



# Internal precooling decreases forehead and core temperature but does not alter choice reaction time during steady state exercise in hot, humid conditions



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## ABSTRACT

This study aimed to determine if precooling via crushed ice ingestion reduces forehead skin temperature ( $T_{\text{head}}$ ) and core temperature ( $T_{\text{core}}$ ) during exercise in the heat and whether it has an effect on choice reaction time (CRT). Ten males commenced a 30 min precooling period, ingesting either 7 g kg<sup>-1</sup> of crushed ice (ICE) or room temperature water (CON) prior to cycling 60 min at 55%  $\dot{V}O_{2\text{peak}}$  in hot, humid conditions (35.0 ± 0.3 °C, 50.2 ± 2.1% Relative Humidity). The CRT task was completed upon arrival and after the precooling period in the lab, then at 15 min intervals during exercise in the heat. Precooling reduced  $T_{\text{head}}$  and  $T_{\text{core}}$  to a greater degree in ICE ( $T_{\text{head}}$ : -0.8 ± 0.31 °C;  $T_{\text{core}}$ : -0.9 ± 0.3 °C) compared with CON ( $T_{\text{head}}$ : -0.2 ± 0.3 °C;  $T_{\text{core}}$ : -0.2 ± 0.2 °C) ( $p \leq 0.001$ ). Choice reaction time performance improved throughout the cycle for both conditions ( $p \leq 0.05$ ). Ice ingestion lowered thermal sensation ( $p = 0.003$ ) and skin temperature ( $d = 0.88$ ;  $T_{\text{skin}}$ ), while heart rate, ratings of perceived exertion and thirst were similar between conditions ( $p > 0.05$ ). Precooling effectively reduced  $T_{\text{head}}$  and  $T_{\text{core}}$  but did not provide additional improvement in CRT during moderate exercise in the heat. Further investigation is required to determine whether the lower central and peripheral temperature after ice ingestion is beneficial for tasks of greater cognitive effort.

## 1. Introduction

The equilibrium between heat production and heat loss in the human brain can be impaired during exercise in the heat as a result of elevated cerebral oxygen consumption along with a reduction in cerebral blood flow (Nybo and Nielsen, 2001; Nybo et al., 2002). This can hamper the removal of metabolic heat from the brain and therefore increase brain temperature ( $T_{\text{brain}}$ ; Nybo and Nielsen, 2001; Nybo et al., 2002), resulting in deleterious effects in cognitive performance (Hocking et al., 2001).

In further detail, after cycling at 50%  $\dot{V}O_{2\text{peak}}$  cerebral heat removal via the jugular venous blood is lower during hyperthermia (0.36 ± 0.09 J g<sup>-1</sup> min<sup>-1</sup>) than during the thermo-neutral trial (0.50 ± 0.10 J g<sup>-1</sup> min<sup>-1</sup>), combined with a 7% higher heat production in the brain, causing heat to be stored in the brain at a rate of 0.20 ± 0.06 J g<sup>-1</sup> min<sup>-1</sup>, while there was no storage of heat in the brain during the same period of time in the thermo-neutral trial (Nybo et al., 2002). Along with increasing  $T_{\text{brain}}$ , exercise in hot, humid conditions can lead to an increase in core temperature ( $T_{\text{core}}$ ), as a result of reduced heat dissipation (Wendt et al., 2007) and increased

competition of blood flow (Gonzalez-Alonso et al., 2008), which may also produce transient cognitive deficits (Epstein et al., 1980; Gaoua et al., 2011; Simmons et al., 2008).

Crushed ice ingestion is an internal precooling method that has commonly reported to effectively reduce  $T_{\text{core}}$  (Brearley, 2012; Ihsan et al., 2010), leading to an improvement in exercise performance in the heat (Ihsan et al., 2010; Zimmermann et al., 2015). The effect of crushed ice ingestion on decision-making has not been investigated, however the importance of a lower pre-exercise  $T_{\text{core}}$  for cognitive function during exercise in the heat is evident in previous research. Clarke et al. (2017) reported that 60 min of cold-water immersion resulted in a significant decrease in  $T_{\text{core}}$  compared to control until 30 min of exercise, leading to improved visual discrimination (go-no/go task) accuracy. Simmons et al. (2008) noted the importance of cooling  $T_{\text{core}}$  in comparison to  $T_{\text{skin}}$  for cognitive performance in the heat, finding that a significant reduction in only  $T_{\text{skin}}$  with head and neck cooling resulted in no effect on cognitive performance (simple reaction time, vigilance, choice reaction time, rapid visual information processing). As crushed ice ingestion is an internal precooling method that can significantly reduce pre-exercise  $T_{\text{core}}$  it may be a beneficial mechanism for

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affecting decision-making during exercise in the heat.

Furthermore, emerging evidence reports that along with  $T_{\text{core}}$ , crushed ice ingestion can also lower  $T_{\text{brain}}$ , which may be beneficial for cognitive performance in the heat. Vanden Hoek et al. (2004) found that after central catheter infusions of a saline ice slushy ( $50 \text{ mL kg}^{-1}$ ) in swine,  $T_{\text{brain}}$  was significantly reduced by  $5.3^\circ\text{C}$ . In humans, Onitsuka et al. (2018) utilised proton magnetic resonance spectroscopy to show that ice slushy ingestion reduced  $T_{\text{brain}}$  by  $0.4^\circ\text{C}$ . The reduction in  $T_{\text{brain}}$  is attributed to the ice ingested resulting in an inflow of cooled carotid blood as well as conductive cooling of the facial skin and brain due to the close proximity of the mouth to brain (Siegel and Laursen, 2012). Currently, the ability to measure  $T_{\text{brain}}$  via a non-invasive method during exercise in the heat is unavailable, therefore forehead skin temperature ( $T_{\text{head}}$ ) has previously been used as a measure of facial temperature and an indirect index of  $T_{\text{brain}}$ , in particular the frontal lobe (Onitsuka et al., 2015; Racinais et al., 2008). The frontal lobe is located under the frontal bone, near the forehead and is involved in cognitive functions such as decision-making (Buchbaum, 2004). Although  $T_{\text{head}}$  is a skin temperature measure located on the forehead, crushed ice ingestion is an internal precooling method that is orally ingested, thus cooling from the inside out. Similar to Onitsuka et al. (2018), Onitsuka et al. (2015) reported that ice slushy ingestion significantly reduced  $T_{\text{head}}$  by  $0.4^\circ\text{C}$  and therefore may be a suitable indirect measure to infer changes in internal head temperature as well as facial temperature.

To date, no study has investigated the effect of crushed ice ingestion on  $T_{\text{head}}$  and decision-making during exercise in hot conditions despite it being a popular precooling method to reduce  $T_{\text{core}}$  during exercise in the heat (Brearley, 2012; Ihsan et al., 2010). Previously CRT has demonstrated to be a useful variable to infer changes in mental processing (Serwah and Marino, 2006). Furthermore, Kazama et al. (2012) reported that cycling at 50% maximum power output with hyperthermia (wearing a water-perfused suit set at  $47^\circ\text{C}$ ) resulted in the impairment of reaction time.

The aim of this study was to investigate whether the internal precooling method of crushed ice ingestion can effectively lower forehead skin temperature ( $T_{\text{head}}$ ), used as an indirect index of internal head temperature and facial temperature, during exercise in the heat. It was hypothesised that  $T_{\text{head}}$  and  $T_{\text{core}}$  would be lower following crushed ice ingestion compared to control, leading to an improvement in CRT during steady state exercise in the heat.

## 2. Material and methods

### 2.1. Participants

Ten healthy active males (age  $23.1 \pm 2.4$  y; height  $177.3 \pm 8.2$  cm; body mass  $73.46 \pm 8.50$  kg;  $\dot{V}\text{O}_{2\text{peak}}$   $48.5 \pm 3.6 \text{ mL}\cdot\text{kg}\cdot\text{min}^{-1}$ , total fat-mass:  $11.04 \pm 7.12$  kg, lean body mass:  $59.14 \pm 5.22$  kg) were recruited for the study. Ethical approval was granted by the Human Research Ethics Office at The University of Western Australia. Informed written consent was attained from all participants prior to their involvement in the study. The study was conducted during winter to minimise heat acclimatisation of participants.

### 2.2. Experimental procedure

Participants visited the laboratory on 3 separate occasions. In the first session participants completed a maximal oxygen uptake test ( $\dot{V}\text{O}_{2\text{peak}}$ ) on a bike attached to a wind trainer ergometer (LeMond, HOIST Fitness, Poway, California, USA), in the laboratory ( $\sim 22^\circ\text{C}$ , 52% relative humidity; RH). The test started at an initial power output of 100 W, which increased by 30 W every 3 min. The test concluded when either: the participant voluntarily stopped or when the required power output could not be maintained for 20 s. The  $\dot{V}\text{O}_{2\text{peak}}$  was defined as the

sum of the highest 4 consecutive 15 s  $\dot{V}\text{O}_2$  values reached during the incremental test (expressed as  $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ). Cycling in the subsequent experimental trials was completed at the power output equivalent to 55% of  $\dot{V}\text{O}_{2\text{peak}}$ . Participants familiarised themselves with the CRT task (described below) while seated on the bike before and after the  $\dot{V}\text{O}_{2\text{peak}}$  test, at rest and while cycling. After a minimum of 3 days following the  $\dot{V}\text{O}_{2\text{peak}}$  test, participants completed 2 experimental trials performed a week apart, at the same time of day.

Participants completed a 24 h food, fluid, exercise and sleep diary prior to the first testing session and replicated this prior to the second trial. They were asked to abstain from strenuous exercise, caffeine and alcohol 24 h prior to each trial as well as any other supplements within a month prior to testing.

A radiotelemetry capsule (CorTemp, HQ Inc., Palmetto, FL, USA) was ingested 8 h prior to experimental testing (Byrne and Lim, 2007). Upon arrival a urine sample was attained and urinary specific gravity (USG) measured to ensure the participant was euhydrated ( $\text{USG} < 1.025$ ). Nude body mass was measured and recorded followed by a heart rate monitor (HR; Polar RS400, Finland) being fitted. Skin thermistors (Skin Sensor SST-1, Physitemp Instruments Inc, Clifton, NJ, USA) were fixed to the left posterior gastrocnemius (at level of largest circumference), anterior forearm (medial point between head of the radius and the styloid process at the wrist) and sternum (medial point between suprasternal notch and xiphoid process) for the measurement of  $T_{\text{skin}}$ . A fourth skin thermistor was fixed to the middle of the forehead to record  $T_{\text{head}}$ . The measurement of  $T_{\text{skin}}$  and  $T_{\text{head}}$  occurred continuously throughout the precooling period and steady state cycle via a computerised program (DASYLab Light, Version 11, National Instruments, Ireland Resources Ltd.). The following formula was used to calculate  $T_{\text{skin}}$  (Burton, 1935):

$$T_{\text{skin}} = 0.5(T_{\text{sternum}}) + 0.14(T_{\text{forearm}}) + 0.36(T_{\text{calf}})$$

Participants completed the CRT task before commencing a 30 min precooling period where they remained seated at room temperature ( $21.7 \pm 1.1^\circ\text{C}$ ,  $51.8 \pm 8.0\%$  RH) and consumed  $7 \text{ g kg}^{-1}$  of crushed ice (ICE;  $0^\circ\text{C}$ ) or tap water (CON;  $22^\circ\text{C}$ ). Following the precooling period participants completed the CRT task, then entered the climate chamber ( $35.0 \pm 0.3^\circ\text{C}$ ,  $50.2 \pm 2.1\%$  RH) and completed 1 h of cycling at a power output of 55% of their  $\dot{V}\text{O}_{2\text{peak}}$ . The cycle was completed using the same bicycle and LeMond trainer ergometer as the familiarisation session, which was calibrated prior to use and connected to a customised computer program Cyclemax (version 7.4 School of Sport Science, Exercise and Health, University of Western Australia, Perth, WA).

The CRT task was completed at 15 min intervals while cycling. Rating of perceived exertion (RPE) was measured using the Borg scale (6: very, very light to 20: maximal exertion; Borg, 1982), while a nine-point scale was used to measure perceived thermal sensation (RPTS; 4: very hot to -4: very cold; Roberts, 1959) and perceived thirst (1: not thirsty at all to 9: very, very thirsty; Maresh et al., 2001). Thermal sensation was recorded at the start and end of precooling. Perceived thirst, RPE and RPTS were recorded throughout the cycle. At the 30 min time point of exercise 100 mL of tap water ( $22^\circ\text{C}$ ) was ingested after the CRT task was completed.

Following the steady state cycle in the heat, participants towel dried and body mass was measured again to determine whole body sweat loss (pre – post body mass + fluid ingested).

### 2.3. Cognitive task

An 8-CRT task (Chronoscope, The University of Western Australia, School of Human Sciences, Perth, Australia) was used in this study as a measure of decision-making speed (Teichner and Krebs, 1974). The cognitive task as described by Camfield et al. (2013) was completed upon arrival, after the precooling period in the lab, at the start of the steady state cycle in the heat and at 15 min intervals throughout. The

CRT task was placed on a height adjustable table in front of the bicycle allowing participants to complete the task while cycling.

The task had eight lights arranged in a semi-circular configuration with a response button adjacent to each light. Participants were required to keep the home button (situated in the centre of the panel) depressed until a target light appeared. When the target light appeared, participants were required to release the home button as quickly as possible and press the response button adjacent to the stimulus light. The task measures reaction time and movement time from total CRT. Reaction time was defined as the time from stimulus onset to the release of the home button and movement time as the time from release of the home button to the depression of the stimulus button. The CRT data was analysed using the mean reaction time and movement time of 15 trials completed at each collection time point.

#### 2.4. Statistical analysis

A repeated measures design was used and applied in a counter-balanced order. Analysis was completed on the software program IBM SPSS statistics version 22 with statistical significance determined by an alpha level of  $p \leq 0.05$ . A two-way repeated measures analysis of variance (ANOVA) was used to compare differences between performance outcomes of the two interventions used (CON vs. ICE) and identify where within group differences occur. When a significant main effect in the ANOVA was found, post-hoc pairwise comparisons were performed using Benjamini Hochberg correction. Analysis of all variables was also performed using Cohen's  $d$  effect sizes with 90% confidence intervals (CI), whereby  $\geq 0.8$  was categorised as a large effect, 0.79–0.50 was a moderate effect and 0.49–0.20 was a small effect with only moderate to large effect sizes reported (Cohen, 1988). All data generated or analysed during this study are included in this published article.

### 3. Results

#### 3.1. Participant characteristics

Urine specific gravity (CON  $1.019 \pm 0.008 \text{ g mL}^{-1}$ ; ICE  $1.020 \pm 0.007 \text{ g mL}^{-1}$ ), pre body mass (CON  $73.4 \pm 7.8 \text{ kg}$ ; ICE  $73.5 \pm 7.8 \text{ kg}$ ) and post body mass (CON  $73.0 \pm 7.9 \text{ kg}$ ; ICE  $73.1 \pm 7.8 \text{ kg}$ ) and sweat loss (CON  $1.0 \pm 0.2 \text{ kg}$ ; ICE  $1.0 \pm 0.1 \text{ kg}$ ) were similar between conditions ( $p > 0.05$ ).

#### 3.2. Temperature

Fig. 1 illustrates  $T_{\text{head}}$  during the precooling period and cycle in the heat. Following precooling,  $T_{\text{head}}$  was significantly lower in ICE

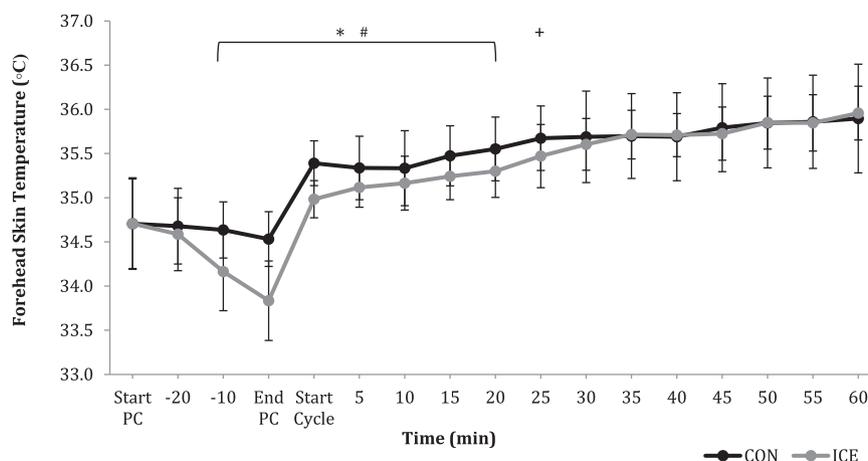


Fig. 1. Mean ( $\pm$  SD) forehead temperature throughout the pre-cooling period (PC) and steady state cycle ( $n = 10$ ). \* Significantly different from ICE ( $p \leq 0.05$ ). # Large effect size between conditions ( $d \geq 0.8$ ). + Moderate effect size between conditions ( $d = 0.50$ –0.79).

( $-0.8 \pm 0.3 \text{ }^\circ\text{C}$ ) compared to CON ( $-0.2 \pm 0.3 \text{ }^\circ\text{C}$ ) ( $p \leq 0.001$ ;  $d = 2.00$ , 1.03–2.80 90% CI). From 20 min of precooling until 20 min of the steady state cycle,  $T_{\text{head}}$  was significantly lower in ICE compared to CON ( $p \leq 0.05$ ) also represented by large effect sizes ( $d \geq 0.8$ ). A moderate effect size was present between conditions at 25 min ( $d = 0.55$ , 0.22–1.27 90% CI), after which conditions were not different ( $p > 0.05$ ;  $d \leq 0.49$ ).

Fig. 2 illustrates  $T_{\text{core}}$  and  $T_{\text{skin}}$  temperature between conditions. From 20 min into the precooling period until the end of the steady state cycle,  $T_{\text{core}}$  was lower in ICE compared with CON ( $p \leq 0.05$ ). At the conclusion of precooling the reduction in  $T_{\text{core}}$  was greater in ICE ( $-0.9 \pm 0.3 \text{ }^\circ\text{C}$ ) compared to CON ( $-0.2 \pm 0.2 \text{ }^\circ\text{C}$ ) ( $p \leq 0.001$ ;  $d = 2.75$ , 1.63–3.63 90% CI).

A non-significant large effect size in  $T_{\text{skin}}$  was found between conditions at the end of precooling ( $d = 0.88$ , 0.08–1.61 90% CI). At the end of precooling a large effect size was present between ICE and CON for  $T_{\text{sternum}}$  ( $d = 0.95$ , 0.01–1.83 90% CI), a moderate effect size for  $T_{\text{forearm}}$  ( $d = 0.54$ , 0.38–1.41 90% CI) and no effect size for  $T_{\text{calf}}$  ( $d = 0.12$ ). A non-significant moderate effect size was present for  $T_{\text{skin}}$  at the start of the steady state exercise ( $d = 0.5$ , 0.27–1.22 90% CI), after which there was no difference between conditions for  $T_{\text{skin}}$  ( $p > 0.05$ ;  $d < 0.5$ ).

#### 3.3. CRT

Reaction time and movement time are shown in Fig. 3. A significant improvement was seen in reaction time ( $p < 0.001$ ) and movement time ( $p = 0.010$ ) over the cycle in the heat in both conditions, but there was no interaction effect or effect sizes present between conditions (reaction time:  $p = 0.625$ ; movement time:  $p = 0.830$ ). Follow up tests using Benjamini Hochberg showed reaction time was significantly faster from 15 min onwards in comparison to the start of the cycle (0 min) and at the end of the cycle (60 min) in comparison to arrival (-35 min; Fig. 3). Although a global time effect was seen in movement time, no significant differences were present between time points using Benjamini Hochberg correction.

#### 3.4. Heart rate and perceptual ratings

A significant increase in HR ( $p < 0.001$ ), RPE ( $p < 0.001$ ) and perceived thirst ( $p < 0.001$ ) occurred for both conditions during the cycle ( $p \leq 0.05$ ), however there were no differences between CON and ICE (HR = 0.646; RPE = 0.80; Thirst = 0.756; see Table 1). Thermal sensation was lower following precooling ( $p = 0.003$ ) in the ICE condition (see Table 1).

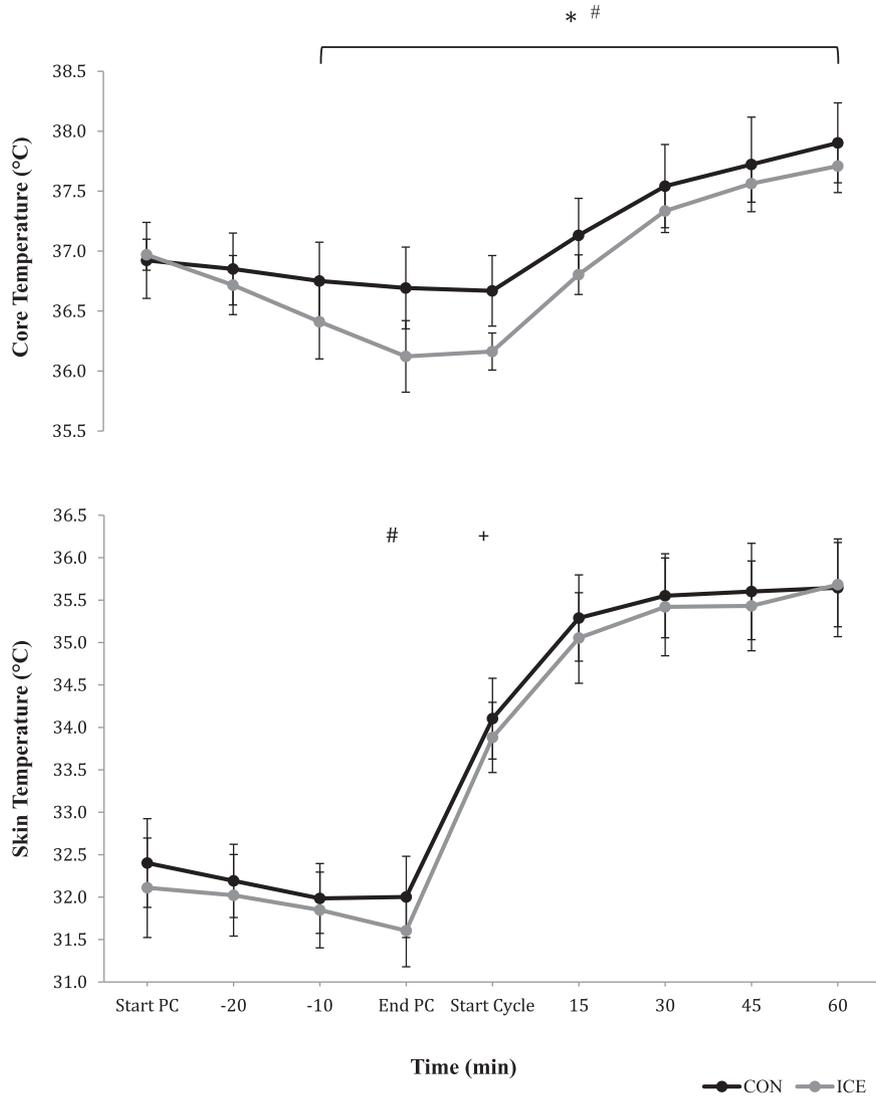


Fig. 2. Mean ( $\pm$  SD) core temperature and skin temperature throughout the pre-cooling period (PC) and steady state cycle ( $n = 10$ ). \* Significantly different from ICE ( $p \leq 0.05$ ). # Large effect size between conditions ( $d \geq 0.8$ ). + Moderate effect size between conditions ( $d = 0.50-0.79$ ).

#### 4. Discussion

The aim of this study was to determine if crushed ice ingestion lowered  $T_{head}$  during exercise in the heat. Secondly, whether a

reduction in  $T_{head}$  and  $T_{core}$  affected CRT during moderate intensity exercise in hot, humid conditions. The present study is the first to reveal that crushed ice ingestion is an effective precooling strategy that reduces  $T_{head}$  ( $-0.8^\circ\text{C}$ ), remaining lower than control from 20 min of

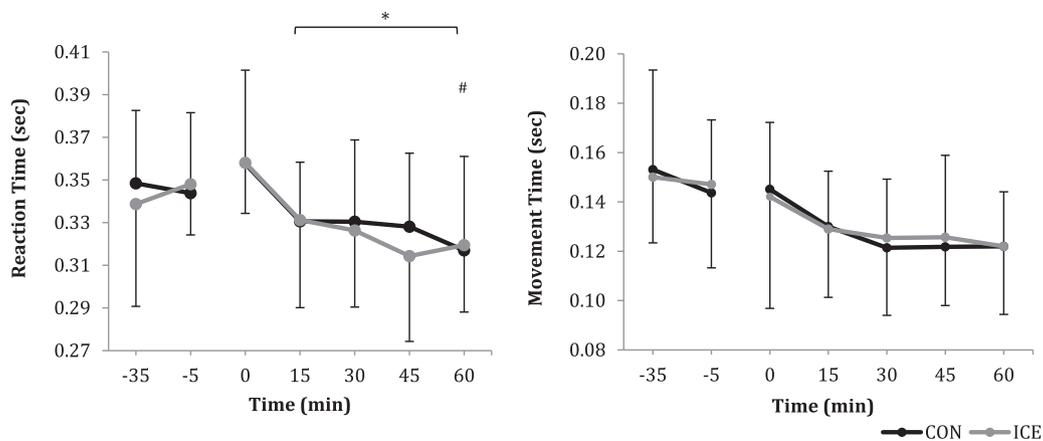


Fig. 3. Mean ( $\pm$  SD) choice reaction time and movement time throughout the precooling period (PC) and steady state cycle ( $n = 10$ ). \* Significantly different from start of cycle (0 min;  $p \leq 0.05$ ). # Significantly different from arrival (-35 min;  $p \leq 0.05$ ).

**Table 1**Mean ( $\pm$  SD) heart rate (HR), Rate of Perceived Thermal Sensation (RPTS), Rating of Perceived Exertion (RPE) and Perceived Thirst.

Time (min)							
Variable	-40	-10	0	15	30	45	60
<i>HR (beats·min<sup>-1</sup>)</i>							
CON	61 $\pm$ 10	60 $\pm$ 10	105 $\pm$ 15	127 $\pm$ 13	136 $\pm$ 15	140 $\pm$ 17	145 $\pm$ 17
ICE	64 $\pm$ 9	59 $\pm$ 12	105 $\pm$ 9	123 $\pm$ 12	133 $\pm$ 11	140 $\pm$ 14	144 $\pm$ 11
<i>RPTS</i>							
CON	-1 $\pm$ 1	-1 $\pm$ 1	1 $\pm$ 1	2 $\pm$ 1	2 $\pm$ 1	2 $\pm$ 1	2 $\pm$ 1
ICE	-1 $\pm$ 0	-3 $\pm$ 1*	1 $\pm$ 1	2 $\pm$ 1	2 $\pm$ 1	2 $\pm$ 1	2 $\pm$ 1
<i>RPE</i>							
CON			10 $\pm$ 1	11 $\pm$ 1	12 $\pm$ 1	13 $\pm$ 2	14 $\pm$ 2
ICE			9 $\pm$ 1	11 $\pm$ 1	12 $\pm$ 1	13 $\pm$ 1	13 $\pm$ 1
<i>Thirst</i>							
CON			3 $\pm$ 2	4 $\pm$ 2	5 $\pm$ 2	4 $\pm$ 2	5 $\pm$ 1
ICE			2 $\pm$ 1	4 $\pm$ 1	4 $\pm$ 1	4 $\pm$ 2	5 $\pm$ 2

\* Indicates significantly different from CON ( $p \leq 0.05$ ).

precooling until 20 min of the cycle.

Siegel and Laursen (2012) suggest that ice ingestion can lower  $T_{\text{brain}}$  and facial temperature, measured in the current study using  $T_{\text{head}}$ , as a result of conductive cooling due to the close proximity of the mouth to brain (Siegel and Laursen, 2012). A lower  $T_{\text{brain}}$  is beneficial during exercise in hot, humid conditions as heat dissipation from the brain can be reduced due to a combination of excessive heat production and insufficient heat loss in addition to compromised cerebral blood outflow (Nybo and Nielsen, 2001; Nybo et al., 2002). In the current study, there was a reduction in internal head temperature following ice ingestion, which may lead to improved tolerance to hyperthermia (Burger and Fuhrman, 1964; Kiyatkin, 2010; Nybo et al., 2002). Furthermore, cooling the forehead and cheeks is beneficial as the increase in skin blood flow during exercise in the heat is greater in the facial area compared to other body sites, thus, cooling the facial area with ice ingestion may reduce the burden placed on heat dissipation in the head and help attenuate the increase in  $T_{\text{brain}}$  (Kondo et al., 1998). Along with the reduction of  $T_{\text{head}}$ , the conductive nature of crushed ice ingestion is further supported in the current study by the large effect size reduction in  $T_{\text{skin}}$  post precooling and moderate effect size reduction at the start of the cycle for ICE compared to CON. Furthermore, post precooling a large effect size was present between conditions for  $T_{\text{sternum}}$  whereas there was no effect size for  $T_{\text{calf}}$ . The greater reduction in temperature of  $T_{\text{sternum}}$  and  $T_{\text{head}}$  supports the notion that areas closer to the region of ingested ice, may result in greater decreases in temperature due to increased ability for conductive cooling.

The reduction in  $T_{\text{head}}$  after ingesting a cold substance is supported by Onitsuka et al. (2015, 2018) however a greater decline is seen in the current study with  $7 \text{ g kg}^{-1}$  crushed ice ( $-0.8^\circ\text{C}$ ; crushed ice only) ingested in 30 min compared to  $7.5 \text{ g kg}^{-1}$  ice slushy ( $-0.4^\circ\text{C}$ ; water + ice drink) ingested in 15 min. This suggests that crushed ice ingestion may reduce  $T_{\text{head}}$  to a greater degree than an ice slushy. Crushed ice may therefore be a more effective alternative than an ice slushy for reducing  $T_{\text{head}}$  possibly due to the greater potential for conductive cooling of the head. Crushed ice may sit in the mouth for a longer period of time compared to drinking a slushy due to the greater phase change from solid ice to liquid water that is required, therefore the importance of conductive cooling of crushed ice in reducing  $T_{\text{head}}$  is further evident. Furthermore, a longer precooling period of 30 min compared to 15 min may allow a greater opportunity for heat transfer to occur. The phase change of crushed ice also results in a significant reduction in  $T_{\text{core}}$  (compared to control) as it requires a larger transfer of heat energy from ice to water (enthalpy of fusion; Merrick et al., 2003). As crushed ice ingestion reduces both  $T_{\text{head}}$  and  $T_{\text{core}}$  it may be a more effective cooling method than other forms such as head cooling or ice vests, attenuating both peripheral and central temperature during exercise in the heat.

The present study found that ice ingestion was not beneficial or detrimental to the CRT task during 60 min of moderate exercise in the heat as CRT improved regardless of condition, despite a higher  $T_{\text{head}}$  and  $T_{\text{core}}$  in control. Faster reaction times have previously been observed in hot environments for lower cognitive demanding tasks (Razmjou, 1996; Simmons et al., 2008), suggesting that the effect of heat stress on cognitive performance may be task dependent. The effect of hyperthermia appears to be amplified if the complexity of the motor task increases and further decrements are observed with increasing task conditioning complexity (Pill et al., 2017). Thus, tasks requiring high attentional load are more so affected by exercise in the heat than simpler tasks requiring automatic processing (Hancock and Vasmatazidis, 2003). This is supported by Racinais et al. (2008) whom found passive hyperthermia caused significant decrements in memory tests (working memory and visual recognition memory) in hot conditions but not in simple tests (attention). Furthermore, the significant time effect seen in the current study for reaction time and movement time could be a result of either faster neural conduction speed (Tomprowski, 2003), an arousal effect (Provins, 1966) or merely due to participants adopting an impulsive and risky response disposition (Colquhoun and Goldman, 1972; Sydicus et al., 2018). Previous research has also suggested that cognitive tasks may only be impaired at a  $T_{\text{core}}$  greater than  $38.5^\circ\text{C}$  (Gaoua et al., 2011; Wilkinson et al., 1964). Hocking et al. (2001) suggests that under thermally straining conditions ( $35^\circ\text{C}$ ) with a  $T_{\text{core}}$  greater than  $38.5^\circ\text{C}$  brain electrical recordings increase in amplitude and a decrease in latency in the frontal and occipito-parietal regions indicating a greater utilisation of the neural resources to maintain the same cognitive performance as thermally neutral conditions. However, due to the short term, moderate intensity exercise,  $T_{\text{head}}$  and  $T_{\text{core}}$  may not have increased to levels where CRT is impaired which is a limitation to the study. Alternatively, the improvement in CRT may be showcasing the fact that the brain may be more resilient to the heat than previously thought and is able to cope with the change in environment (Robertson and Marino, 2017; Trangmar et al., 2014), which may be a possible explanation for why impairment of CRT was not seen in the current study. However, as crushed ice ingestion effectively reduced  $T_{\text{head}}$  until 20 min of exercise and  $T_{\text{core}}$  until the end, it is possible to speculate that ice ingestion may be beneficial for more demanding cognitive tasks, such as tasks that emphasise memory and executive function, where  $T_{\text{core}}$  is increased beyond  $38.5^\circ\text{C}$ .

A limitation of this study was that  $T_{\text{head}}$  was used as an indirect index of internal head temperature, as a direct non-invasive measure of the brain is not available for use on humans during exercise in the heat. Forehead skin temperature is an external measure, however crushed ice ingestion is an internal cooling method, which resulted in a decrease in  $T_{\text{head}}$  and  $T_{\text{core}}$ . As ice ingestion cools from the inside out and through

conduction, evidence exists of a relationship between  $T_{\text{head}}$  and changes in internal head temperature, as supported by Onitsuka et al. (2015, 2018). A measure of  $T_{\text{brain}}$  is available via magnetic resonance spectroscopy, however such measurement cannot be utilised during exercise as it requires a participant to remain in supine position. Tympanic temperature determined via the method of Nielsen and Jessen (1992) had noted to cause some level of discomfort and pain, which may act as a cognitive distractor requiring some attentional resources and, therefore, introduce an extraneous variable impacting on cognitive performance. Onitsuka et al. (2015) utilised  $T_{\text{head}}$  as an indirect measurement of  $T_{\text{brain}}$  and later Onitsuka et al. (2018) used magnetic resonance spectroscopy to find that both methods recorded a reduction of 0.4 °C after ice slushy ingestion. Furthermore, in the current study, ice ingestion resulted in  $T_{\text{core}}$  remaining lower than control throughout the whole protocol but  $T_{\text{head}}$  was not different between conditions after 25 min. Gastro-intestinal temperature is an internal index for  $T_{\text{core}}$ , thus the measure is not affected by heat release on the skin. However  $T_{\text{head}}$  is an external measurement placed on the facial area, which is important for heat dissipation due to increased blood flow to this area during exercise in the heat (Kondo et al., 1998). As  $T_{\text{head}}$  could be affected by heat release from the skin, crushed ice ingestion may actually have greater potential of cooling the head during exercise than  $T_{\text{head}}$  suggests.

## 5. Conclusions

Crushed ice ingestion significantly reduced  $T_{\text{head}}$  until 20 min of exercise and  $T_{\text{core}}$  during the entire cycle in the heat in comparison to control, thus may be a more effective cooling method due to the attenuation of both peripheral and central temperature. As a result this study can contribute to the development of effective body cooling strategies for cognitive function and exercise performance in the heat. Further investigation is warranted to determine whether the lower  $T_{\text{head}}$  and  $T_{\text{core}}$  seen with ice ingestion during exercise in the heat is beneficial for cognitive tasks that require greater cognitive effort, such as tasks that emphasise executive function and working memory. Furthermore, ice ingestion is an acceptable intervention to apply to most populations thus there is potential for future studies to investigate the application of ice ingestion to populations other than healthy young men – such as children who have a lower ability to thermo-regulate as well as occupations in the heat that require thermo-protective clothing.

## Compliance with ethical standards

This study is compliant with ethical standards.

## Declarations of Interest

None.

## References

Borg, G., 1982. Psychophysical base of perceived exertion. *Med. Sci. Sports Exerc.* 14, 377–381. <https://doi.org/10.1249/00005768-198205000-00012>.

Brearley, M., 2012. Crushed ice ingestion – a practical strategy for lowering core body temperature. *J. Mil. Veterans' Health* 20 (2), 25–30.

Buchbaum, M.S., 2004. Images in neuroscience: frontal cortex function. *Am. J. Psychiatry* 161, 12.

Burger, F.J., Fuhrman, F.A., 1964. Evidence of injury by heat in mammalian tissues. *Am. J. Physiol.* 206, 1057–1061. <https://doi.org/10.1152/ajplegacy.1964.206.5.1057>.

Burton, A.C., 1935. Human calorimetry II. The average temperature of the tissues of the body. *J. Nutr.* 9, 261–280.

Byrne, C., Lim, C.L., 2007. The ingestible telemetric body core temperature sensor: a review of validity and exercise applications. *Br. J. Sports Med.* 4, 126–133. <https://doi.org/10.1136/bjsm.2006.026344>.

Camfield, D.A., Silber, B.Y., Scholey, A.B., Nolidin, K., Goh, A., Stough, C.A., 2013. Randomised placebo-controlled trial to differentiate the acute cognitive and mood effects of chlorogenic acid from decaffeinated coffee. *PLoS One* 8, e82897. <https://doi.org/10.1371/journal.pone.0082897>.

Clarke, N.D., Duncan, M.J., Smith, M., Hankey, J., 2017. Pre-cooling moderately

enhances visual discrimination during exercise in the heat. *Sports Sci.* 35, 355–360. <https://doi.org/10.1080/02640414.2016.1164885>.

Cohen, J., 1988. *Statistical Power Analysis for the Behavioural Sciences*. Lawrence Erlbaum Associates, Hillsdale, NJ.

Colquhoun, W.P., Goldman, R.F., 1972. Vigilance under induced hyperthermia. *Ergonomics* 15, 621–632. <https://doi.org/10.1080/00140137208924463>.

Epstein, Y., Keren, G., Moisseiev, J., Gasko, O., Yachin, S., 1980. Psychomotor deterioration during exposure to heat. *Aviat. Space Environ. Med.* 51 (6), 607–610.

Gaoua, N., Racinais, S., Grantham, J., El Massioui, F., 2011. Alterations in cognitive performance during passive hyperthermia are task dependent. *Int. J. Hyperth.* 27 (1), 1–9. <https://doi.org/10.3109/02656736.2010.516305>.

Gonzalez-Alonso, J., Crandall, C.G., Johnson, J.A., 2008. The cardiovascular challenge of exercising in the heat. *J. Physiol.* 586, 45–53. <https://doi.org/10.1113/jphysiol.2007.142158>.

Hancock, P.A., Vasmatzidis, I., 2003. Effects of heat stress on cognitive performance: the current state of knowledge. *Int. J. Hyperth.* 19 (3), 355–372. <https://doi.org/10.1080/0265673021000054630>.

Hocking, C., Silberstein, R.B., Lau, W.M., Stough, C., Roberts, W., 2001. Evaluation of cognitive performance in the heat by functional brain imaging and psychometric testing. *Comp. Biochem. Physiol. Part A Mol. Integr. Physiol.* 128, 719–734. [https://doi.org/10.1016/S1095-6433\(01\)00278-1](https://doi.org/10.1016/S1095-6433(01)00278-1).

Ihsan, M., Landers, G., Brearley, M., Peeling, P., 2010. Beneficial effects of ice ingestion as a precooling strategy on 40-km cycling time-trial performance. *Int. J. Sports Physiol. Perform.* 5, 140–151. <https://doi.org/10.1123/ijspp.5.2.140>.

Kazama, A., Takatsu, S., Hasegawa, H., 2012. Effect of increased body temperature on cognitive function during prolonged exercise. *Jpn. J. Phys. Fit. Sport. Med.* 61 (5), 459–467. <https://doi.org/10.7600/jspfsm.61.459>.

Kiyatkin, E.A., 2010. Brain temperature homeostasis: physiological fluctuations and pathological shifts. *Front. Biosci.* 15, 73–92. <https://doi.org/10.2741/3608>.

Kondo, N., Takano, S., Aoki, K., Shibasaki, M., Tominaga, H., Inoue, Y., 1998. Regional differences in the effect of exercise intensity on thermoregulatory sweating and cutaneous vasodilation. *Acta Physiol. Scand.* 164, 71–78. <https://doi.org/10.1046/j.1365-201X.1998.00407.x>.

Maresh, C.M., J.A., Herrera-Soto, L.E., Armstrong, D.J., Casa, S.A., Kavouras, F.T., Hacker, F.T., et al., 2001. Perceptual responses in the heat after brief intravenous versus oral rehydration. *Med. Sci. Sports Exerc.* 33, 1039–1045. <https://doi.org/10.1097/00005768-200106000-00025>.

Merrick, M.A., Jutte, L.S., Smith, M.E., 2003. Cold modalities with different thermodynamic properties produce different surface and intramuscular temperatures. *J. Athl. Train.* 38, 28–33.

Nielsen, B., Jessen, C., 1992. Evidence against brain stem cooling by face fanning in severely hyperthermic humans. *Eur. J. Physiol.* 422, 168–172. <https://doi.org/10.1007/BF00370416>.

Nybo, L., Nielsen, B., 2001. Hyperthermia and central fatigue during pro-longed exercise in humans. *J. Appl. Physiol.* 91 (3), 1055–1060. <https://doi.org/10.1152/jappl.2001.91.3.1055>.

Nybo, L., Secher, N.H., Nielsen, B., 2002. Inadequate heat release from the human brain during prolonged exercise with hyperthermia. *J. Physiol.* 545 (2), 697–704. <https://doi.org/10.1113/jphysiol.2002.030023>.

Onitsuka, S., Nakamura, D., Onishi, T., Arimitsu, T., Takahashi, H., Hasegawa, H., 2018. Ice slurry ingestion reduces human brain temperature measured using non-invasive magnetic resonance spectroscopy. *Sci. Rep.* 8, 2757. <https://doi.org/10.1038/s41598-018-21086-6>.

Onitsuka, S., Zheng, X., Hasegawa, H., 2015. Ice slurry ingestion reduces both core and facial skin temperatures in a warm environment. *J. Therm. Biol.* 51, 105–109. <https://doi.org/10.1016/j.jtherbio.2015.03.008>.

Piil, J.F., Lundbye-Jensen, J., Trangmar, S.J., Nybo, L., 2017. Performance in complex motor tasks deteriorates in hyperthermic humans. *Temperature* 4 (4), 420–428. <https://doi.org/10.1080/23328940.2017.1368877>.

Provins, K.A., 1966. Environmental heat, body temperature and behavior: an hypothesis. *Aust. J. Psychol.* 18, 118–129. <https://doi.org/10.1080/00049536608255722>.

Racinais, S., Gaoua, N., Grantham, J., 2008. Hyperthermia impairs short-term memory and peripheral motor drive transmission. *J. Physiol.* 586, 4751–4762. <https://doi.org/10.1113/jphysiol.2008.157420>.

Razmjou, S., 1996. Mental workload in heat: toward a framework for analyses of stress states. *Aviat. Space Environ. Med.* 67, 530–538.

Roberts, B., 1959. *Environmental testing*. IHVE 27, 238–250.

Robertson, C.V., Marino, F.E., 2017. Cerebral responses to exercise and the influence of heat stress in human fatigue. *J. Therm. Biol.* 63, 10–15. <https://doi.org/10.1016/j.jtherbio.2016.10.001>.

Serwah, N., Marino, F.E., 2006. The combined effects of hydration and exercise heat stress on choice reaction time. *J. Sci. Med. Sport* 9, 157–164. <https://doi.org/10.1016/j.jsams.2006.03.006>.

Siegel, R., Laursen, P.B., 2012. Keeping your cool: possible mechanisms for enhanced exercise performance in the heat with internal cooling methods. *Sports Med.* 42, 89–98. <https://doi.org/10.2165/11596870-000000000-00000>.

Simmons, S.E., Saxby, B.K., Mcglone, F.P., Jones, D.A., 2008. The effect of passive heating and head cooling on perception, cardiovascular function and cognitive performance in the heat. *Eur. J. Appl. Physiol.* 104, 271–280. <https://doi.org/10.1007/s00421-008-0677-y>.

Syndicus, M., Wiese, B.S., van Treeck, C., 2018. In the heat and noise of the moment: effects on risky decision making. *Environ. Behav.* 50 (1), 3–27. <https://doi.org/10.1177/0013916516680700>.

Teichner, W., Krebs, M., 1974. Laws of visual choice reaction time. *Psychol. Rev.* 81, 75–98.

Tomprowski, P.D., 2003. Effects of acute bouts of exercise on cognition. *Acta Psychol.*

- 112, 297–324. [https://doi.org/10.1016/S0001-6918\(02\)00134-8](https://doi.org/10.1016/S0001-6918(02)00134-8).
- Trangmar, S.J., Chiesa, S.T., Stock, C.G., Kalsi, K.K., Secher, N.H., González-Alonso, J., 2014. Dehydration affects cerebral blood flow but not its metabolic rate for oxygen during maximal exercise in trained humans. *J. Physiol.* 592 (14), 3143–3160. <https://doi.org/10.1113/jphysiol.2014.272104>.
- Vanden Hoek, T.L., Kasza, K.E., Beiser, D.G., Abella, B.S., Franklin, J.E., Oras, J.J., et al., 2004. Induced hypothermia by central venous infusion: saline ice slurry versus chilled saline. *Crit. Care Med.* 32, 425–431. <https://doi.org/10.1097/01.CCM.0000134259.59793.B8>.
- Wendt, D., Loon, L., Lichtenbelt, W., 2007. Thermoregulation during exercise in the heat. *Sports Med.* 37 (8), 669–682. <https://doi.org/10.2165/00007256-200737080-00002>.
- Wilkinson, R.T., Fox, R.H., Goldsmith, R., Hampton, I.F.G., Lewis, H.E., 1964. Physiological and psychological responses to raised body temperature. *J. Appl. Physiol.* 19, 287–291. <https://doi.org/10.1152/jappl.1964.19.2.287>.
- Zimmermann, M., Landers, G., Wallman, K., 2015. Ice ingestion improves cycling hot, humid conditions with no change in energy expenditure or sweat response (e5-e5). *J. Sci. Med. Sport* 19. <https://doi.org/10.1016/j.jsams.2015.12.393>.