watkins et al., 2014), eight between 31°C and 38°C (Cvirn et al., 2019; Donnan et al., 2020; Gerhart et al., 2020; Macleod et al., 2018; McMorris et al., 2006; Parker et al., 2013; Roh, So, Cho, & Suh, 2017; Shibasaki et al., 2019), three between 39°C and 42°C (Radakovic et al., 2007; Tamm et al, 2014; 2015), and one at 48°C (20%rh) (Caldwell, Patterson, & Taylor, 2012). Another observed the effect of progressive heat exposure in only hot conditions (28.6 – 33.2°C) within one trial (Chandra et al., 2010). Thirteen of the studies also gave an indication of relative humidity which varied between 18% and 75%. Eight of the studies manipulated solely the environmental temperature (Cvirn et al., 2019; Donnan et al., 2020; Gerhart et al., 2020; McMorris et al., 2006; Parker et al. 2013; Shibasaki et al., 2019; Taylor et al., 2014; Watkins et al., 2014). Three studies investigated differences in fluid intake between conditions (Macloed et al., 2018; Roh et al., 2017; Tikuisis & Keefe, 2005), two looked at the effectiveness of heat acclimation protocols (Radakovik, 2007; Tamm et al., 2015) and two included the use of a liquid conditioning garment (Caldwell et al., 2012; Tikuisis & Keefe, 2005) to manipulate core temperature. One study (Tamm et al., 2014) also compared the effects of passive (i.e., at rest) and active (i.e., involving exercise) heat exposure compared to temperate conditions. Five of the sixteen heat studies included cognitive tests during exercise (Caldwell et al., 2012; Donnan et al., 2020; Tamm et al., 2014; 2015; Tikuisis & Keefe, 2005), four of which included pre-exercise tests (Caldwell et al., 2012; Donnan et al., 2020; Tamm et al., 2014; 2015). The remaining eleven studies investigated cognitive function pre- and post-exercise bouts.

The effect of exercise on cognition in the heat.

Light exercise. Three studies investigated the effects of light exercise performed in hot compared to temperate environmental conditions on cognition (pre-to-post exercise) and reported equivocal findings. Specifically, Watkins et al. (2014) manipulated hot (30˚C), temperate (18˚C) and cold (-5˚C) environmental conditions, but no differences were found between the hot and temperate condition on vigilance or dual-task performance following 90-minutes of exercise. However, a time effect revealed impairments in vigilance scores post-exercise compared to pre-exercise across all conditions, and tracking performance declined from pre-exercise to a 45-minute mid-trial break. In contrast, McMorris et al. (2006) found a decline in random movement generation working-memory from pre- to post-exercise in 36°C (75%rh) with a large effect size, but no significant changes were found in 20°C (40%rh). Though, no effects were found for choice RT, verbal recall and spatial recall over time or between 20°C and 36°C conditions. Moreover, Chandra et al. (2010) examined progressive heat loads (i.e., ≥ 28°C) in the same trial and found that simple visual and auditory RT was faster following the first 5-minutes of exercise in 28.6°C, but saw RT become slower immediately after 10 and 15 minutes of exercise in 30.6°C and in 33.2°C, respectively. However, these inferences need to be considered with caution due to limited statistics being reported in the paper, and as all temperatures were in the same condition with short exposure time (5 minutes) at each temperature, it is not possible to determine if changes in RT were due to duration of exercise or heat exposure, or a combination of both.

Two studies also assessed cognitive parameters *during* light exercise. Both identified no effects on cognitive functions, including attention, verbal working memory, problem solving, perceptual RT (Caldwell et al., 2012) as well as target detection and rifle marksmanship performance (Tikuisis & Keefe, 2005). With one exception whereby a small but significant target (i.e., foe vs. friendly) × condition × time interaction was identified in the study by Tikuisis & Keefe (2005), which indicated a less accurate detection rate of friendly targets at 180-minutes during hot hydrated (30-32˚C) trials compared to temperate (22˚C) and hot dehydrated (30-32˚C) trials.

Moderate exercise. Five studies involved moderate exercise performed in hot compared to temperate environmental conditions on cognition (pre-to-post exercise). Specifically, Radakovic et al. (2007) reported significant declines in rapid visual information processing accuracy (% correct responses) and reaction movement time slowed down after an exertional heat stress test (wearing combat uniform and carrying a 20kg load) in 40°C compared to pre-exercise for an un-acclimated group. However, no such significant changes were found in a group exercising in temperate conditions (20°C) or in acclimated groups. Cvirn et al. (2019) found an interaction effect whereby congruent (i.e., simple) Stroop RT was slower after the first two of three simultaneous 55-minute physical work circuits over an afternoon in the temperate (18 to 20˚C) compared to the hot (33 to 35˚C) condition. Conversely, a main condition effect for incongruent (i.e., more complex) Stroop revealed RT was slower in the hot compared to temperate condition across all circuits. However, no effects were identified for Stroop accuracy. Moreover, interaction effects revealed more lapses in vigilance were found following the third circuit in the hot condition compared to the temperate condition, as well as after the two previous circuits. Greater vigilance lapses were also found when dehydrated in the hot condition after the third circuit compared to when euhydrated in the heat as well as when dehydrated or euhydrated in the temperate condition. Therefore, suggesting that RT during simpler cognitive tasks may be quicker following up to two acute exercise bouts in the heat compared to temperate conditions, but more complex RT appears to deteriorate, and more frequent lapses are observed following repeated, interspersed exercise bouts in the heat, more so if dehydrated. Conversely, Parker et al. (2013) found no effect of heat (35-38°C vs. 22-24°C) on psychomotor vigilance or Wisconsin Card Sorting Test (WCST) scores. Only a main effect for time was reported whereby cognitive performance improved following moderate exercise in both hot and temperate conditions, reflected by fewer errors and more conceptual responses on the WCST. Likewise, Gerhart et al. (2020) observed no condition, time or condition × time interaction for the Stroop task following two 10-minute walks interspersed with 15 × sandbag lifts (between ~30-50% VO_2 max throughout exercise) in 25˚C to 37.8˚C. However, cognitive tasks were only implemented pre- and 30-minutes post-exercise. Additionally, exercise in this study was manipulated within each condition to maintain a HR of ~70-75%, and therefore, work output was reduced in hot conditions to reflect this, also resulting in peak core temperature not rising beyond ~38.0˚C. Similarly, internal temperature (tympanic in this instance) in Shibasaki et al. (2019) only reached peaks of ~38.0˚C in the final exercise bout during a protocol involving 4 × 15-minute cycling bout (132 ± 27 W) interspersed with 10-minutes rest in 35˚C compared to 20˚C. They too observed no effects for condition, time or interactions for RT or error rate on a Go/No-Go task. However, it is worth noting that when examining brain evoked potentials using an electroencephalograph (EEG), a significantly lower peak P300 amplitude was found in 35˚C compared to 18˚C after the fourth exercise bout, reflecting reduced depth of processing during the cognitive task after the final bout of exercise in this protocol in the heat.

Vigorous exercise. Three studies involved vigorous exercise in hot compared to temperate environmental conditions on cognition (pre-to-post exercise). In a sample of athletes where a temperate condition (18°C) was compared with hot conditions (32°C) that involved no fluid intake, fluid intake, and fluid intake with sports drink, Roh et al. (2017) found that simple and complex Stroop accuracy significantly improved immediately after exercise in temperate (18°C) conditions, but no change was observed post-exercise in hot conditions (32°C). Additionally, colour word (incongruent) scores were significantly lower immediately after exercise in 32°C without fluid ingestion than in other conditions. Therefore, suggesting exercise in the heat and particularly combined with lack of fluid intake contributed to negating any potential benefits of vigorous exercise on simple or complex RT after exercise. This somewhat aligns with Cvirn et al.'s (2019) findings which observed improved simple RT for up to two moderate exercise bouts in the heat which were negated later in the protocol when dehydrated, alongside complex RT declines. In another study, Macleod et al. (2018) found mixed findings whereby overall Stroop RT was quicker from pre-to-post-exercise in the heat (~33°C) but not in temperate (~16°C). Additionally, complex visual search RT and working-memory RT were significantly quicker in hot compared to temperate conditions. However, an interaction effect for working memory accuracy indicated that accuracy scores were significantly higher post-exercise than pre-exercise in 16°C but were unchanged in 33.3°C. Thus, suggesting RT can become quicker post vigorous exercise in the heat compared to temperate conditions, but aligns with Roh et al. (2017) whereby vigorous exercise in the heat negated any post-exercise benefits on cognitive *accuracy* observed in temperate conditions.The remaining study examining pre-to-post exercise cognition following vigorous exercise (90 minutes) in hot (30˚C) and temperate (18˚C) conditions found no condition, time, or condition × time interaction effects on dual-task or vigilance performance measures (Taylor et al., 2014).

Three studies also assessed cognitive performance *during* vigorous exercise, two of which observed that the heat impaired performance on a time perception task compared to temperate conditions (Tamm et al., 2014; 2015). Tamm et al., (2014) identified a greater relative compression of perceived time indicative of a quicker internal pacemaker during vigorous exercise to exhaustion in 42˚C (18%rh) compared to 22˚C (35%rh). Specifically, a more pronounced decline was found at 10-minutes and 60-minutes during exercise in proportionality between perceived and objective time (a_1), in the hot condition compared to the temperate condition (Tamm et al., 2014). In a similar study, Tamm et al. (2015) also identified a greater compression of produced time intervals in hot (42˚C) compared to a temperate (22˚C) condition, including a greater compression of perceived time at 60-minutes compared to pre-exercise in the hot condition, but not in the temperate condition.

Interestingly, the final study implementing cognitive measures *during* vigorous exercise found after confirming no differences in cognition scores at baseline (pre-exercise), that congruent (i.e., simple) Stroop RT's were quicker in team sport athletes between the 20th and 40th minute of a cycling intermittent sprint protocol (CISP) in 32˚C compared to 18˚C (Donnan et al., 2020). However, no differences in Stroop RT were found in the first 20-minutes or following 40-minutes of exercise, coinciding also with the only time-point where core temperature was significantly higher than in temperate conditions. In terms of Stroop accuracy, no effects of condition or condition × time interactions were observed, however incongruent (complex) Stroop accuracy was impaired between the 20th-60th minutes of the CISP across conditions. No main effects or interactions were found for simple vigilance measures. Taken together, the results of these studies indicate a quicker pacemaker rate, and therefore, a distorted perception of time *during* vigorous exercise in hot conditions (Tamm et al., 2014, 2015), though when core temperature is moderately increased (~38.40˚C) in hot conditions, quicker RTs were observed for simple indices (Donnan et al., 2020).

Discussion

Active Cold Exposure on Cognitive Function

The findings from studies in the present review support the notion that acute bouts of moderate exercise enhance aspects of cognitive function (e.g., reaction time) post-exercise, as well as during exercise, compared to pre-exercise in temperate conditions (e.g., Tomporowski et al., 2003). However, when a moderate dosage of exercise is undertaken in cold conditions, these typical cognitive benefits may be reduced or negated (Adam et al., 2008; Ji et al., 2017). Though no cognitive benefits were observed following light or vigorous exercise in both temperate and cold conditions (Taylor et al., 2014; Van Cutsem et al., 2015; Watkins et al., 2014), including some decrements being observed following light exercise (Watkins et al., 2014). Although just one study implemented cognitive function during exercise, the quickening of choice RT between rest and during light-to-moderate exercise stages of an incremental exercise protocol was less notable in cold compared to temperate conditions (Kruk et al., 2001). The delayed reaction time during higher workloads (i.e., at 300W) observed in this study also align with the curvilinear relationship described by the inverted-U hypothesis (Davey, 1973), where specifically moderate bouts of exercise are thought to induce optimal levels of arousal which can facilitate reaction time, however more vigorous bouts can result in overarousal, consequently impairing reaction time. Additionally, there is some suggestion that stimulants (i.e., caffeine) consumed prior to exercise appear to quicken choice RT in temperate conditions, but these effects are negated in the cold (Kruk et al., 2001).

It has also been proposed that passive (i.e., no exercise) cold exposure that induces a 2°C or more reduction in core temperature commonly elicits decrements to cognitive performance, specifically response time capability, but less than 2°C have little effects on cognitive performance (Giesbrecht, Arnett, Vela, & Bristow, 1993; Hancock et al., 2007). However, when exploring active cold exposure (i.e., involving physical activity), exercise induced heat production may negate the adverse effects of cold exposure on cognitive function by limiting alterations in core temperature from the homeostatic range (Hancock & Vasmatzidis, 2003), and may lead to little or no effects on cognitive function (negative nor positive).

When looking at the effect of light exercise on cognition (Watkins et al., 2014), vigilance was lower in cold conditions (-5°C) compared to temperate (18°C), however no changes in cognitive performance from pre-to-post exercise were found across conditions. A lack of exercise-induced heat production from light exercise suggests that this dosage was unable to attenuate adverse effects from cold exposure on cognitive function, as well as potentially being an insufficient dosage of exercise to stimulate physiological arousal enough in temperate conditions to facilitate clear pre-to-post exercise improvements in cognitive function (e.g., Davey, 1973).

Moderate exercise was found to benefit cognition, specifically processing speed, reaction time and response latency, where performance appears to speed up post-exercise in temperate conditions (Adam et al., 2008; Ji et al., 2017). However, when moderate exercise is performed in cold conditions, these benefits were negated, or more temporary, compared to temperate conditions. There were also some decrements in cognitive performance (i.e., slower target detection times) noted following exercise in the cold in the absence of any core temperature differences between conditions (Adam et al., 2008). These effects were attributed to increased perceptual demand, lower mood, and a potential distraction effect whereby cold exposure may have drawn attention away from cognitive tasks on to thermal discomfort (e.g., Muller et al., 2012; Teichner, 1958), thereby counteracting potential cognitive benefits following moderate exercise (Adam et al., 2008). Interestingly, Ji et al., (2017) identified that working-memory accuracy deteriorated in response to 60-min passive cold exposure, but following moderate exercise, no such accuracy decrements were observed. In part, supporting that an acute bout of moderate exercise may minimise or nullify some cognitive decrements observed by cold stress due to exercise-induced heat production (Hancock & Vasmatzidis, 2003).

In regard to vigorous exercise bouts, no effects were found on post-exercise vigilance or dual-task performance across conditions (Taylor et al., 2014), despite core temperature being significantly lower in cold compared to temperate conditions. Moreover, a study that compared a cooler temperate condition with a warmer temperate condition (i.e., 15˚C vs. 25˚C) found no effects of temperature, and no changes in psychomotor vigilance were noted from pre-to-post vigorous exercise (Van Cutsem et al., 2015). These findings support the notion that vigorous exercise may not improve cognition post-exercise (Chmura, Nazar, &

Kaciuba-Ulscilko, 1994), perhaps due to surpassing the optimal level of physiological arousal to benefit both simple and complex cognitive functions (Cooper, 1973; Davey, 1973). However, vigorous exercise may reduce the detrimental impact of cold exposure on cognitive functioning observed post-exercise in studies employing light exercise protocols (e.g., Watkins et al., 2014). It is suggested this may be due to vigorous exercise inducing greater metabolic heat production (Sawka, Leon, Montain, & Sonna, 2011), thus reducing the extent to which core temperature declines in cold conditions. Nonetheless, these effects could be due to a range of factors (e.g., how long after exercise cognition was measured) and thereby due to limited research, it is presently difficult to make strong inferences about these propositions.

Only one study has measured cognitive performance during exercise in the cold that was relevant for the present review, which revealed that during incremental exercise to exhaustion, psychomotor performance (i.e., reaction time) improved between rest and low-to-moderate exercise in temperate conditions (Kruk et al., 2001). However, RT began to slow at higher intensities which is aligned to other previous work showing such effects whereby RT improves up to intensities of ~75% VO_2 max, and then begins to slow rapidly (Chmura et al., 1994). However, it's notable that the quickening of reaction time was only observed between rest and 200W in 4˚C compared to lower work stages (100W – 200W) in 22˚C, suggesting that cold exposure may reduce the beneficial effects of light-to-moderate exercise on reaction time during, as well as post-exercise. Also, the beneficial effect of caffeine ingestion on choice RT observed in 22°C was blunted in 4°C (Kruk et al., 2001). Therefore, individuals requiring to simultaneously perform exercise of exhaustive nature in the cold may need to consider other approaches to help limit these effects (e.g., clothing).

Active Heat Exposure on Cognitive Function

It was anticipated that studies incorporating acute bouts of light exercise would affect cognition to a lesser extent in hot environments than those implementing more prolonged, vigorous exercise bouts in the heat due to the latter expected to induce higher levels of thermal strain (Sawka et al., 2011). Additionally, it was expected that greater decrements would be observed for complex central executive tasks which have been shown to be more sensitive to changes in the concentration and proportion of central catecholamines (McMorris et al., 2016), often reported when under physiological strain such as that induced by exercise and the heat (Roelands, De Pauw, & Meeusen, 2015).

Studies implementing light exercise protocols found little to no effects of heat exposure on varied indices of cognitive function both post (Watkins et al., 2014) and during exercise (Caldwell et al., 2012; Tikuisis & Keefe, 2005), including in more complex cognitive tests (e.g., problem solving). As anticipated light exercise appeared generally to result in lower physiological strain (i.e., lower HR and core temperatures) than moderate, or vigorous dosages of exercise, resulting in little to no differences in cognitive function between hot and temperate conditions. Despite some, but not all (Watkins et al., 2014), light exercise protocols inducing some thermal strain, as identified by significantly higher core temperatures in hot compared to temperate conditions, these were up to ~39˚C and thereby perhaps not sufficient enough to impair cognition during exercise (Caldwell et al., 2012; Tikuisis & Keefe, 2005). However, it has previously been suggested that complex cognitive deficits begin to be identified once a core temperature threshold of ~38.5˚C is surpassed, where when reaching >~39°C, cognitive impairment appears to extend to simpler tasks (Schmit et al., 2017). Conversely, McMorris et al. (2006), observed working-memory decrements (immediately, and 70-minutes) following light exercise in 36°C, but not in 20°C. Whilst the protocol employed by McMorris et al. (2006) was classified as ‘light’ in this review, the workload was notably higher than the protocol used by Caldwell et al. (2012).

Therefore, although limited combined effects of light exercise and heat on cognitive function post-exercise was noted, the only clear decrements were observed in the study incorporating the highest work-load within the ‘light’ category, on a complex central executive task.

Regarding moderate intensity exercise, two (Cvirn et al., 2019; Radakovic et al., 2007) studies identified cognitive deficits post-exercise in hot compared to temperate environments, particularly on complex visual processing accuracy when unacclimated (Radakovic et al., 2007). That said, Cvirn et al., (2019) also identified decrements in psychomotor vigilance, which is considered a “simpler” form of cognitive function. This effect may be because Cvirn et al. employed a unique protocol that spread exercise across a whole day involving several circuits and cognitive testing periods that may have contributed to additional accumulative fatigue, particularly as the majority of these decrements were found following the final circuit, often when dehydrated. However, some observed no detrimental effects for simple or complex indices of performance following moderate exercise in the heat, though this was commonly when core (or tympanic) temperate did not rise above ~38.0˚C – 38.2˚C in hot conditions (Gerhart et al., 2020; Parker et al., 2013; Shibasaki et al., 2019), in comparison to Radakovic et al. (2007) recording heights of >~39.3˚C in the unacclimated heat condition.

It was expected that studies involving vigorous exercise protocols would observe more consistent and amplified decrements in cognitive function post-exercise in the heat compared to temperate conditions due to greater physical (e.g., increased metabolic heat production) and perceptual (e.g., negative affective responses) strain (Sawka et al., 2011; Ekkekakis, Hall, & Petruzzello, 2005). Some research aligned with this whereby post-exercise executive function improved in temperate conditions, but not in the heat (Roh et al., 2017). That said, another study (Macleod et al., 2018) found some evidence for post-exercise benefits to simple cognitive indices (i.e., RT) in hot compared to temperate conditions following high-intensity intermittent exercise in elite hockey players, but found working-memory accuracy (higher level cognitive functioning) improved post vigorous exercise in the temperate condition, but not in the heat. Therefore, offering some alignment to suggestions that increased concentrations of catecholamines elicited by more physically demanding environments may improve response speed but reduce accuracy in responding (McMorris et al., 2011).

Furthermore, a compression of subjective time (or a speeding up of the internal clock or faster pacemaker) was found *during* vigorous exercise in the heat compared to temperate conditions (Tamm et al., 2014; 2015). This compression of subjective time observed could contribute some understanding as to why quicker RT's, particularly for simple indices, have been observed in other studies (i.e., Donnan et al., 2020; Macleod et al., 2018) in the heat. Where individuals perceive they have less time, they may respond quicker (and potentially impulsively), potentially compromising the consideration of all influential stimuli and thereby negatively impacting the ability to respond accurately. Future research employing more complex cognitive tasks during exercise, as well as adopting moderate and vigorous exercise, would help to further test these possibilities. These findings align with the transient hypo-frontality hypothesis (Dietrich, 2006) that suggests as physical demand increases, such as during vigorous exercise, neural resources are diverted toward regions of the brain responsible for supporting movement or other physical or sensory functions, thereby reducing resources in the pre-frontal cortex, responsible for complex cognitive functioning. Therefore, this may explain clearer decrements in cognitive function, particularly for complex tasks, during vigorous exercise compared to during light exercise.

Limitations and Future Research

This review examined studies where environmental temperature was manipulated to offer insights about the modulating role of environmental temperature on the effects of acute bouts of exercise on cognition. To date, there is limited existing research which has investigated the cognitive response to exercise in two or more environmental temperatures (particularly comparing cold with temperate conditions), and therefore it is difficult to draw strong conclusions. Some research has also examined the effect of exercise on cognition in one temperature condition (e.g., in 25°C; Coull et al., 2015) as well as examined chronic exposure to environmental temperature (Lieberman et al., 2009) on cognition that could offer some further insights. This review focused only on laboratory-based studies to ensure that the manipulation of environmental temperature and study characteristics (e.g., exercise dosage, cognitive measures) within studies were controlled to facilitate a direct examination of how different temperatures may influence the effect of exercise on cognitive function. However, it is worth noting that there is also field-based research investigating the effects of exercise and environmental temperature on cognitive function (e.g., Bandelow et al., 2010). That said, most field-based research investigates the effect of exercise on cognition in one temperature condition due to not being able to manipulate environmental conditions in the field (e.g., Bandelow et al., 2010). Therefore, though such research may offer additional relevant insights, these were included to directly address the aims of the present review.

In terms of limitations in relation to the research evidence to date, some studies did not include core temperature measures (Chandra et al., 2010; Cvirn et al., 2019; Ji et al., 2017; Kruk et al., 2001), so whether changes in environmental temperature induced changes in core temperature could not be determined in many studies. Consistency in the reporting of core temperature is recommended in future research to avoid making assumptions of the level of cold or heat stress experienced. That said, although core temperature is a potential key factor in explaining the effect of environmental temperature on cognitive performance following or during exercise (Hancock & Vasmatzidis, 2003), research would benefit from considering other potential mediating variables, such as catecholamines and emotionalregulation strategies, to further examine how environmental temperature may influence the effects of exercise on cognitive function. Limited research has also implemented cognitive function measures during exercise (as opposed to after), which does not reflect the simultaneous cognitive and physical demands experienced in a range of occupational and athletic contexts within hot and cold environments. Additionally, more context-specific cognitive tasks should be implemented, enhancing the ecological validity of such tasks. For instance, by using sport-specific decision-making protocols in athletic samples during exercise. There is also a profound lack of research investigating the effects of acute cold exposure on cognitive function both during and after exercise. Therefore, research would benefit from further investigating the effects of cold exposure to provide implications to places where cold strain is commonly experienced. Furthermore, research has focused on assessing cognitive performance in males, and thereby in future, research would benefit from configuring difficulties of having to control for the menstrual cycle within physiological research in order to better understand how these stressors also affect female performance.

Implications and Conclusions

Overall, based on the (rather limited) research to date that has compared the effects of exercise on cognitive performance across cold and temperate conditions, it appears that moderate dosages of exercise could stimulate improved cognitive performance after exercise in temperate conditions. However, cold exposure may blunt such beneficial cognitive effects following acute moderate exercise. Although it is difficult to draw robust conclusions due to the limited evidence directly manipulating cold exposure on the effects of exercise on cognition, the findings to date suggest that if one was to consider exercising to improve cognitive performance post-exercise (e.g., during break times for office workers), then it appears consideration is needed in regard to the temperature and dosage of exercise conducted.

In terms of cognitive function during or following exposure to a hot environment, decrements were generally found particularly when prolonged moderate or vigorous exercise dosages were implemented; suggesting that decrements are due to a combination of heightened exercise-induced physiological arousal in response to additional heat exposure. With the exception of one study (McMorris et al., 2006), which also comprised the highest intensity of the studies in the 'light' exercise category), no differences in cognitive function were found between temperate and hot conditions when light exercise protocols were implemented. Thus, individuals in roles that require moderate-to-vigorous dosages of exercise, and therefore more physically demanding work in hot environments, should be conscious that optimal cognitive functioning may be jeopardised particularly for more complex, executive functioning tasks. For instance, it seems that the ability to accurately process time may be impaired during exercise in the heat, where a speeding up of the internal pacemaker has been observed that could result in individuals making more impulsive, (and potentially less-accurate) decisions.

In sum, research to date indicates that exercise in cold and hot environments can impair cognitive performance compared to temperate conditions, particularly in relation to moderate dosages of exercise (and also in the most part for vigorous exercise in the heat). However, these effects vary across studies likely due to variation in exercise dosages, cognitive measures employed, and approaches to manipulate temperature. In future, research would benefit from greater consideration of more context-specific cognitive performance during exercise as well as other mediators that may account for these effects (e.g., catecholamine response, coping strategies).

References

American College of Sports Medicine. (2000). *ACSM's Guidelines for Exercise Testing and Prescription*, 6th Edition. BA Franklin. Philadelphia, PA: Lippincott Williams & Wilkins, 143– 151.

Adam, G. E., Carter, R., Cheuvront, S. N., Merullo, D. J., Castellani, J. W., Liberman, H. R., & Sawka, M. N. (2008). Hydration effects on cognitive performance during military tasks in temperate and cold environments. *Physiology & Behaviour*, *93*, 748-756. doi: 10.1016/j.physbeh.2007.11.028

Bandelow, S., Maughan, R., Shirreffs, S., Ozgünen, Kurdak, S., Ersöz, G., Binnet, M. & Dvorak, J. (2010). The effects of exercise, heat, cooling and rehydration strategies on cognitive function in football players. Scandinavian Journal of Medicine and Science in Sports. doi.org/10.1111/j.1600-0838.2010.01220.x

Basso, J. C. & Suzuki, W. A. (2017). The Effects of Acute Exercise on Mood, Cognition, Neurophysiology, and Neurochemical Pathways: A Review. *Brain Plasticity, 2*, 127-152. doi: 10.3233/BPL-160040

Blondell, S. J., Hammersley-Mather, R., & Veerman, J. L. (2014). Does physical activity prevent cognitive decline and dementia?: A systematic review and meta-analysis of longitudinal studies. *BMC Public Health*, *14,* 510. doi: 10.1186/1471-2458-14-510

Brisswalter, J., Collardeau, M., & René, A. (2002). Effects of Acute Physical Exercise Characteristics on Cognitive Performance. *Sports Medicine, 32*, 555-566. doi: 10.2165/00007256-200232090-00002

Byrne, N. M., Hills, A. P., Hunter, G. R., Weinsier, R.L & Schutz, Y. (2005). Metabolic equivalent: one size does not fit all. *Journal of Applied Physiology, 99*, 1112-1119. doi:10.1152/japplphysiol.00023.2004

Caldwell, J. N., Patterson, M. J., & Taylor, N. A. S. (2012). Exertional thermal strain, protective clothing and auxiliary cooling in dry heat: evidence for physiological but not cognitive impairment. *European Journal of Applied Physiology, 112*, 3597-3606. doi:10.1007/s00421-012-2340-x

Chandra, A. M., Ghosh, S, Barman, S., Iqbal, R., & Sadhu, N. (2010). Effect of Exercise and Heat-Load on Simple Reaction Time of University Students. *International Journal of Occupational Safety and Ergonomics, 16*, 497-505. doi:10.1080/10803548.2010.11076862

Chang, Y-K., & Etnier, J. L. (2009). Exploring the Dose-Response Relationship Between Resistance Exercise Intensity and Cognitive Function. *Journal of Sport and Exercise Psychology, 31*, 640-656. doi:10.1123/jsep.31.5.640

Chang, Y. K., Labban, J. D., Gapin, J. I., & Etnier, J. L. (2012). The Effects of Acute Exercise on Cognitive Performance: A Meta-Analysis. *Brain Research, 1453*, 87-101. doi: 10.1016/j.brainres.2012.02.068

Chmura, J., Nazar, K., & Kaciuba-Ulscilko, H. (1994). Choice reaction time during exercise in relation to blood lactate and plasma catecholamine threshold. *International Journal of Sports Medicine, 15*, 172– 176. doi:10.1055/s-2007-1021042

Clarke, N. D., Duncan, M. J., Smith, M., & Hankey, J. (2017). Pre-cooling moderately enhances visual discrimination during exercise in the heat. *Journal of Sports Sciences, 35*, 355-360. doi:10.1080/02640414.2016.1164885

Cooper, C. J. (1973). Anatomical and Physiological Mechanisms of Arousal, with Special Reference to the Effects of Exercise. *Ergonomics, 16*, 601-609. doi: 10.1080/00140137308924551

Coull, N. A., Watkins, S. L., Aldous, J. W. F., Warren, L. K., Chrismas, B. C. R., Dascombe, B. … Taylor, L. (2015). Effect of Tyrosine Ingestion on cognitive and physical performance utilising an intermittent soccer performance test (iSPT) in a warm environment. *European Journal of Applied Physiology, 115*, 373-386. doi:10.1007/s00421-014-3022-7

Cvirn, M. A., Dorrian, J., Smith, B. P. & Vincent, G., Jay S. M., Roach, G. D. … Ferguson, S. A. (2019). The effects of hydration on cognitive performance during a simulated wildfire suppression shift in temperate and hot conditions. *Applied Ergonomics. 77*, 9-15. doi:10.1016/j.apergo.2018.12.018

Davey, C. P. (1973). Physical Exertion and Mental Performance. *Ergonomics, 16*, 595-599. doi:10.1080/00140137308924550

Davis, J. M. & Bailey, S. P. (1997). Possible Mechanisms of Central Nervous System Fatigue During Exercise. *Medicine & Science in Sports & Exercise, 29,* 45-57. doi: 10.1097/00005768-199701000-00008.

Dietrich, A. (2006). Transient hypofrontality as a mechanism for the psychological effects of exercise. *Psychiatry Research, 145,* 79-83. doi:10.1016/j.psychres.2005.07.033

Donnan, K. J., Williams, E. L., Stanger, N. (2020). The Effects of Heat Exposure During Intermittent Exercise on Physical and Cognitive Performance Among Team Sport Athletes. *Perceptual and Motor Skills*. doi:10.1177/0031512520966522

Downs, S. H. & Black, N. (1998). The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. *Journal of Epidemiology Community Health, 51,* 377-384.

Ekkekakis, P., Hall, E. E. & Petruzzello, S. J. (2005). Variation and homogeneity in affective responses to physical activity of varying intensities: An alternative perspective on dose-response based on evolutionary considerations. *Journal of Sports Science, 23*, 477-500. Doi: 10.1080/02640410400021492

Ferguson, S. A., Smith, B. P., Browne, M., & Rockloff, M. J. (2016) Fatigue in emergency services operations: assessment of the optimal objective and subjective measures using a simulated wildfire deployment. *International Journal of Environmental Research and Public Health, 13*, 171. doi: 10.3390/ijerph13020171

Fisher, G. G., Chacon, M. & Chaffee, D. S. (2019). Chapter 2 – Theories of Cognitive Ageing and Work. In B. Baltes, C. W. Rudolph, & Z. Hannes (Eds.). *Work Across the Lifespan* (pp. 17-235). Elsevier Academic Press. doi:10.1016/B978-0-12-812756-8.00002-5

Gerhart, H. D., Fiorentini, A. B., Storti, K. L., Alman, R., Bayles, M. P., Pesci, L. & Seo, Y. (2020). Psychophysiological Responses in Emergency Medical Technician Students during Simulated Work Activities in a Hot Environment. *International Journal of Environmental Research and Public Health,* 17, 3443. doi: 10.3390/ijerph17103443

Giesbrecht, G. G., Arnett, J. L., Vela, E. & Bristow, G. K. (1993). Effect of task complexity on mental performance during immersion hypothermia. *Aviation, Space & Environmental Medicine, 64,* 206-211

Girard, O., Brocherie, F., & Bishop, D. J. (2015) Sprint performance under heat stress: A review. *Scandinavian Journal of Medicine and Science in Sports, 25*, 79-89. doi:10.1111/sms.12437

Hancock, P. A., Ross., J. M., & Szalma, J. L. (2007). A Meta-Analysis of Performance Response Under Thermal Stressors. *Human Factors. 49,* 851-877. doi:10.1518/001872007X230226

Hancock, P. A., & Vasmatzidis, I. (2003). Effects of heat stress on cognitive performance: the current state of knowledge. *International Journal of Hyperthermia, 19,* 355-372. doi: 10.1080/0265673021000054630

Hogervorst, E., Riedel, W., Jeukendrup, A., & Jolles, J. (1996). Cognitive performance after strenuous physical exercise. *Perceptual and Motor Skills, 83,* 479-488. doi: 10.2466/pms.1996.83.2.479

Ji, L. Y., Li, X. L., Liu, Y., Sun, X. W., Wang, H. F, Chen, L., & Gao, L. (2017). Time-Dependent Effects of Acute Exercise on University Students' Cognitive Performance in Temperate and Cold Environments. *Frontiers in Psychology, 8,* 1192. doi:10.3389/fpsyg.2017.01192

Kruk, B., Chmura, J., Krzeminski, K., Ziemba, A.W., Nazar, K., Pekkarinen, H., Kaciuba-Uscilko, H. (2001). Influence of caffeine, cold and exercise on multiple choice reaction time. *Psychopharmacology, 157,* 197-201. doi:10.1007/s002130100787

Lambourne, K., & Tomporowski, P. (2010). The effect of exercise-induced arousal on cognitive task performance: a meta-regression analysis. *Brain Research, 1341,* 12-24. doi: 10.1016/j.brainres.2010.03.091

Lieberman, H. R., Castellani, J. W., & Young, A. J. (2009). Cognitive function and mood during acute cold stress after extended military training and recovery. *Aviation, Space and Environmental Medicine. 80,* 629–36.

Macleod, H., Cooper, S., Bandelow, S., Malcolm, R., & Sunderland, C. (2018). Effects of heat stress and dehydration on cognitive function in elite female field hockey players. *BMC Sports Science, Medicine and Rehabilitation, 10,* 12. doi:10.1186/s13102-018-0101-9

Marrao, C., Tikuisis, P., Keefe, A. A., Gil, V., & Giesbrecht, G. G. (2005). Physical and Cognitive Performance During Long-Term Cold Weather Operations. *Aviation, Space and Environmental Medicine, 76,* 744-752

Martin, K., McLeod, E., Périard, J., Rattray, B., Keegan, R., & Pyne, D. B. (2019). The Impact of Environmental Stress on Cognitive Performance: A Systematic Review. *Human Factors, 61*, 1205-1246. doi: 10.1177/0018720819839817

Masento, N. A., Golightly, M., Field, D. T., Butler, L. T., & van Reekum, C. M. (2014). Effects of hydration status on cognitive performance and mood. *British Journal of Nutrition, 111*, 1841-1852. doi:10.1017/S0007114513004455

Maughan, R. J. (2010). Distance running in hot environments: a thermal challenge to the elite runner. *Scandinavian Journal of Medicine and Science in Sports. 20*, 95-102. doi: 10.1111/j.1600-0838.2010.01214.x

McMorris, T. (2016). Developing the catecholamines hypothesis for the acute exercise-cognition interaction in humans: Lessons from animal studies. *Physiology & Behavior, 165*, 291-299. doi: 10.1016/j.physbeh.2016.08.011

McMorris, T., Davranche, K., Jones, G., Hall, B., Corbett, J., & Minter, C. (2009). Acute incremental exercise, performance of a central executive task, and sympathoadrenal system and hypothalamic-pituitary-adrenal axis activity. *International Journal of Psychophysiology, 73*, 334-40. doi: 10.1016/j.ijpsycho.2009.05.004

McMorris, T. & Hale, B. J. (2012). Differential effects of differing intensities of acute exercise on speed and accuracy of cognition: A meta-analytical investigation. *Brain and Cognition, 80*, 338-351. doi: 10.1016/j.bandc.2012.09.001

McMorris, T. & Hale, B. J. (2015). Is there an acute exercise-induced physiological/biochemical threshold which triggers increased speed of cognitive function? A meta-analytic investigation. *Journal of Sport and Health Science, 4*, 4-13. doi:10.1016/j.jshs.2014.08.003

McMorris, T., Sproule, J., Turner, A., & Hale, B. J. (2011). Acute, intermediate intensity exercise, and speed and accuracy in working memory tasks: A meta-analytical comparison of effects. *Physiology and Behaviour, 102*, 421-428. doi:10.1016/j.physbeh.2010.12.007

McMorris, T., Swain, J., Smith, M., Corbett, J., Delves, S., Sale, C. … Potter, J. (2006). Heat stress, plasma concentrations of adrenaline, noradrenaline, 5-hydroxytryptamine and cortisol, mood state and cognitive performance. *International Journal of Psychophysiology, 61*, 204-215. doi:10.1016/j.ijpsycho.2005.10.002

McMorris, T., Turner, A., Hale, B. J., & Sproule, J. (2016). Chapter 4 – Beyond the Catecholamines Hypothesis for an Acute Exercise-Cognition Interaction: A Neurochemical Perspective. In T. McMorris (Ed.), *Exercise-Cognition Interaction; Neuroscience Perspectives* (pp. 65-103). Elsevier Academic Press. doi:10.1016/B978-0-12-800778-5.00004-9

Meeusen, R., & De Meirleir, K. (1995). Exercise and Brain Neurotransmission. *Sports Medicine, 20*, 160-188. doi: 10.2165/00007256-199520030-00004

Meeusen, R., Watson, P., & Dvorak, J. (2006). The brain and fatigue: New opportunities for nutritional interventions? *Journal of Sports Sciences*, *24*, 773-782. doi:10.1080/02640410500483022

Moher, D., Liberati, A., Tetzlaff, J., & Altmans, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *The BMJ, 339*, 1-8. doi: 10.1136/bmj.b2535

Muller, M. D., Gunstad, J., Alosco, M. L., Miller, L. A., Updegraff, J., Spitznagel, M. B., Glickman, E. L. (2012). Acute cold exposure and cognitive function: evidence for sustained impairment. *Ergonomics*, *55*, 792-798. doi: 10.1080/00140139.2012.665497

Parker, S. M., Erin, J. R., Pryor, R. R., Khorana, P., Suyama, J., Guyette, F. X., … Hostler, D. (2013). The Effect of Prolonged Light Intensity Exercise in the Heat on Executive Function. *Wilderness & Environmental Medicine*, *24*, 203-210. doi: 10.1016/j.wem.2013.01.010

Perry, C. M., Sheik-Nainer, M. A., Segall, N., Ma, Ruiqi., & Kaber, D. B. (2008). Effects of physical workload on cognitive task performance and situation awareness. *Theoretical Issues in Ergonomics Science, 9*, 95-113. doi: 10.1080/14639220600959237

Radakovic, S. S., Maric, J., Surbatovic, M., Radjen, S., Stefanova, E., Stankovic, N., & Filipovic, N. (2007). Effects of acclimation on cognitive performance in soldiers during exertional heat stress. *Military Medicine, 172*, 133-136. doi:10.7205/milmed.172.2.133

Rattray, B., & Smee, D. J. (2016). The Effect of High and Low Exercise Intensity Periods on a Simple Memory Recognition Test. *Journal of Sport & Health Science, 5,* 342-348. doi:10.1016/j.jshs.2015.01.005

Roelands, B., De Pauw, K., & Meeusen, R. (2015). Neurophysiological effects of exercise in the heat. *Scandinavian Journal of Medicine and Science in Sports, 25*, 65-78. doi: doi.org/10.1111/sms.12350

Roh, H-T., So, W-Y., Cho, S-Y., & Suh, S-H. (2017). Effects of Fluid Ingestion on Brain-Derived Neurotrophic Factor and Cognition During Exercise in the Heat. *Journal of Human Kinetics, 58*, 73-86. doi: 10.1515/hukin-2017-0074

Sawka, M. N., Leon, L. R., Montain, S. J. & Sonna, L. A. (2011). Integrated Physiological Mechanisms of Exercise Performance, Adaptation, and Maladaptation to Heat Stress. Comprehensive Physiology, 1, 1883-1928. doi: 10.1002/cphy.c100082

Schmit, C., & Brisswalter, J. (2018). Executive functioning during prolonged exercise: A fatigue-based neurocognitive perspective. *International Review of Sport and Exercise Psychology.* doi: 10.1080/1750984X.2018.1483527

Schmit, C., Hausswirth, C., Le Meur, Y., & Duffield, R. (2017). Cognitive Functioning and Heat Strain: Performance Responses and Protective Strategies. *Sports Medicine, 47*, 1289-1302. doi:10.1007/s40279-016-0657-z.

Shibasaki, M., Namba, M., Kamijo, Y-I., Ito, T., Kakigi, R. & Nakata, H. (2019). Effects of repetitive exercise and thermal stress on human cognitive processing. *Physiological Reports,* 7, 1-12. doi: 10.14814/phy2.14003

Sutoo, D., & Akiyama, K. (2003). Regulation of brain function by exercise. *Neurobiology of Disease, 13*, 1-14. doi:10.1016/S0969-9961(03)00030-5

Swain, D. P. (2005). Moderate or vigorous intensity exercise: which is better for improving aerobic fitness? *Preventative Cardiology, 8,* 55-58. doi:10.1111/j.1520-037x.2005.02791.x.Tamm, M., Jakobson, A., Havik, M., Burk, A., Timpmann, S., Allik, J., … Kreegipuu, K. (2014). The compression of perceived time in a hot environment depends on physiological and psychological factors. *The Quarterly Journal of Experimental Psychology, 67*(1), 197-208. doi:10.1080/17470218.2013.804849

Tamm, M., Jakobson, A., Havik, M., Timpmann, S., Burk, A., Ööpik, V. … & Kreegipuu K. (2015). Effects of heat acclimation on time perception. *International Journal of Psychophysiology, 95*(3), 261-269. doi: 10.1016/j.ijpsycho

Taylor, L., Fitch, N., Castle, P., Watkins, S., Aldous, J., Sculthorpe, N., … Mauger, A. (2014). Exposure to hot and cold environmental conditions does not affect the decision-making ability of soccer referees following an intermittent sprint protocol. *Frontiers in Physiology, 5,* 185. doi:10.3389/fphys.2014.00185

Taylor, L., Watkins, S. L., Marshall, H., Dascombe, B. J., & Foster, J. (2016). The Impact of Different Environmental Conditions on Cognitive Function: A Focused Review. *Frontiers in Physiology, 6,* 1-12. doi:10.3389/fphys.2015.00372

Teichner, W. H. (1958). Reaction time in the cold. *Journal of Applied Psychology, 42*, 54-59. doi:10.1037/h0049145

Tikuisis, P., & Keefe, A. A. (2005). Heat strain at high levels does not degrade target detection and rifle marksmanship. *Aviation, Space and Environmental Medicine, 75*, 963-969.

Tomporowski, P.D. (2003). Effects of acute bouts of exercise on cognition. *Acta Psychologica, 112*, 297-324. doi: 10.1016/S0001-6918(02)00134-8

Van Cutsem, J., Pattyn, N., Vissenaeken, D., Dhondt, G., De Pauw1, K., Tonoli1, C. … Roelands, B. (2015). The influence of a mild thermal challenge and severe hypoxia on exercise performance and serum BDNF. *European Journal of Applied Physiology, 115*, 2135-2148. doi:10.1007/s00421-015-3193-x

Watkins, S., Castle, P., Mauger, A. R., Sculthorpe, N., Fitch, N., Aldous, J., Brewer, J., … Taylor, L. (2014). The Effect of Different Environmental Conditions on the Decision-making Performance of Soccer Goal Line Officials. *Research in Sports Medicine, 22,* 425-437. doi:10.1080/15438627.2014.948624

Winter, B., Breitenstein, C., Mooren, F.C., Voelker, K., Fobker, M., Lechtermann, A., … Knecht, S. (2007). High impact running improves learning. *Neurobiology of Learning and Memory, 87*, 597-609. doi:10.1016/j.nlm.2006.11.003

Yerkes, R.M. & Dodson, J.D. (1908). The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology and Psychology, 18*, 459-482. doi:10.1002/cne.920180503

Table 1. Risk of Bias Quality Assessment by Downs and Black Checklist (1998).

Study	Reporting (11)	External Validity (3)	Internal Validity: Bias (6)	Internal Validity: Confounding (6)	Power (1)	**Total Score**	
						(27)	**%**
1. Adam et al. (2008)	10	1	4	4	1	**20**	**74**
2. Chandra et al. (2010)	7	1	3	4	0	**15**	**56**
3. Caldwell et al. (2012)	10	0	4	4	0	**18**	**67**
4. Cvirn et al. (2019)	10	1	4	2	0	**18**	**67**
5. Donnan et al. (2020)	11	1	4	5	1	**22**	**81**
6. Gerhart et al. (2020)	11	1	3	5	0	**20**	**74**
7. Kruk et al. (2001)	9	1	6	5	0	**21**	**78**
8. Ji et al. (2017)	11	1	4	5	0	**21**	**78**
9. MacLeod et al. (2018)	11	1	4	5	1	**22**	**81**
10. McMorris et al. (2006)	10	1	4	4	0	**19**	**70**
11. Parker et al. (2013)	11	1	4	2	1	**19**	**70**
12. Radakovic et al. (2007)	10	1	4	3	0	**18**	**67**
13. Roh et al. (2017)	10	1	4	4	0	**19**	**70**
14. Shibasaki et al. (2019)	10	1	3	5	0	**19**	**70**
15. Tamm et al. (2014)	9	1	4	4	0	**18**	**67**
16. Tamm et al. (2015)	9	1	4	4	0	**18**	**67**
17. Taylor et al. (2014)	11	1	4	5	1	**22**	**81**
18. Tikuisis & Keefe (2005)	10	1	4	4	0	**19**	**70**
19. Van Cutsem et al. (2015)	11	1	5	6	0	**23**	**85**
20. Watkins et al. (2014)	11	1	4	5	0	**21**	**78**

Table 2. Summary of included studies for effects of exercise in cold and hot environments on cognition

AUTHORS	SAMPLE	EXP. DESIGN	ENV. TEMP (°C, %RH)	EXERCISE	T_C (°C)	COGNITIVE TASK	FINDINGS
ADAM ET AL. (2008)	8 (6**M**, 2**F**) moderately fit soldiers (24 ± 6yrs; 48 ± 9ml.kg^{-1}.min^{-1})	Repeated measures partially counter-balanced	*Cold:* 2°C (50%) euhydrated 2°C (50%) hypohydrated *Temperate:* 20°C (50%) euhydrated 20°C (50%) hypohydrated	1-hr cycling @ 60% VO_2 peak (~550kcal exp) **Moderate**	No difference post-exercise ≠ between conditions.	30-min marksmanship simulator pre- and post-exercise – 120 (300m) 6-s targets presented and scanning visual vigilance.	A significant temperature × exercise interaction for total response latency ($F = 8.65$, $p < .05$); significantly faster response post-exercise in temperate vs. pre-exercise, but not in cold. Target detection time was significantly longer in the cold than temperate during sentry duty performance ($p < .05$). Friend-foe % accuracy improved from pre-to-post exercise across all conditions ($p < .05$).
JI ET AL. (2017)	20**M** moderately active university students (23.5±2yrs; #VO_2max).	Repeated measures randomised counter-balanced	*Cold:* 10°C (50%) *Temperate:* 25°C (50%)	60-min passive exposure → Running 3-min WU @ 5km/hr → Running @ 60% HRR (~23min) **Moderate**	#	~15-min cognitive battery at baseline, post 45-min rest (rest), immediately post-exercise, and 30-min post-exercise. Identification processing speed, 2-back working-memory and set-shifting cognitive flexibility task.	Significant condition × time interaction ($F = 5.23$, $p <.01$, $\eta p^2 = .23$) and main effect of condition ($F = 6.70$, $p =.02$, $\eta p^2 = .27$) for working-memory RT. RT faster post-exercise compared to pre-exercise in temperate, but not different between pre-to-post exercise in cold. Significant main effect of condition on working-memory accuracy ($F = 4.78$, $p = .04$, $\eta p^2 = .21$); lower in cold vs. temperate. Main effect for condition ($F = 6.44$, $p = .02$, $\eta p^2 = .26$), time ($F = 2.94$, $p = .04$, $\eta p^2 = .14$) and condition × time interaction ($F = 3.16$, $p = .03$, $\eta p^2 = .15$) on identification processing speed, driven by RT slowing between baseline and rest time-points (pre-exercise) ($p = .01$).
KRUK ET AL. (2001)	9**M** Polish 3rd league footballers (19 ± 2.6yrs; 54.9 ± 8.3 ml.kg^{-1}.min^{-1} ¶)	Repeated measures randomised double-blind	*Cold:* 4°C (70%) placebo 4°C (70%) caffeine	Graded cycling test (50W start) 50W ↑ every 3-min; 30-s rest between loads. **Vigorous**	#	Multiple choice RT pre-, during the end of each exercise load and post-exercise.	RT quicker between 100-200W stages vs baseline in 22˚C ($p < .05$) and at 200W vs. baseline in 4˚C but was slower >300W compared to baseline in both conditions ($p < .05$). Condition × supplement interaction described (no values reported); RT significantly quicker with

AUTHORS	SAMPLE	EXP. DESIGN	ENV. TEMP (°C, %RH)	EXERCISE	T_C (°C)	COGNITIVE TASK	FINDINGS
			Temperate: 22°C (60%) placebo 22°C (60%) caffeine				caffeine vs. placebo in temperate ($p < .01$) at 100, 150 and 200W, but no difference in cold ($p > .05$).
VAN CUTSEM ET AL. (2015)	9**M** well-trained athletes (23 ± 3yrs; 63.6 ± 4.5ml.kg^{-1}.min^{-1})	Repeated measures, randomised, double-blind	*Lower Temperate*: 15°C (0m) *Lower Temperate + Altitude*: 15°C (3800m) *Higher Temperate*: 25°C (0m) *Higher Temperate + Altitude*: 25°C (3800m). (30-40%)	5-min WU **C** at 100W ↓ 30-min TT at 75% W_{MAX} (free to ↓ or ↑ power output). **Vigorous**	No effect of temperature condition on T_C≠	Pre- and post-exercise; 5-min PVT task	No two-way interaction effects were observed for mean RT. Higher temperatures did not show any influence on mean RT ($p > .05$). No two-way interaction effects observed for individual RT variability ($p > .05$). The higher temperature had no effect on RT variability. No main effects for time were noted.
WATKINS ET AL. (2014)	13**M** active participants (19.6 ± 3yrs, **#**VO_2max).	Repeated measures, randomised, counter-balanced	*Cold:* -5°C (50%) *Temperate:* 18°C (50%) *Hot:* 30°C (50%)	90-min protocol; 2 × 45-min halves (/15-min rest) side-stepping in 2 × 1m box. **Light**	Lower T_C in -5°C (36.9 ± 0.4°C) than 18°C (37.1 ± 0.2°C) at all time-points post 5-min ($p < .001$).	Pre-, half-time and post-exercise numerical vigilance, and tracking/visual RT dual-task tests.	Main effects for condition ($F = 5.70$; $p = .01$) and time ($F = 4.50$, $p < .01$) for vigilance hit scores. Hit scores higher in temperate than in cold and were higher at 0-min than 90-min across conditions ($p = .02$). A main effect for time was found for vigilance miss scores ($F = 5.60$, $p < .01$). Miss score % increased at 90-min vs. 0-min ($p < .05$) across all conditions. Main effect for time for dual-task tracking ($F = 5.10$; $p < .01$) and dual-task miss scores ($F = 3.70$, $p = .02$). Tracking declined from 0-min to 45-min across conditions, and % miss scores increased after 45-min vs 0-min.

AUTHORS	SAMPLE	EXP. DESIGN	ENV. TEMP (°C, %RH)	EXERCISE	T_C (°C)	COGNITIVE TASK	FINDINGS
TAYLOR ET AL. (2014)	13**M** PA semi-pro football players (6) or referees (7) (20.3 ± 2.2yrs; #VO_2max).	Repeated measures randomised	*Cold:* -5°C (50%) *Temperate*: 18°C (50%) *Hot*: 30°C (50%)	105-min protocol; 90-min running, 2 × 45-min halves of intermittent running /15-min rest). **Vigorous**	No overall difference between 18°C and 30°C (p > .05). T_C Δ pre-to-post exercise greater in 30°C vs 18°C (p < .001).	Pre-, HT and post-exercise numerical vigilance, and tracking/visual RT dual-task tests.	No condition, time or condition × time interaction effects for vigilance hit, false, or miss scores, or for dual-task false, miss or tracking scores (p's > .05).
CALDWELL ET AL. (2012)	8**M** active university students (27.1 ± 6.2yrs; #VO_2max).	Repeated measures, counter-balanced	*Temperate*: 20°C (30%) *Hot-Dry (HD)*: 48°C (20%) *HDLC*: 48°C (20%) + liquid cooling (15°C)	2-hour protocol. 8 × 13-minute low intensity cycling bouts at 30W **Light**	Higher T_C max in HD (38.9 ± 0.3°C) than HDLC (37.3 ± 0.1°C) and temperate (37.0 ± 0.1°C) (p < .05).	~10-min test battery pre- and 30-minute intervals during exercise; vigilance, divided attention and filtering, verbal working-memory, problem solving and perceptual RT.	No main effects or treatment by time interactions for any cognitive measure (p > .05).
TIKUISIS & KEEFE (2005)	11 (9**M**, 2**F**) military personnel (28.9 ± 6yrs; #VO_2max)	Repeated measures, partially counter-balanced	*Temperate*: 22°C *Hot Hydrated (HH):* 28-30°C *Hot Dehydrated (HD):* 28-30°C (#%) 42°C liquid suit worn to ↑ T_C	30-min bouts of 25-min walking at 3km•hr^{-1} followed by 5 min seated rest (max 4-hrs). → 15-min friend vs foe detection shooting task during last 15 mins of walking in each bout **Light**	Higher T_C in HH and HD than temperate after 50-min (p <.05); 180-min: temperate 37.35 ± 0.26°C; HH 38.41 ± 0.29°C; HD 38.47 ± 0.2	Simulated patrol scenario using combat firing simulator. 3 × 5-min shooting segments during last 15 mins of walking in each bout; friend vs. foe detection task, 12 × 6-s targets presented, 8 foe & 4 friendlies.	Marginally lower friendly target detections across all trials compared with foe targets (p < .05), attributed to lower detection rate of friendly targets at 180-min during HH than in temperate and HD.

AUTHORS	SAMPLE	EXP. DESIGN	ENV. TEMP (°C, %RH)	EXERCISE	T_C (°C)	COGNITIVE TASK	FINDINGS
MCMORRIS ET AL. (2006)	8**M** active paid volunteers (22.2 ± 3.23 yrs.; #VO_2 max).	Repeated measures, counter-balanced	*Temperate:* 20°C (40%) *Hot:* 36°C (75%)	20-min cycling at 100W → 10-min rest → 20-min cycling at 100W → 70-min seated rest. **Light**	Mean Δ T_C post-treatment higher in 36°C (+1.10 ± 0.1°C) than 20°C (-0.35 ± 0.22°C) (p < 0.001).	Pre-, post-exercise and post-recovery working-working memory, visual choice RT, verbal and spatial short-term memory tests.	Working-memory poorer post-exercise than pre-exercise in 36°C (p < .01, d = 1.60). Working-memory post-recovery worse than pre-exercise in 36°C (p < .01, d = 1.40). Post-exercise Δ working-memory poorer in 36°C than in 20°C (p < .05, d = 1.10).
CVIRN ET AL. (2019)	73 (62**M**, 11**F**) firefighters *Temperate*: 45 participants (38**M**, 7**F**; 36.4 ± 14.2 yrs) *Ho*t: 28 participants (24**M**, 4**F**; 34.7 ± 13.2 yrs) #VO_2max	Independent measures	*Temperate:* 18-20˚C *Hot:* 33-35˚C (#%)	3 × 2-hour sessions (13:50, 15:50 and 17:50hrs) including: 55-min self-paced timed circuit (physical woodland firefighter tasks) → 20-25-min of physiological tests → 20-25-min cognitive tests → 15-20-minute rest period **Moderate**	#	Pre- and (~20-25 minutes) post-exercise bouts, Stroop and Walter Reed PVT	Stroop matching word-pairs RT slower in temperate vs. hot (F = 4.01, p < .05). Condition × time-of-day effect for Stroop matching word-pairs (F = 3.51, p = .04) found RT was slower in temperate at 13:50h (p = .03) and 15:50h (p = .02) vs. hot. Effect of condition for Stroop non-matching word-pairs RT (F = 6.84, p = .01): RT was slower in hot vs. cold. Effect of time-of-day for Stroop non-matching word-pairs RT (F = 4.95, p = .01): RT was slower at 17:50h vs. 13:50h (p = .01) and 15:50h (p < .01). A condition × hydration interaction was found for PVT RT (F = 4.17, p = .04), showing dehydrated RTs in the hot condition were slower vs euhydrated values in both temperate and hot conditions. A hydration × condition × time-of-day interaction for PVT lapses (F = 6.99, p = .001). Lapses were higher by 17:50h for hot dehydrated values vs. hot euhydrated values (p < .001) and were higher than euhydrated (p < .001) and dehydrated values (p = .001) in temperate. Lapses were higher by 17:50h for dehydrated values in hot compared to 13:50h (p < .001) and 15:50h (p < .001).

AUTHORS	SAMPLE	EXP. DESIGN	ENV. TEMP (°C, %RH)	EXERCISE	T_C (°C)	COGNITIVE TASK	FINDINGS
							A time-of-day effect (*F* = 7.15, *p* = .001) showed PVT lapses were higher at 17:50h vs 13:50h (*p* < .001) and 15:50h (*p* < .01). Condition × time-of-day interaction on lapses (*F* = 4.42, *p* = .01) showed lapses were higher by 17:50h in hot than control (*p* = .003).
GERHART ET AL. (2020)	10 **(8M, 2F)** PA future emergency service personnel (24 ± 2.5 yrs; height 177.2 ± 4.9 cm; weight 88.2 ± 20.2 kg; body fat 23.9 ± 12.9%; 49.7 ± 15.8 ml/kg/min)	Repeated measures, counter-balanced	*Temperate:* 25.0˚C (40%) *Hot:* 37.8˚C (60%)	10-minute walk (70-75% HRmax) → 15 × sandbag lifts → 10-minute walk (70-75% HRmax) → 15 sandbag lifts (between ~30-50% of VO_2 max throughout exercise) ¶ **Moderate**	Marginally higher 30-mins post in hot vs temperate conditions (*p* = .002) but was not different during exercise where it increased throughout exercise across both conditions (*p* < .05). Max reached ~38.0˚C ≠.	Pre-, and 30-minutes post-exercise; Stroop Colour-Word Test (SCWT)	No condition × time interaction (*F* = 0.355, *p* = .80), condition (*F* = 1.266, p = .29) or time (*F* = 1.644, *p* = .20) effect for SCWT.
PARKER ET AL. (2013)	40 (**24M, 16F)** healthy participants. Temperate: 9**M** (31 [24-37] yrs); 11**F** (27 [24-31] yrs).	Independent measures, randomised	*Temperate*: 22-24°C *Hot*: 35-38°C (#%)	90-min treadmill walking @ 40-45% VO_2 max with a weighted backpack (20% BM) / 3 × 10-min breaks. **Moderate**	Rate of increase greater in hot (*p* < .07) but no main effect of condition (*p* = .08).	Pre- and post-exercise; Walter Reed PVT and Wisconsin Card Sorting Test (WCST).	More correct responses (*p* < .001), fewer errors (*p* < .001) and more conceptual responses (*p* = .001) for WCST post-exercise in both hot and temperate conditions. Perseverations and perseverative errors (*p* < .01) decreased in both conditions' pre-to-post exercise.

AUTHORS	SAMPLE	EXP. DESIGN	ENV. TEMP (°C, %RH)	EXERCISE	T_C (°C)	COGNITIVE TASK	FINDINGS
	Hot: 15**M** (26 [23-30] yrs.); 5**F** (27 [20-34] yrs.) >35ml.kg^{-1}.min^{-1}#						
RADAKOVIC ET AL. (2007)	40**M** soldiers (20.1 ± 0.9yrs; 16.6 ± 3.2%; 57.8 ± 7.2ml.kg^{-1}.min^{-1}¶)	Independent measures, randomised	*Temperate*: 20°C *Hot-Unacclimated*: 40°C (UN) *Hot-Passive acclimated:* 40°C (P) *Hot-Active acclimated*: 40°C (A) (#%)	Exertional Heat Stress Test (90-min max); walking at 5.5km/hr on a treadmill in combat uniform with a 20kg backpack. **Moderate**	Steady tympanic ˚C increase throughout EHST in all 40°C groups ≠ (max >~39.3˚C in UN)	Pre- and immediately post- EHST; Cambridge Neuro-psychological Battery; selective, divided and sustained attention, motor screening, RT and rapid visual information processing.	For complex rapid visual information processing, in 40°C (UN), correct response % declined pre-post EHST. A delay in RT movement time post-EHST compared to baseline in 40°C (UN) was also found (p < .05).
SHIBASAKI ET AL. (2019)	15**M** college well-trained rugby and baseball players (20.8 ± 0.9yrs; 83.6 ± 8.1kg; 173.2 ± 6.5cm)	Repeated measures, randomised	*Temperate:* *20*°C *Hot:* *35*°C (30-40%)	4 × 15 min cycling bouts; intensity set to maintain a HR of ~130 bpm in temperate (132 ± 27 W) / 10 min rest **Moderate**	Tympanic ˚C was higher in hot compared to temperate across all time-points (max ~38.0 ˚C) in final exercise bout) **≠.**	Pre- and immediately post- each 15 min exercise bout; Go/No-go paradigm	A significant condition × time interaction was observed for Go/No-go RT (p < .05) **≠,** though **f**urther analyses showed no significant effects under the 20°C and 35°C conditions. Additionally, no significant main effects or interactions were noted for Go/No-go error rate (p > .05).
DONNAN ET AL. (2020)	12**M** well-trained football players	Repeated measures, counter-balanced	*Temperate:* 18˚C (50%) *Hot:* 32˚C (50%)	2 × 40-minute cycling intermittent sprint protocol / 15-min rest	Higher between 20-40 mins in hot (38.40 ± .43˚C) than temperate	Pre- and during exercise (every 10-minutes). Stroop and vigilance tasks.	Preliminary analyses revealed no differences in any cognitive function score at baseline (pre-exercise). Condition × time interaction (F = 3.673, p = .022) where congruent RT was quicker between 20th-40th min of the CISP in hot compared to control was not

AUTHORS	SAMPLE	EXP. DESIGN	ENV. TEMP (°C, %RH)	EXERCISE	T_C (°C)	COGNITIVE TASK	FINDINGS
				Vigorous	(37.92 ±.53 ˚C) (*p* = .015). Higher overall in hot compared to temperate (p = .047).		different between conditions in the first 20 mins or following half-time (*p*'s > .05). No condition, time, or condition × time interactions for congruent Stroop accuracy (*p* > .05). A main effect for time was found for incongruent Stroop accuracy (*F* = 6.136, p = .002), where % accuracy was lower between 20-40 mins and 40-60 mins of the CISP compared to the first 20 mins. No condition (*F* = 2.723, *p* = .127) or condition × time interaction (*F* = 1.375, *p* = .268) was found for incongruent accuracy. No effects for condition, time or condition × time interactions were found for incongruent Stroop RT. No effects for condition, time or condition × time interactions were found for vigilance RT or accuracy (*p*'s > .05).
MACLEOD ET AL. (2018)	8**F** elite hockey players (22 ± 3yrs; 53.4 ± 2.2 ml.kg^{-1}.min^{-1})	Repeated measures, randomised	*Temperate*: 16 ± 3°C (53 ± 2%) **+** Fluid Intake 16 ± 3°C (53 ± 2%) **–** Fluid Intake *Hot*: 33.3 ± 0.1°C (59 ± 1%) **+** Fluid Intake 33.3 ± 0.1°C (59 ± 1%) **–** Fluid Intake	2 × 25min blocks: standing, walking, fast walking, jogging (75% VO_2 max), cruising (95% VO_2 max) and lunging on a treadmill / 10-min rest **Vigorous**	T_C increased over time (*p* < .001); greater increase in 33.3°C than 16°C (*p* <.05) ≠	~15-min cognitive test battery pre- and post-exercise. Stroop, visual search (VS) and Sternberg WM.	Condition × time interaction *trend* (*p* = .08) was found where Stroop RT was quicker post-exercise in the heat (*p* = .01; *d* = 0.39) vs pre-exercise, but not in temperate (*p* = .51, *d* = 0.16). A significant effect of condition was found, where complex VS RT was quicker in hot conditions than in temperate (*p* = .001; *d* = 0.47). A condition × time interaction (*p* < .01) found WM % accuracy increased pre-to-post exercise in temperate (*p* = .04; *d* = 0.46) but not in hot (*p* = .61, *d* = 0.12). Main effects for condition (*p* = .02, *d* = 0.13) and time (*p* < .01, *d* = 0.26) were found for WM RT. WM RT was quicker in hot than in temperate. RT got faster pre-to-post exercise across all conditions (*p* < .05).
ROH ET AL. (2017)	10**M** rugby and soccer collegiate	Repeated measures	*Temperate*: 18°C (50%)	60-min running at 75% HRR	Tympanic ˚C higher in 32°C (NF)	Stroop Colour and Word Test performed at rest, immediately	Stroop word scores increased immediately post-exercise in 18°C vs. rest (*p* < .05). No change in other conditions (*p* > .05).

AUTHORS	SAMPLE	EXP. DESIGN	ENV. TEMP (°C, %RH)	EXERCISE	T_C (°C)	COGNITIVE TASK	FINDINGS
	athletes (18.8 ± 0.2yrs; 56.6 ± 1.6 ml.kg^{-1}.min^{-1}).	P1-5 = 18°C→32°C →32°C+W →32°C+S P6-10 = 32°C→32+S →18°C→32 °C+W	*Hot*: 32°C (50%) + No Fluid (NF) 32°C (50%) + Water (W) 32°C (50%) + Sports Drink (S)	**Vigorous**	vs all conditions at 30-min, immediately post-exercise and 60-min post-exercise ≠ ($p < .05$).	after exercise and 60-min post-exercise. Comprised of word, colour and colour-word scores.	Colour scores increased immediately post-exercise and 60-min post-exercise in 18°C vs. rest ($p < .05$). No change in other conditions ($p > .05$). Colour word scores were lower immediately post-exercise in 32°C (NF) vs. all other conditions ($p < .05$). At 60-min post-exercise, colour word scores were lower in 32°C (NF) than 18°C ($p < .05$). Colour-word scores increased immediately post-exercise in 18°C and 32°C (W) and 32°C (S) vs. rest, and 60-min post-exercise in 18°C and 32°C (W) ($p < .05$). Values ≠.
TAMM ET AL. (2014)	24**M** healthy volunteers (25.3 ± 3.9yrs; 52.4 ± 6.9ml.kg^{-1}.min^{-1})	Repeated measures, pseudo-randomised *(H_{EX} always preceded N_{EX})*	*Temperate passive* (T_{NE}): 22°C (35%) *Temperate active* (T_{EX}): 22°C (35%) *Hot passive* (H_{NE}): 42°C (18%) *Hot active* (H_{EX}): 42°C (18%)	In H_{EX} and N_{EX} 20-min stood static before walking at 60% max until exhaustion. (H_{EX} duration; 85 ± 28-min, #N_{EX}). **Vigorous**	T_C difference in N_{EX} (38.2 ± 0.07°C) vs H_{EX} (39.2 ± 0.09) ($p <.001$).	Pre, at 10-min and 60-min during exercise and post-exercise. Time production task – 4x7 target intervals (0.5, 0.75, 1, 2, 3, 5 and 10-s).	A compression in the proportionality between subjective and objective time (a_1) was observed at 10-minutes ($F = 10.31$, $p < .05$) and 60-minutes ($F_{1,18} = 9.13$, $p < .01$) in H_{EX} (b = 0.97 ± 0.04s; 0.87 ± 0.04s) compared to T_{EX} (b = 1.14 ± 0.09s; 1.11 ± 0.07s) – indicating a quicker pacemaker rate in H_{EX}.
TAMM ET AL. (2015)	20**M** healthy volunteers (24.9 ± 3.7yrs; 53.8 ± 7.1 ml.kg^{-1}.min^{-1}).	Repeated measures	*Hot-Dry* (HD): 42°C (18%) *Temperate:* 22°C (35%) *Hot-Dry Acclimated* (HD_{AC}): 42°C (18%) + 10-day acclimation	Treadmill walking @ 60% VO_2 peak until exhaustion. 6km.hr^{-1}, between 7-15% incline. **Vigorous**	T_C lower post-exercise in neutral (38.2 ± 0.5) vs. HD (39.7 ± 0.4) and HD_{AC} (39.7 ± 0.4) ($p < .05$).	Pre, at 10-min and 60-min during exercise and post-exercise. Time production task – 4x7 target intervals (0.5, 0.75, 1, 2, 3, 5 and 10-s).	An effect of condition ($F_{2,28} = 5.06$, $p < .05$) and time ($F_{2,28} = 3.60$, $p < .001$), and a marginal interaction effect ($F_{4,56} = 2.26$, $p = .07$) for the proportionality between perceived and objective time. A compression in the proportionality between subjective and objective time (a_1) was observed at 60-minutes in HD compared to temperate and HD_{AC} conditions – indicating a quicker pacemaker rate in the non-acclimated hot condition. A significant effect of time ($F_{2,28} = 6.63$, $p < .01$) and condition × time interaction ($F_{4,56} = 3.51$, $p < .05$) found for shortest time residual produced by participants (a_0). Significantly smaller time

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							residuals produced at 60-minutes compared to post-exercise in temperate condition ($p < .05$).
CHANDRA ET AL. (2010)	15**M** university students (24.45 ± 1.34yrs; #VO_2max).	One trial only; 3 progressive heat loads	*Hot:* 28.6°C → 30.6°C → 33.2°C (~61%) *5-min exposures*	15-min (3x5-min bouts) cycling at 60kg•m/h (60rpm) **Light**	#	Simple auditory and visual RT – pre- and post- each 5-min bout of exercise	Faster visual and auditory RT (p = **#)** post-exercise in 28.6°C vs. pre-exercise. Followed by slowed RT post-exercise in 30.6°C and in 33.2°C. *Please note*: No clear specific coefficients are reported to compare pre-to-post scores (only stated in text whether differences were statistically significant)

Footnote: **M** = Male; **F** = Female, PVT = psychomotor vigilance task; **#** = values not reported or measured; **≠** = values demonstrated in graph form only; **¶** = calculated from temperate placebo conditions. a_1 = slope of linear function (i.e. proportionality between subjective and objective time), a_0 = intercept of linear function (i.e. shortest time residual participant produced)

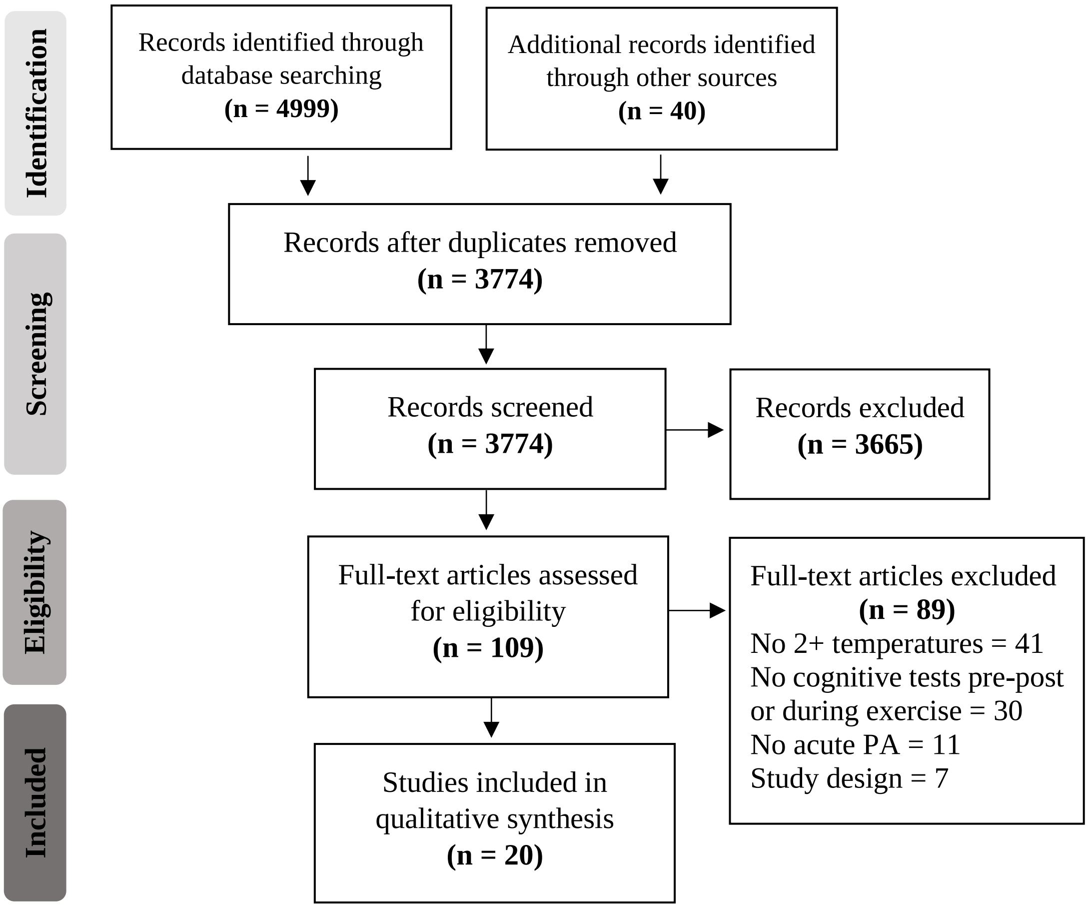

Figure 1: PRISMA Protocol for Systematic Review Screening Process across the three searches conducted (PA = physical activity)