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Research article

A Combination of Ice Ingestion and Head Cooling Enhances Cognitive Performance during Endurance Exercise in the Heat

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Abstract

This study assessed the effectiveness of head cooling during exercise in the heat on cognitive performance, either alone or with ice ingestion. Ten healthy males, non-acclimatized to heat, ran (70% $\dot{V}O_2peak$) for 2×30 min in heat (35 ± 0.9°C, 68.2 ± 6.9% RH). Participants completed 3 trials: 10 min of head cooling during exercise (HC); precooling with crushed ice ($7g \cdot kg^{-1}$) and head cooling during exercise (MIX); or no-cooling/control (CON). Working memory was assessed using the automated operation span task (OSPAN) and serial seven test (S7). Following MIX, S7 scores were improved compared to CON (12 ± 9.5, p = 0.004, *d* = 1.42, 0.34-2.28) and HC (4 ± 5.5, p = 0.048, *d* = 0.45, -0.47 to 1.3) during exercise. Moderate to large effect sizes were recorded for S7 and OSPAN following MIX and HC compared to CON, suggesting a tendency for improved cognitive performance during exercise in heat. Following precooling (MIX), core body temperature (T_c) and forehead temperature (T_h) were lower compared to baseline (-0.75 ± 0.37°C, p < 0.001; -0.31 ± 0.29°C, p = 0.008, respectively) but not in HC or CON (p > 0.05). Thermal sensation (TS) was lower in MIX and HC compared to CON during exercise (p < 0.05). The reduction in T_c, T_h and TS with MIX may have attenuated the effect of heat and subsequently improved working memory during exercise in heat.

Key words: Cooling, forehead temperature, cognitive function.

Introduction

Cognitive function refers to mental processes that involve information processing, decision making and producing appropriate responses for problem solving (Purves, 2008) which occur in the frontal lobe of the brain (Buchbaum, 2004). Notably, sporting success requires cognitive function (perception, attention, and working memory) to operate optimally, particularly when exercising in the heat (Furley and Memmert, 2010). However, mental fatigue and reduction in cognitive capacity have been observed whilst exercising in thermally strain environment and these effects are associated with rise in core body temperature (T_c). During heat exposure and/or exercise, T_c increases, thus raising the temperature of blood flowing to the brain (Nybo et al., 2002). This is associated with the reduction in cerebral blood flow that could impair the delivery of substrates to the brain specifically oxygen and glucose and can potentially compromise brain function (Nybo et al., 2002). Notably, impairment in cognitive function has been reported when $T_c \geq 38.5°C$ (Gaoua et al., 2011; Racinais et al., 2008; Saldaris et al., 2020; Hocking et al., 2001).

Methods (external or internal) that cool the head/brain have been investigated with the aim of improving complex cognitive performance in heat mainly in working memory and decision making (Lee at al., 2014; Saldaris et al., 2019). Notably, Lee et al. (2014) reported that 5 min of necktie precooling prior to running in the heat (30°C, 70% relative humidity, RH), reduced neck temperature (~10.4°C, p ≤ 0.05) and improved cognitive performance (reaction time & executive control) assessed before and after exercise compared to control. Wearing a cooling cap represents another external method for cooling the head with only one study having assessed this method to date with no benefit on complex cognitive performance (working memory) found (Mazalan et al., 2021). Although cold water immersion has been suggested to be a gold standard in reducing heat strain, the cooling impact on muscle temperature and the administration whilst exercising need to be considered (Quod et al., 2006).

In regard to internal precooling, Saldaris et al. (2020) reported that precooling with crushed ice ingestion for 30 min (-0.1°C; $7g \cdot kg^{-1}$) reduced thermal sensation (TS), T_c by -0.8°C and T_h by -0.5°C compared to no cooling during running in the heat (35°C, 53% RH). Importantly, precooling maintained decision making (choice reaction time) and working memory (serial seven test [S7]) compared to no-cooling (Saldaris et al., 2020).

Further, combining internal and external cooling prior to exercise in the heat has also resulted in positive physiological outcomes. Levels et al. (2013), reported that precooling using a cooling cap (-10°C) combined with ice ingestion ($2 g \cdot kg^{-1}$) lowered T_c by ~0.6°C and reduced TS immediately after cooling but did not alter subsequent power output during a 15 km cycling time-trial in heat (30°C, 50% RH), compared to no-cooling. Cognitive performance and T_h were not assessed in this study.

Another cooling technique growing in popularity is percooling, which refers to cooling parts of the body during exercise either continuously or intermittently. This method of cooling has resulted in a greater cooling effect on physiological (Ruddock et al., 2017; Tyler and Sunderland, 2011; Stevens et al. 2016) and cognitive performance assessed during rest and after exercise in the heat (Racinais et al., 2008; Saldaris et al., 2020) compared to precooling. Constant head and neck cooling during exercise has been found to sustain a lower T_c compared to no-cooling or precooling thus reducing thermal strain associated with exercise in the heat (Kenefick et al., 2007). Gaoua et al. (2011)

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reported that continuous head cooling whilst walking in the heat (50°C, 50% RH), decreased T_c by ~0.6°C, T_h by ~1.9°C, and improved cognitive performance (spatial span test) assessed after exercise compared to a no-cooling (50°C, 50% RH). To date, no published studies have assessed the effect of intermittent percooling, using head cooling, on cognitive performance during exercise in the heat. This form of cooling may be preferable for athletes who are uncomfortable wearing a cooling cap for long periods of time.

The combination of precooling and percooling during exercise in the heat has been found to have greater physiological and psychological benefit than the use of either cooling modality alone (Best et al., 2018). Specifically, Hasegawa et al. (2006) reported that a combination of water immersion, 25°C (precooling: 30 min) and water ingestion, 14-16°C every 5 min (percooling) resulted in lower T_c and skin temperature (T_{sk}); longer exercise time to exhaustion; lower TS and rating of perceived exertion (RPE) compared to water ingestion alone (percooling) and no-cooling during cycling in heat (32°C, 80% RH). Cognitive performance was not assessed in this study.

Therefore, this study aimed to assess the effects of combining precooling (internal) and intermittent percooling (external) on cognitive performance assessed prior, during and after exercise in the heat. It was hypothesised that combining precooling via crushed ice ingestion with head cooling during exercise (percooling) would lower T_c and T_h, leading to improved cognitive performance (specifically, working memory function, assessed with S7 and operation span [OSPAN] tasks) in the heat compared to intermittent percooling (head cooling) or no-cooling alone.

Methods

Participants

Ten healthy males, non-acclimatized to heat (age 26.1 ± 1.9 y; height 1.75 ± 0.04 m; body-mass 76.8 ± 3.8 kg; $\dot{V}O_2$peak 53.89 ± 4.3 $mL^{-1}\cdot kg^{-1}\cdot min$), participated in this study. All participants reported previous training/running of ≥ 60 min performed ≥ four times per week. Ethical approval was granted (The University of Western Australia). Informed written consent were completed prior to participation in the study.

Preliminary procedures

In the 24 h prior to the first trial session, participants we asked to avoid strenuous exercise, alcohol, and caffeine. Upon arrival, body-mass (Model ED3300; Sauter Multi-Range, Ebingen, Germany) and height (Seca, Hamburg, Germany) were measured. Aerobic capacity was determined via a graded $\dot{V}O_2$peak test on a motorized treadmill (H/P Cosmos, Quasar 3p Medical treadmill, Nussdorf-Traunstein, Germany). Participants begun at 8 $km\cdot h^{-1}$ (1% incline), increasing speed by 1 $km\cdot h^{-1}$ every 3 min until volitional exhaustion (with 1 min recovery in between stages). Oxygen uptake ($\dot{V}O_2$) was measured continuously. Running speed during the subsequent trials was performed at a speed equivalent to 70% of each participant's $\dot{V}O_2$peak. Participants were then familiarized with the cognitive tasks (OSPAN & S7), ingested crushed ice, wore the cooling cap and ran in the climate chamber (35°C, 70% RH) for 30 min.

Experimental designs

Three experimental trials were performed in a randomized order. All trials were conducted at the same time of day, seven days apart to control for circadian variability. Each trial involved running in the heat at 70% of $\dot{V}O_2$peak for 2×30 min bout with a 10 min break between periods. The interventions included: (1) sitting in the climate chamber for 30 min prior to running and head cooling applied during the last 10 min of each 30 min running period (HC: percooling); (2) crushed ice (7$g\cdot kg^{-1}$) ingested whilst sitting during the 30 min prior to the running protocol (precooling) and HC (MIX); (3) a no-cooling trial that involved consuming an equivalent amount of room temperature water while sitting for 30 min prior to running (CON).

Experimental protocol

Eight hours prior to each trial, participants ingested a telemetry capsule (CorTemp®, Palmetto, FL, USA) to enable measurement of gastrointestinal (core) temperature (T_c). On arrival, a mid-stream urine sample (1 ml) was collected to determine pre-exercise hydration status via urine specific gravity (USG) using a refractometer (TE-RM10SG, 1.000-1.070, Test Equip, Dandenong, Australia). In case of hypohydration (USG > 1.020; Volpe et al., 2009), participants then consumed 500 ml of water. Skin thermistors (Skin Sensor S7-1, Physitemp Instruments Inc, NJ, USA) were taped to the forehead (T_h), sternum, left mid-anterior forearm and left mid-posterior calf. Mean skin temperature (T_{sk}) was calculated using the formula described by Burton (1935): $T_{sk} = (0.5 \times T_{sternum}) + (0.14 \times T_{forearm}) + (0.36 \times T_{calf})$.

Participants entered the climate chamber (35°C, 70% RH) and completed a baseline cognitive test (OSPAN) before ingesting either 7 $g.kg^{-1}$ (-0.1°C) crushed ice (MIX) or water, ~22°C (HC and CON) in the subsequent 30 min whilst in a seated position. Participants then ran at 70% of $\dot{V}O_2$peak for 2 × 30 min periods on the treadmill with a 10 min break after the first 30 min. Head cooling (for HC and MIX) was performed whilst running during the last 10 min of each exercise bout. In CON, the cap was worn but not activated. The S7 was performed after the first minute of running during the first bout and then at the 27 min mark of both exercise bouts. The OSPAN was re-administered after the first and second bout of exercise. A 100 ml drink of water (22°C) was ingested every 10 min during exercise to prevent dehydration. Finally, T_c, T_h, T_{sk}, HR, TS (0 = unbearably cold to 8 = unbearably hot; Young et al., 1987), and RPE (Borg scale 6-10; Borg, 1982) were measured every 5 min during exercise.

For MIX, participants ingested 7 $g.kg^{-1}$ body-mass of crushed ice (-0.1°C) 30 min prior to exercise. The ice was ingested in three equal amounts at 0, 10, and 20 min. Commercially available headgear, Elasto-Gel Cranial Cap (Southwest Technologies, Inc, Missouri, USA) was used for HC and MIX (weight: 1.13 kg, thickness: 1.3 mm, dimensions: 31.8 × 22.6 mm). The device covered the whole head and neck areas and was secured around the neck with a velcro strap. Prior to testing, the headgear was kept in a freezer at -10ºC.

The automated OSPAN task, a so-called complex span task used to assess working memory capacity (Turner and Engle, 1989), was performed 30 min prior to the running protocol, immediately after the first 30-min bout of running (during the 10 min break) and at the end of the exercise. The test was administered using Inquisit 5 software (Millisecond Software, Seattle, USA). Participants were required to memorize and then recall in order sequences of between 3 and 7 letters. Letters were presented individually at a rate of 1 item/s. During letter presentation, there was a distractor task: each letter was preceded by a simple math equation (e.g., $8 \times 7 = 65$) that participants had to assess as correct or incorrect. In total, there were 15 trials, and the outcome was measured by the total number of letters recalled correctly-in-position out of 75 (Bayliss et al., 2003). The task's internal consistency is $\alpha = 0.78$, while the test-retest reliability coefficient has been recorded to be $r = 0.83$ (Unsworth et al., 2005).

The serial seven test (S7) assesses concentration and working memory function (Bristow et al., 2016) and was administered after min 1 during the first 30-min bout of running (baseline) and again at the 27th min mark of the first and second 30-min bout of running. Here, participants were required to count down aloud, in sevens, from a random number provided to them (between 900 to 1000) for 1 min. The total number of correct answers and incorrect responses were recorded as outcome measures.

Statistical analyses

Data analysis was computed using the Statistical Package for Social Sciences version 25.0 (SPSS Inc, Chicago, IL, USA). Data was assessed for normality (Shapiro-Wilk test) and sphericity (Mauchly's test). Two-way repeated measures analyse of variance (ANOVA) with within-subject factors time (baseline vs. bout-1 and bout-2 measures at various intervals) and trials (CON; HC; MIX) were used. Statistical significance was accepted at $p < 0.05$. Where main interaction effects occurred, post hoc comparisons (Bonferroni) were conducted and if significance was found, paired sample *t*-tests were used to identify specific condition differences. In addition, Cohen's *d* effect sizes (ES) were used to identify meaningful differences in the data (Cohen, 1988) with only moderate (0.5-0.8) and large (>0.8) ES reported. All values are expressed as mean ± SD.

Results

There were no differences in temperature and humidity (35.5 ± 0.6°C, 69.3 ± 5.2% RH) in the environmental chamber between trials (all $p > 0.05$).

Cognitive tests

Serial seven test performance declined in CON trial but remained stable or even improved over time in the cooling trials. Accordingly, S7 scores yielded main effects of time ($p = 0.007$) and trials ($p = 0.022$), as well as a significant interaction ($p < 0.001$). A significant score reduction was found for CON after the first 27 min bout of exercise versus baseline ($p < 0.001$, $d = 0.21$, -0.68 to 1.08 95% CI), with scores further declining after bout two of exercise versus baseline ($p < 0.001$, $d = 0.68$, -0.27 to 1.52 95% CI). For MIX, S7 scores were greater after 27 min of exercise in both bouts relative to baseline ($p < 0.001$, $d = 0.63$, -1.48 to 0.31 95% CI; $p < 0.001$, $d = 0.47$, -0.45 to 1.32 95% CI, respectively). We observed moderate to large ES after min 27 of the first bout of exercise between HC and CON ($d = 0.66$, 0.29 to1.50 95% CI) and MIX and CON ($d = 1.09$, 0.07 to 1.93 95% CI), with lower scores in the CON trial. Scores were numerically greater in HC after min 27 in the second bout of exercise compared to CON ($d = 0.93$, 0.09 to 1.77 95% CI). Finally, at the end of the second bout of exercise, more correct answers were recorded in MIX compared to CON ($p = 0.004$, $d = 1.42$, 0.34 to 2.28 95% CI) and HC ($p = 0.048$, $d = 0.45$, 0.47 to 1.30 95% CI; Table 1).

The same pattern emerged for the OSPAN scores. The ANOVA returned no significant main effect of trials ($p = 0.27$) but a main effect of time ($p = 0.002$) and a significant interaction effect ($p = 0.001$). A significant score reduction was found for CON after exercise (bout two) compared to baseline ($p = 0.001$, $d = 1.54$, 0.45 to 2.41 95% CI). A large ES was observed for MIX after min 30 of exercise (bout 1) compared to baseline with scores increasing over time ($d = 0.89$, 0.09 to 1.74 95% CI). Further, large ES were found for HC and MIX compared to CON ($d = 1.12$, 0.10 to 1.97 95% CI and $d = 2.18$, 0.93 to 3.09 95% CI, respectively) at min 30 (bout 1), with lower scores in CON. Finally, a large ES indicated a tendency for greater scores in HC and MIX trials compared to CON ($d = 1.63$, 0.51 to 2.49 95% CI; $d = 2.26$, -3.90 to -1.01 95% CI, respectively) after bout two of exercise; Table 1.

Table 1. Mean (±SD), S7 total correct scores and OSPAN total correct scores across cooling and no-cooling trials when exercising in the heat (*n*=10).

Test	Time (min)	Control		Head cooling		Mix cooling	
		Scores	In-correct answer	Scores	In-correct answer	Scores	In-correct answer
S7	0 (baseline)	36 ± 9.6	0 ± 0.8	36 ± 13.1	0 ± 0.3	38 ± 8.1	0 ± 0.4
	Bout 1 exercise-27 min	34 ± 8.9$	1 ± 0.7	40 ± 9.3^{a}	0 ± 0.5	43 ± 7.7$^{a}	0 ± 0.8
	Bout 2 exercise-27 min	30 ± 8.1*$#	2 ± 0.7	38 ± 9.1*#^{a}	1 ± 1.0	42 ± 8.8*#^{a}	1 ± 0.9
OSPAN	Time (min)	Scores					
	-30 (baseline)	60 ± 5.4		60 ± 5.3		62 ± 6.1	
	Bout 1 exercise-30 min	56 ± 5.1$		62 ± 5.6^{a}		67 ± 5.0^{ab}	
	Bout 2 exercise-30 min	51 ± 6.2 #$^{b}		61 ± 6.1#^{a}		65 ± 6.2#^{a}	

The * indicates a significant main effect of trials ($p < 0.05$). The # indicates a significant main effect of time ($p < 0.05$). The $ indicates a significant difference from baseline ($p < 0.05$). The a indicates moderate to large effect size compared to control (d = 0.5-0.8). The b indicates a large effect size compared to baseline ($d > 0.8$).

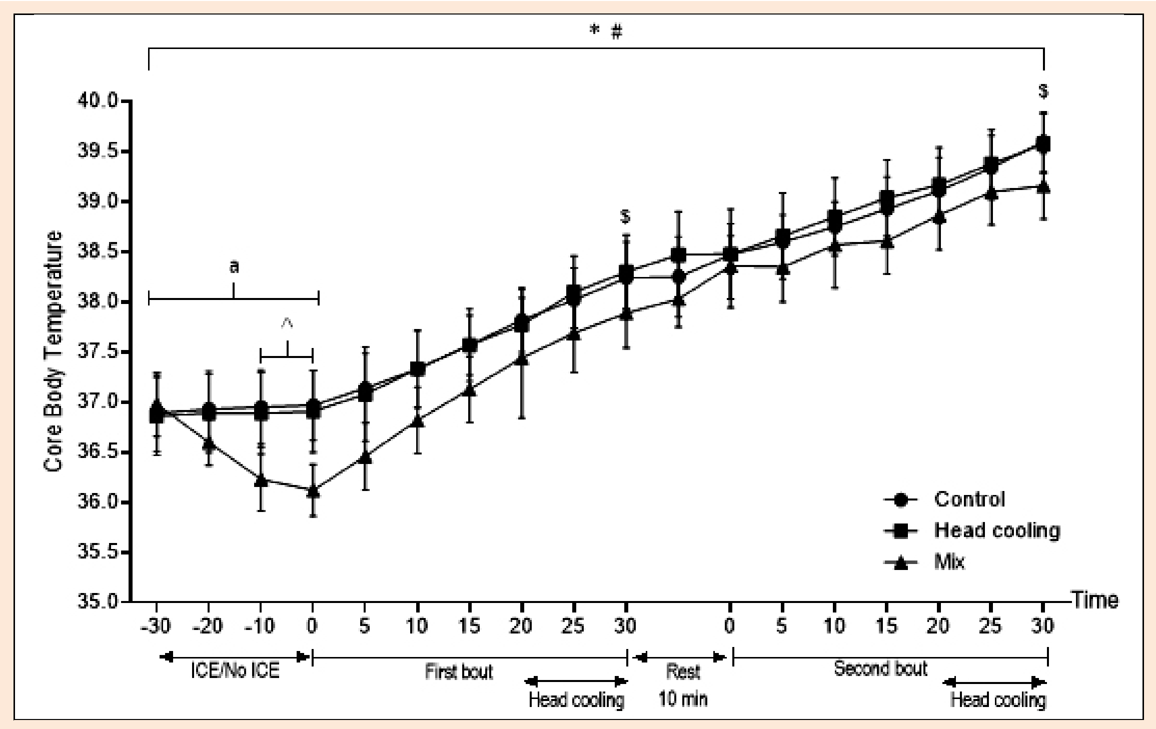

Figure 1. Core body temperature (ºC) of participants in experimental trials (*n* = 10). The * indicates a significant main effect of all trials ($p < 0.05$). The # indicates a significant main effect of time for all trials ($p < 0.05$). The ^ indicates a significant difference of MIX compared to baseline ($p < 0.05$). The a indicates a large effect size of MIX compared to control ($d > 0.8$). The $ indicates a significant effect of MIX compared to HC and CON ($p < 0.05$).

Core body temperature

There was an interaction effect for T_c ($p < 0.001$), and main effects for trials (p = 0.002) and time ($p < 0.001$). Core body temperature was similar at baseline (-30 min) for all trials (CON: 36.89 ± 0.38ºC, HC: 36.84 ± 0.39ºC, MIX: 36.98 ± 0.32ºC, p = 0.618), but became lower in MIX (36.23 ± 0.31ºC) at 20 min of precooling versus baseline (-0.75 ± 0.37ºC, $p < 0.001$, *d* = 2.38, 1.09 to 3.31 95% CI). After precooling, MIX remained lower compared to CON (0.85 ± 0.29ºC, $p < 0.001$, *d* = 2.65, 1.18 to 3.44 95% CI) and HC (0.79 ± 0.42ºC, $p < 0.001$, *d* = 2.12, 0.89 to 3.03 95% CI).

After the first bout of exercise, MIX remained lower compared to CON and HC (MIX: 37.89 ± 0.35ºC, $p < 0.001$, *d* = 2.65, 1.18 to 3.44 95% CI; HC: 38.30 ± 0.37ºC, $p < 0.001$, *d* = 2.12, 0.89 to 3.03 95% CI). This was similar at the end of bout two of exercise where T_c was lower in MIX (39.16 ± 0.33ºC) compared to CON (39.60 ± 0.30ºC, p = 0.001, *d* = 11.41, 7.15 to 13.91 95% CI) and HC (39.58 ± 0.30ºC, p = 0.01, *d* = 1.31, 0.26 to 2.16 95% CI; Figure 1).

Forehead temperature

Main effects for trials (p = 0.031) and time ($P < 0.001$) were found for T_h. Forehead values were similar between trials at baseline (CON 35.61 ± 0.45ºC; HC 35.45 ± 0.53ºC; MIX 35.61 ± 0.33ºC; $p > 0.05$). Following precooling, T_h was lower in MIX by -0.31ºC compared to baseline (p = 0.008, *d* = 0.81, 0.16 to1.65 95% CI) but not in HC (+0.15ºC) and CON (+0.11ºC) ($p > 0.05$). Following the first percooling during exercise, T_h decreased by -0.48ºC (MIX) and -0.47ºC (HC) during min 25 versus min 20 (p = 0.001, *d* = 0.75, 0.21 to 1.6 95% CI; p = 0.012, *d* = 0.99, 0.01 to 1.83 95% CI, respectively). After exercise (bout 1), T_h remained lower in MIX and HC compared to CON (p = 0.009, *d* = 1.53, 0.85 to 8.2 95% CI; p = 0.04, *d* = 1.06, 0.57 to 0.76 95% CI, respectively). Over the second percooling bout T_h was lower by -0.54ºC (MIX) and -0.58ºC (HC) in min 25 compared to min 20 (p = 0.001, *d* = 1.1, 0.09 to 1.95 95% CI; p = 0.001, *d* = 1.2, 0.17 to 2.05 95% CI, respectively). At the end of exercise, T_h was lower in MIX and HC versus CON ($p < 0.001$, *d* = 2.4, 1.1 to 3.33 95% CI and p = 0.002, *d* = 2.7, 1.3 to 3.6 95% CI, respectively; Figure 2).

Skin temperature

While T_{sk} increased in a similar pattern over time in all trials ($p < 0.001$, *d*: CON = 14.25, 8.98 to 17.32 95% CI; *d*: HC = 12.69, 7.97 to 15.43 95% CI; *d*: MIX = 14.28, 9 to 17.36 95% CI) (Figure 3), no differences were found between trials for any time point assessed ($p > 0.05$).

Thermal sensation

An interaction effect was found for TS (p = 0.001), while main effects were found for trials (p = 0.001) and time (*P* = 0.001; Table 2). Following the first percooling, TS decreased over time in HC and MIX, with results different to CON at min 25 (p = 0.001, *d* = 10.61, 6.63 to 12.95 95% CI and p = 0.001, *d* = 7.5, 4.6 to 9.24 95% CI, respectively). Further, TS was lower in HC and MIX versus CON until the end of 30 min (bout 1) of exercise (p = 0.001, *d* = 5.88, 3.53 to 7.33 95% CI and p = 0.001, *d* = 4.24, 2.42 to 5.41 95% CI).

During the second bout of percooling, TS was lower in HC and MIX compared to CON at min 25 (p = 0.001, *d* = 3.64, 2.0 to 4.72 95% CI and p = 0.001, *d* = 3.16, 1.66 to

4.18 95% CI, respectively). Further, TS remained lower until the end of exercise (bout 2) for HC and MIX compared to CON (HC: p = 0.001, *d*=2.91, 1.48 to 3.9 95% CI; MIX: p = 0.001, *d* = 3.35, 1.8 to 4.39 95% CI).

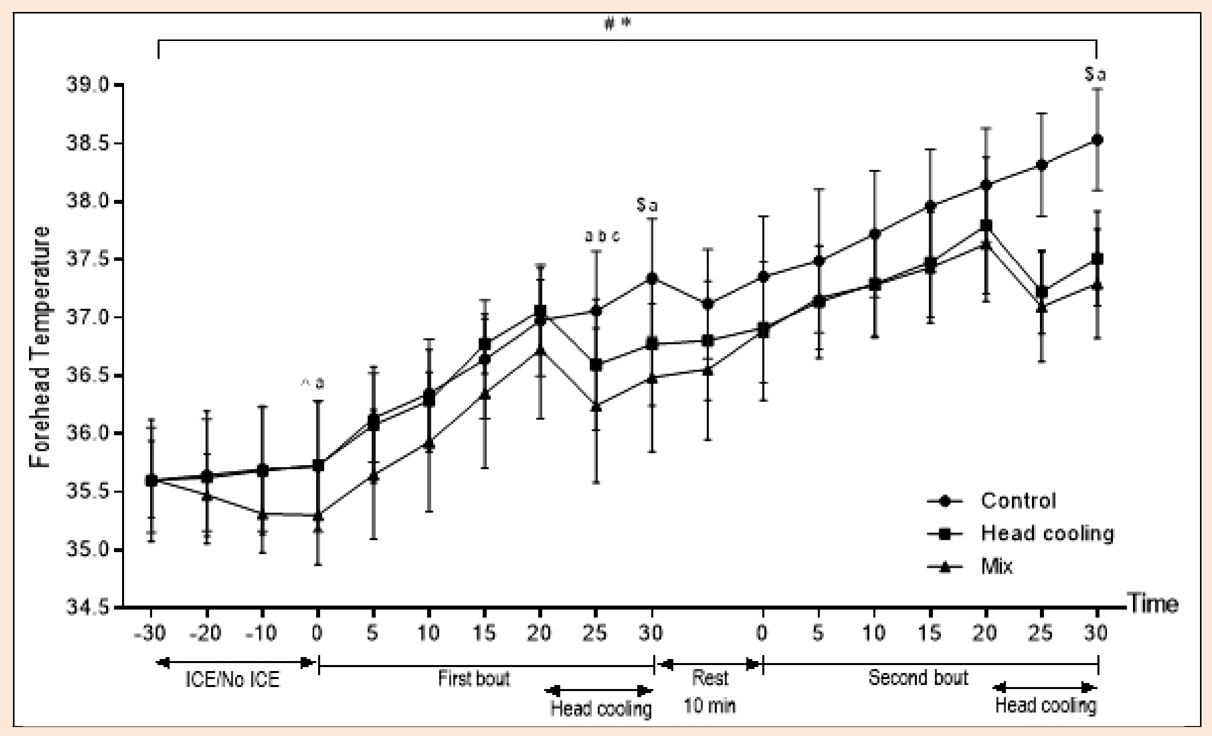

Figure 2. **Forehead temperature (°C) of participants in experimental trials (*n* = 10)**. The * indicates a significant main effect of trials ($p < 0.05$). The # indicates a significant main effect of time for all trials ($p < 0.05$). The ^ indicates a significant difference of MIX compared to baseline ($p < 0.05$). The $ indicates a significant difference of MIX and HC compared to CON ($p < 0.05$). The a indicates a large effect size of MIX compared to CON ($d > 0.8$). The b indicates a large effect size of HC compared to CON ($d > 0.8$). The c indicates a moderate effect size of MIX compared to HC (d = 0.5 - 0.79).

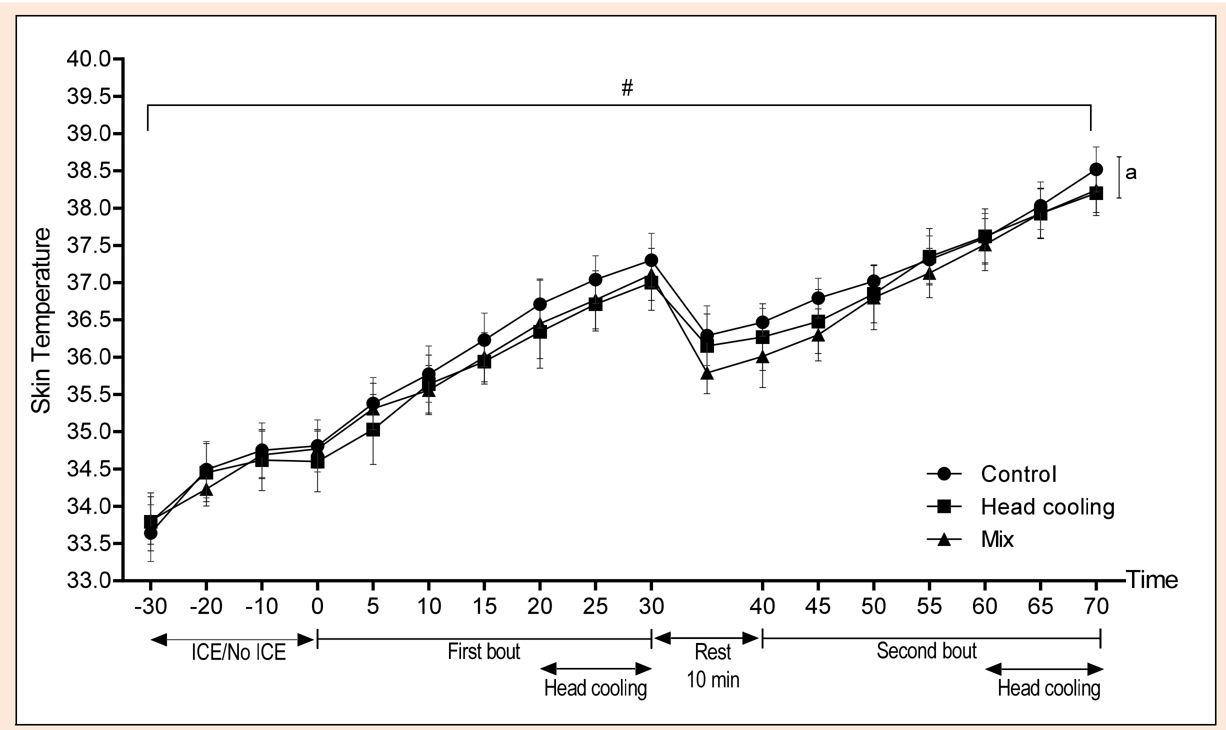

Figure 3. **Skin temperature (°C) of participants in experimental trials (*n* = 10).** The # indicates a significant main effect of time for all trials ($p < 0.05$). The a indicates a large effect size for time of all trials compared to baseline ($d > 0.8$).

Table 2. **Mean (±SD) Thermal Sensation (TS) responses to exercise in the heat (*n* = 10).**

Time (min)	Control	Head Cooling	Mix Cooling
Exercise Bout 1			
0	4.5 ± 0.3	4.5 ± 0.4	4.5 ± 0.3
5	5.0 ± 0.3	4.5 ± 0.5	5.0 ± 0.3
10	5.0 ± 0.3	5.0 ± 0.3	5.5 ± 0.3
15	6.0 ± 0.3	5.5 ± 0.3	6.0 ± 0.2
20	6.0 ± 0.3	6.0 ± 0.2	6.0 ± 0.2
25	6.5 ± 0.2	5.0 ± 0.0^a	5.0 ± 0.2^a
30	7.0 ± 0.3	5.5 ± 0.2^a	5.5 ± 0.4^a
10 min rest			
Exercise Bout 2			
0	4.5 ± 0.4	5.0 ± 0.3	4.5 ± 0.3
5	5.0 ± 0.3	5.0 ± 0.2	5.5 ± 0.2
10	5.5 ± 0.3	5.5 ± 0.2	5.5 ± 0.3
15	6.0 ± 0.4	6.0 ± 0.2	6.0 ± 0.4
20	6.5 ± 0.2	6.5 ± 0.3	6.5 ± 0.4
25	7.0 ± 0.3	5.5 ± 0.5^a	5.5 ± 0.6^a
30	7.5 ± 0.2*#	6.0 ± 0.7*#^a	6.0 ± 0.6*#^a

The * indicates a significant main effect of trials (p < 0.05). The # indicates a significant main effect of time for all trials (p < 0.05). The ^ indicates a significant difference of HC and MIX compared to CON (p < 0.05). The a indicates a large effect size compared to control (*d* > 0.8).

Rating of perceived exertion

An interaction effect and main effect for time were found for RPE ($p < 0.001$; Table 3). There was no main effect for trials ($p = 0.061$). During exercise (bout 1), RPE was lower in HC and MIX compared to CON at min 25 ($p = 0.001$, $d = 2.36$, 1.07 to 3.28 95% CI and $p = 0.001$, $d = 4.71$, 2.74 to 5.69 95% CI, respectively). Further, RPE values remained lower in MIX, but not in HC compared to CON at min 30 ($p = 0.004$, $d = 1.99$, 0.79 to 2.88 95% CI). Following percooling during exercise (bout 2), there were no differences between trials at any time points assessed ($p > 0.05$). Notably, during bout 2 of cooling, RPE values tended to be lower for HC compared to CON at min 25 ($d = 1.0$, 0.01 to 1.84 95% CI).

Table 3. **Mean (±SD) Rating of Perceived Exertion (RPE) responses to exercise in the heat (*n* = 10).**

Time (min)	Control	Head Cooling	Mix Cooling
Exercise Bout 1			
0	6.0±0.0	6.0±0.0	6.0±0.0
5	11.0±0.7	11.0 ±1.4	10.5±1.1
10	12.0±0.8	12.5±1.2	12.5±0.7
15	14.0±0.8	13.5±1.2	14.0±0.8
20	15.0±0.0	15.5±1.1	15.0±1.2
25	16.0±0.0	14.5±0.9^a	14.0±0.6^a
30	16.5± 0.6	16.0± 0.8a	15.5±0.5^a
10 min rest			
Exercise Bout 2			
0	11.5±0.7	12.0±2.3	12.0±2.3
5	14.0±0.6	14.0±1.4	13.5±1.8
10	14.5± 0.8	15.5±1.4	15.5±1.2
15	15.0±1.1	16.5±1.1	16.5±0.9
20	16.5±1.1	17.5±0.9	17.5±0.5
25	17.5±0.9	16.5±1.1a	17.5±0.7
30	18.5±0.7#	18.5±0.5#	18.5±0.5#

The # indicates a significant main effect of time (p < 0.05). The ^ indicates a significant difference between MIX and HC compared to CON (p < 0.05). The a indicates a large effect size compared to control (*d* > 0.8).

There were no differences in temperature and humidity (35.5 ± 0.6°C, 69.3 ± 5.2% RH) in the environmental chamber between trials (all $p > 0.05$).

Cognitive tests

Serial seven test performance declined in CON trial but remained stable or even improved over time in the cooling trials. Accordingly, S7 scores yielded main effects of time ($p = 0.007$) and trials ($p = 0.022$), as well as a significant interaction ($p < 0.001$). A significant score reduction was found for CON after the first 27 min bout of exercise versus baseline ($p < 0.001$, $d = 0.21$, -0.68 to 1.08 95% CI), with scores further declining after bout two of exercise versus baseline ($p < 0.001$, $d = 0.68$, -0.27 to 1.52 95% CI). For MIX, S7 scores were greater after 27 min of exercise in both bouts relative to baseline ($p < 0.001$, $d = 0.63$, -1.48 to 0.31 95% CI; $p < 0.001$, $d = 0.47$, -0.45 to 1.32 95% CI, respectively). We observed moderate to large ES after min 27 of the first bout of exercise between HC and CON ($d = 0.66$, 0.29 to1.50 95% CI) and MIX and CON ($d = 1.09$, 0.07 to 1.93 95% CI), with lower scores in the CON trial. Scores were numerically greater in HC after min 27 in the second bout of exercise compared to CON ($d = 0.93$, 0.09 to 1.77 95% CI). Finally, at the end of the second bout of exercise, more correct answers were recorded in MIX compared to CON ($p = 0.004$, $d = 1.42$, 0.34 to 2.28 95% CI) and HC ($p = 0.048$, $d = 0.45$, 0.47 to 1.30 95% CI; Table 1).

The same pattern emerged for the OSPAN scores. The ANOVA returned no significant main effect of trials ($p = 0.27$) but a main effect of time ($p = 0.002$) and a significant interaction effect ($p = 0.001$). A significant score reduction was found for CON after exercise (bout two) compared to baseline ($p = 0.001$, $d = 1.54$, 0.45 to 2.41 95% CI). A large ES was observed for MIX after min 30 of exercise (bout 1) compared to baseline with scores increasing over time ($d = 0.89$, 0.09 to 1.74 95% CI). Further, large ES were found for HC and MIX compared to CON ($d = 1.12$, 0.10 to 1.97 95% CI and $d = 2.18$, 0.93 to 3.09 95% CI, respectively) at min 30 (bout 1), with lower scores in CON. Finally, a large ES indicated a tendency for greater scores in HC and MIX trials compared to CON ($d = 1.63$, 0.51 to 2.49 95% CI; $d = 2.26$, -3.90 to -1.01 95% CI, respectively) after bout two of exercise; Table 1.

Core body temperature

There was an interaction effect for T_c ($p < 0.001$), and main effects for trials ($p = 0.002$) and time ($p < 0.001$). Core body temperature was similar at baseline (-30 min) for all trials (CON: 36.89 ± 0.38ºC, HC: 36.84 ± 0.39ºC, MIX: 36.98 ± 0.32ºC, $p = 0.618$), but became lower in MIX (36.23 ± 0.31ºC) at 20 min of precooling versus baseline (-0.75 ± 0.37ºC, $p < 0.001$, $d = 2.38$, 1.09 to 3.31 95% CI). After precooling, MIX remained lower compared to CON (0.85 ± 0.29ºC, $p < 0.001$, $d = 2.65$, 1.18 to 3.44 95% CI) and HC (0.79 ± 0.42ºC, $p < 0.001$, $d = 2.12$, 0.89 to 3.03 95% CI).

After the first bout of exercise, MIX remained lower compared to CON and HC (MIX: 37.89 ± 0.35ºC, $p < 0.001$, $d = 2.65$, 1.18 to 3.44 95% CI; HC: 38.30 ± 0.37ºC, $p < 0.001$, $d = 2.12$, 0.89 to 3.03 95% CI). This was similar at the end of bout two of exercise where T_c was lower in MIX (39.16 ± 0.33ºC) compared to CON (39.60 ± 0.30ºC, p = 0.001, *d* = 11.41, 7.15 to 13.91 95% CI) and HC (39.58 ± 0.30ºC, p = 0.01, *d* = 1.31, 0.26 to 2.16 95% CI; Figure 1).

Forehead temperature

Main effects for trials (p = 0.031) and time (p < 0.001) were found for T_h. Forehead values were similar between trials at baseline (CON 35.61 ± 0.45ºC; HC 35.45 ± 0.53ºC; MIX 35.61 ± 0.33ºC; p > 0.05). Following precooling, T_h was lower in MIX by -0.31ºC compared to baseline (p = 0.008, *d* = 0.81, 0.16 to1.65 95% CI) but not in HC (+0.15ºC) and CON (+0.11ºC) (p > 0.05). Following the first percooling during exercise, T_h decreased by -0.48ºC (MIX) and -0.47ºC (HC) during min 25 versus min 20 (p = 0.001, *d* = 0.75, 0.21 to 1.6 95% CI; p = 0.012, *d* = 0.99, 0.01 to 1.83 95% CI, respectively). After exercise (bout 1), T_h remained lower in MIX and HC compared to CON (p = 0.009, *d* = 1.53, 0.85 to 8.2 95% CI; p = 0.04, *d* = 1.06, 0.57 to 0.76 95% CI, respectively). Over the second percooling bout T_h was lower by -0.54ºC (MIX) and -0.58ºC (HC) in min 25 compared to min 20 (p = 0.001, *d* = 1.1, 0.09 to 1.95 95% CI; p = 0.001, *d* = 1.2, 0.17 to 2.05 95% CI, respectively). At the end of exercise, T_h was lower in MIX and HC versus CON (p < 0.001, *d* = 2.4, 1.1 to 3.33 95% CI and p = 0.002, *d* = 2.7, 1.3 to 3.6 95% CI, respectively; Figure 2).

Skin temperature

While T_{sk} increased in a similar pattern over time in all trials (p < 0.001, *d*: CON= 14.25, 8.98 to 17.32 95% CI; *d*: HC= 12.69, 7.97 to 15.43 95% CI; *d*: MIX= 14.28, 9 to 17.36 95% CI) (Figure 3), no differences were found between trials for any time point assessed (p > 0.05).

Thermal sensation

An interaction effect was found for TS (p = 0.001), while main effects were found for trials (p = 0.001) and time (p = 0.001; Table 2). Following the first percooling, TS decreased over time in HC and MIX, with results different to CON at min 25 (p = 0.001, *d* = 10.61, 6.63 to 12.95 95% CI and p = 0.001, *d* = 7.5, 4.6 to 9.24 95% CI, respectively). Further, TS was lower in HC and MIX versus CON until the end of 30 min (bout 1) of exercise (p = 0.001, *d* = 5.88, 3.53 to 7.33 95% CI and p = 0.001, *d* = 4.24, 2.42 to 5.41 95% CI).

During the second bout of percooling, TS was lower in HC and MIX compared to CON at min 25 (p = 0.001, *d* = 3.64, 2.0 to 4.72 95% CI and p = 0.001, *d* = 3.16, 1.66 to 4.18 95% CI, respectively). Further, TS remained lower until the end of exercise (bout 2) for HC and MIX compared to CON (HC: p = 0.001, *d* = 2.91, 1.48 to 3.9 95% CI; MIX: p = 0.001, *d* = 3.35, 1.8 to 4.39 95% CI).

Rating of perceived exertion

An interaction effect and main effect for time were found for RPE (p < 0.001; Table 1). There was no main effect for trials (p = 0.061). During exercise (bout 1), RPE was lower in HC and MIX compared to CON at min 25 (p = 0.001, *d* = 2.36, 1.07 to 3.28 95% CI and p = 0.001, *d* = 4.71, 2.74 to 5.69 95% CI, respectively). Further, RPE values remained lower in MIX, but not in HC compared to CON at min 30 (p = 0.004, *d* = 1.99, 0.79 to 2.88 95% CI). Following percooling during exercise (bout 2), there were no differences between trials at any time points assessed (p > 0.05). Notably, during bout 2 of cooling, RPE values tended to be lower for HC compared to CON at min 25 (*d* = 1.0, 0.01 to 1.84 95% CI).

Discussion

This study found that, in hot conditions, the combination of crushed ice (precooling) with head cooling (percooling) significantly improved S7 performance, meanwhile, single cooling method with HC maintained S7 over the duration of exercise compared to baseline respectively. Additionally, OSPAN scores in both cooling trials (MIX and HC) showed a tendency to be maintained over the same time compared to CON. Further, S7 and OSPAN scores were significantly impaired over time without a cooling intervention.

The impairment recorded for working memory over time in the CON trial was most likely due to rising T_c and T_h as a result of exercise in the heat. Prolonged exercise in hot conditions will continuously store and accumulate heat in the body, which can disrupt the thermal equilibrium and diminish heat removal from the brain and body (Nybo et al., 2002). Previous studies have reported that a T_c ≥38.5ºC has been found to be the onset of decrement on cognitive performance (Hocking et al., 2001; Schmit et al., 2017). Specifically, Hocking et al. (2001) reported that cognitive performances (Rey Auditory Verbal Learning Test, Digit Span and Inspection Time tasks) deteriorated when T_c increased above 38.5ºC (peak: ~38.9ºC) during exercise (walking at 5 km·h^{-1}, incline 8-12%, for 40 min) in hot conditions (35ºC, 65% RH) compared to a thermoneutral condition (25ºC, 65% RH). In this study, forehead temperature was not measured. In the current study, working memory (S7 and OSPAN) was impaired in CON at a lower T_c ranging between 37.89ºC and 38.30ºC that occurred during the last five minutes of bout 1 of exercise. These values equated to a T_h of 37.06 ± 0.51ºC and 37.35 ± 0.51ºC at the 25 and 30 min mark of bout 1 for CON. Conversely, S7 scores improved over time in both cooling trials compared to CON and baseline scores, despite Tc values peaking at 39.16 ± 0.33ºC (MIX) and 39.58 ± 0.30ºC (HC) at the end of the exercise protocol. Additionally, S7 scores were also significantly higher in MIX compared to HC at the end of bout 2 of exercise, with T_c being significantly lower in the MIX trial at this time point.

While increasing T_c values may have played some role in impairing S7 performance in HC at the end of bout 2 compared to MIX, the question arises as to why performance was significantly improved in the cooling trials compared to CON (and baseline) despite peak T_c values being greater than 38.5ºC. It is possible that the most important factor in respect to S7 performance during exercise in the heat relates to T_h, with this variable found to be lower in both cooling trials compared to CON at the end of both bouts of exercise, with peak T_h values being 37.30 ± 0.47ºC (MIX) and 37.51 ± 0.36ºC (HC) compared to 38.54 ± 0.44ºC (CON). This observation appears to also apply to

OSPAN performance, where the tendency for better performance in both MIX and HC compared to CON, was associated with lower T_h values at the end of both bouts of exercise compared to CON, while T_c was significantly lower in the MIX trial only (bout 1, 37.89 ± 0.35°C; and bout 2, 39.16 ± 0.33°C) when compared to CON. The higher T_h values found for CON trial at the 25-30 min mark of bouts 1 and 2 compared to HC and MIX, may explain the impairment found in OSPAN scores for this trial compared to the cooling trials. These results suggest that factors associated with T_h may play a role in working memory performance during and after exercise in the heat. These results are consistent with Gaoua et al. (2011) who reported improved working memory (spatial span test) performance in the heat following head cooling with ice packs compared to no-cooling, where T_h was lower in the cooling trial (T_h peak: ~38°C for cooling versus ~39.5°C for no-cooling).

Another consideration is that TS for MIX and HC was significantly lower than CON during the last 5 min of each bout of exercise, with RPE also being lower in either one or both cooling trials following both bouts of exercise compared to CON. Previous research reported significantly lower TS, along with T_c and T_h, during 60 min of steady-state cycling (55% $\dot{V}O_2$peak) in the heat, compared to a control following crushed ice ingestion (Saldaris et al., 2019). In the current study, this reduction in TS could be related to the wearing of the cooling cap during exercise in the heat. Notably, the increased sensation of coolness following head cooling during exercise could mask the true state of the body (Tyler and Sunderland, 2011) even with T_c rising above 39°C by the end of the exercise protocol. This lower TS may have contributed to the improvement in cognitive performance, particularly during the final stages of exercise, despite T_c being ≥38.5°C; the critical value associated with cognitive fatigue.

In the current study, the combination of cooling removed heat from the body in several possible ways. Firstly, ice ingestion creates a heat sink in the body when ice is changed from a solid to liquid, with this process absorbing heat from the body (Seigel and Laursen, 2012). In the current study, this most likely led to significantly lower pre-exercise T_c and T_h in MIX. Further, the significant reduction in T_h seen at the start of exercise in MIX may have been due to the convective cooling of carotid blood inflow to the brain associated with swallowing crushed ice (Saldaris et al., 2019; Seigel and Laursen, 2012). Saldaris et al. (2020) reported lower T_c and T_h following crushed ice in the heat compared to a control condition and found that precooling enabled participants to maintain decision making and working memory during exercise.

Further, head-cooling during exercise most likely removed heat away from the head region (skin, skull and brain) through conductive cooling. This process was found to lower T_h following cooling in MIX and HC compared to CON. While head-cooling may have lowered T_h, it did not reduce T_c due to similar T_c values recorded between the HC and CON trials over the course of the protocol. Further, the effect of head-cooling on MIX is speculative as there was no trial that assessed the effects of precooling with ice ingestion alone.

In the current study, despite the changes in T_c and T_h associated with MIX, T_{sk} was not impacted, with results for this variable being similar between trials. Lack of change in T_{sk} between trials suggests that T_{sk} values that increase from ~34.7°C to 38.32°C have no obvious impact on S7 and OSPAN performance. This finding is supported by Simmons et al. (2008) who reported that T_{sk} was unlikely to influence/alter cognitive performance.

In this study, although S7 and OSPAN assessed complex cognitive tasks for working memory, the results differed from one another. The difference in the complexity level of each task (Hancock and Vasmatzidis, 2003) and the timing of the S7, which was completed whilst wearing the cooling cap (with participants feeling cooler as shown by TS scores), could be relevant factors. Further, the complexity of the OSPAN task required administration post rather than during exercise. As such, the impact of the cooling manipulation may have been stronger for the S7 task. Also, S7 is a single-verbal task and may provide a less specific but more sensitive measure, whereas OSPAN is a computer-based multifactorial task.

Conclusion

In conclusion, this study demonstrated that while prolonged exercise in the heat impaired working memory, MIX resulted in significant improvement in S7 compared to HC and CON. Meanwhile, a tendency for S7 improvement was observed with single cooling alone via HC which indicate maintenance in cognitive function. Although OSPAN performance was not significantly improved with MIX and HC compared to CON, tendency of improvement in both trials were observed and this indicate that cooling may preserve working memory. This improvement in cognitive function in MIX most likely relates to a reduced T_h associated with MIX and HC, compared to CON, that occurred after both bouts of exercise, with a lower T_c and TS also possibly contributing to this outcome.

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Key points

- The combination of crushed ice ingestion (precooling) and head cooling cap (percooling) significantly improved cognitive performance (working memory) on endurance exercise in the heat and this effect is attributed to the reduction in reduced core temperature, forehead temperature and thermal sensation.
- Single cooling method during exercise via head cooling cap effective for attenuating impairment of working memory by providing maintenance during endurance exercise in the heat and this associated with reduced forehead temperature and thermal sensation following cooling.
- Decrement in forehead temperature and thermal sensation with head cooling during exercise may benefit cognitive performance although with the absence of core body temperature.

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