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Hand and torso pre-cooling does not enhance subsequent high intensity cycling or cognitive performance in heat.

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Abstract

The purpose of this study was to compare the separate and combined effects of two practical cooling methods (hand and torso) used prior to exercise on subsequent high-intensity cycling performance in heat. Ten trained male cyclists ($\dot{V}O_2$peak: 65.7±10.7 ml.kg^{-1}.min^{-1}) performed four experimental trials (randomised within-subjects design) involving 30 min of pre-cooling (20 min seated; PRE-COOL, 10 min warm-up; PRE-COOL+WUP), while using a: (1) hand cooling glove (CG); (2) cooling jacket (CJ); (3) both CG and CJ (CG+J); or (4) no-cooling (NC) control, followed by a cycling race simulation protocol (all performed in 35.0±0.6°C and 56.6±4.5% RH). During the 30 min of pre-cooling, no reductions in core (Tc) or mean skin temperature (Tsk) occurred, however Tsk remained lower in the CJ and CG+J trials compared to NC and CG (p=0.002-0.040, d=0.55-1.01). Thermal sensation ratings also indicated that participants felt 'hotter' during NC compared to all other trials during both PRE-COOL and PRE-COOL+WUP (p=0.001-0.015, d=1.0-2.19), plus the early stages of exercise (sets 1-2; p=0.005-0.050, d=0.56-1.22). Following cooling, no differences were found for absolute Tc and Tsk responses between trials over the entire exercise protocol ($p>0.05$). Exercise and cognitive (working memory) performance also did not differ between trials (p=0.843), however cognitive performance improved over time in all trials ($p<0.001$). In summary, pre-cooling (20 min seated and 10 min warm-up) in heat did not improve subsequent high-intensity cycling performance, cognitive responses and associated thermoregulatory strain (Tc and Tsk) compared to control.

Keywords: *core temperature, thermoregulation, hand cooling, cooling jacket, thermal sensation, working memory.*

Abbreviations:

BLa – Blood lactate

bpm – beats per minute

BSA – Body surface area

CG – Cooling glove

CG+J – Cooling glove and jacket

CJ – Cooling jacket

CWI – Cold water immersion

ES – Effect size

HR – Heart rate
NC – No-cooling
RH – Relative humidity
RPE – Rating of perceived exertion
Tc – Core temperature
TS – Thermal sensation
Tsk – Skin temperature
WUP – Warm up

Introduction

Exercise in heat can limit physical and cognitive performance capacity as a result of a rise in internal heat load and in particular, core temperatures (Tc) [1,2]. Cooling the body prior to exercise (pre-cooling) is a common strategy used to manage heat related fatigue as this procedure can create a larger heat storage capacity that is proposed to enable a greater amount of work to be performed during subsequent exercise [3]. Several pre-cooling techniques applied to the body (cold air, water, ice or cooling jackets/vests/shirts) or ingested (cold liquid or crushed ice), either separately or in combination, have resulted in subsequent performance benefits, particularly for prolonged exercise in heat (see meta-analyses: [4,5]).

To date, cold-water immersion (CWI) is recognised as one of the most effective methods of reducing pre-exercise Tc and mean skin temperatures (Tsk), thus increasing heat storage capacity and improving subsequent prolonged endurance performance in heat (fixed time or time to exhaustion; [1,6-8]). However, this method requires extended treatment times (up to 1 h) and is often impractical to implement in the field (especially outdoors in heat) due to lack of refrigeration and/or suitable water receptacles. Consequently, less cumbersome pre-cooling methods such as cooling jackets (CJ) have been trialed. Importantly, wearing a CJ prior to exercise in heat (i.e. pre-cooling) has been found to improve subsequent endurance performance in heat (compared to no-cooling: NC) in 5 km running [9] and 16.1 km cycling time-trials [10], plus run [11] and cycling times to exhaustion [12,13]. These results indicate that cooling with a CJ prior to exercise can be effective at reducing Tc and Tsk compared to NC, therefore blunting the rise in thermoregulatory strain (Tc, heart rate, perception of thermal discomfort) during the initial stages of exercise and, in turn, may enable faster speeds during later stages of an endurance event [9]. However, while CJ represent a practical and effective method of pre-cooling, their use during race settings can be difficult due to the need to keep them cold prior to wearing.

A recent alternative cooling method that can be applied in the field is a transportable hand-cooling glove (CG). This device covers the entire hand and utilises cold circulating water (~16°C) combined with subatmospheric pressures (-40 mmHg) to increase blood flow to the packed vascular structures underlying the palm (a non-hairy, glabrous skin surface), thereby extracting heat and cooling venous blood returning to the core [14]. Used during aerobic exercise (walking uphill at 5.6 $km.h^{-1}$) in heat (40°C, 20-45% RH), the CG did attenuate the rise in Tc and significantly extend exercise duration compared to NC (2.1±0.4°C.h^{-1} and 46.1 min vs. 2.9±0.5°C.h^{-1} and 32.3 min, respectively [15]). Further, Hsu et al. [16] reported that wearing the CG during 1 h of submaximal cycling (60% $\dot{V}O_2max$) in heat attenuated the rise of Tc, compared to NC (1.2°C v 1.8°C) and improved 30 km cycling time-trial performance (by 6%, compared to NC). However, participants in these studies wore the CG during exercise, with this unlikely to be replicated in any sporting scenario. Nevertheless, as the CG is easily transportable and does not need power (battery operated) or refrigeration, it may be practical and effective for pre-cooling in the field as recent studies have shown significant reductions in Tc and Tsk when used during [17] and post-exercise [18]. However, no studies have assessed the pre-cooling capacity of the CG prior to exercise whilst resting or during a warm-up (WUP) period (in heat) on subsequent prolonged performance.

Of relevance, prolonged repeated-sprint activity is common in many sports and has been associated with greater physiological and thermal strain than submaximal endurance exercise of a matched intensity. This is likely due to the extra metabolic heat generated by working at a higher intensity when performing repeated-sprints compared to steady-state continuous exercise [19]. While beneficial effects of pre-cooling with CJ have been observed for endurance-based activity, their effectiveness prior to prolonged repeated-sprint exercise remains equivocal. Both Clarke et al. [20] and Duffield et al. [21] have reported improved (albeit non-significant) effects of pre-cooling using a CJ on subsequent prolonged (60-90 min) cycling and running repeated-sprint performance in heat (30°C). Other studies have reported improved subsequent prolonged repeated-sprint performance (running or cycling for greater than 30 min) in heat associated with pre-cooling that used a combination of a CJ with other methods (i.e. ice slushy ingestion, quadriceps ice packs, head and neck ice towels) for 20-30 min [22-24]. Therefore, combining pre-cooling methods (such as CG and CJ) is of interest in that this may provide a greater benefit for high intensity prolonged repeated-sprint efforts in heat than using one application alone. However, this premise is yet to be assessed. Further, practical cooling strategies that can be easily implemented in thermally stressful field environments (e.g. the upcoming 2020 Tokyo Summer Olympics) should be investigated, particularly as events such as the men's cycling road race are predicted to be exposed to very high levels of solar ultraviolet radiation exposure (941 J.m^{-2} [25]).

Specific to cycling, events of 45-60 min duration (e.g. criterium or time-trials) consist of multiple high-intensity sprints, eliciting greater thermal and physiological strain [26] and mean power output than flat or hilly road races [27]. Moreover, repeated maximal sprints and short time-trial efforts are required within a continuous effort, with no opportunity for breaks or cool downs during these particular events. Of relevance, complex cognitive processes, in particular tactical decision-making, choice reaction time and working memory are also important considerations for successful sporting performance [28,29]. Notably, previous studies have reported impairments in attention, decision-making and working memory following exercise in heat, often associated with body-mass losses of >2% caused by a high Tc that resulted in increased sweat output during these conditions [30-32]. Importantly, neck cooling utilised during running to exhaustion at 70% $\dot{V}0_2$max improved cognitive tasks of greater complexity compared to simple cognitive tasks following exercise in heat (30°C, 71% RH) [33]. Therefore, it is possible that applying cooling prior to exercise in heat may delay an increase in Tc and sweat rate compared to NC [34], which in turn may enhance complex cognitive functions, (such as alertness and decision-making), thereby ultimately improving cycling race execution.

Therefore, the aim of this study was to determine whether cooling applied to the hand (CG) and torso (CJ), either separately or in combination prior to exercise would result in improved cycling and cognitive performance in heat. It was hypothesised that cooling prior-to and during the WUP (in heat) would improve cycling and cognitive performance due to reduced thermal strain during the early stages of exercise. Further, it was expected that the combined application of the two cooling methods would enhance these effects to a greater extent.

Methods:

Participants

Ten, non-heat acclimatised, competitive male cyclists [mean±SD: age: 21.1±3.3 y; height: 180.1±7.5 cm; body-mass: 73.9±10.9 kg; body surface area (BSA): 1.9±0.2 m^2; sum of seven skinfolds: 45.4±15.3 mm; $\dot{V}O_2$peak: 65.7±10.7 $ml.kg^{-1}.min^{-1}$] participated in this study. All were experienced cyclists (5.1±2.0 y cycling) and maintained a consistent training volume (~300±113 km of road cycling and ~6±4 h of moderate-high intensity cross training in other physical activity per week) over the study. Testing was conducted during the latter winter/early spring months (where average monthly temperatures in Perth ranged between 18.4-20.3°C; July-September) to ensure that participants were not heat acclimatised. Using a G-power analysis [35], it was determined that ten participants were needed based on a study by Barr et al. [36] that used an effect size of 1.4, at an alpha level of 0.05 and power of 0.80. All participants provided informed consent and ethical approval was granted by the Human Research Ethics Committee of the University of Western Australia.

Experimental Design

Participants attended a familiarisation session, followed by four randomised experimental trials performed at the same time of day at least 3 days apart to control for circadian variability. Trials (all in heat: 35.0±0.6°C and 56.6±4.5% RH) involved a 30 min pre-cooling period, where participants were first seated for 20 min (PRE-COOL) and then commenced warming up for 10 min (PRE-COOL+WUP) while using: (1) hand CG; (2) CJ; (3) both the CG and CJ (CG+J); or (4) NC (control), followed by a cycling race simulation protocol. In the 24 h prior to testing, participants replicated food and fluid intake and abstained from vigorous exercise and alcohol.

Familiarisation Session

Anthropometric measurements were first recorded (as described earlier) then a graded exercise test on a cycle ergometer was performed to determine $\dot{V}O_2$peak, commencing at an intensity of 160 W and increasing by 30 W every 3 min until volitional exhaustion. Expired air was analysed via a metabolic cart (TrueOne 2400, Parvo Medics Inc, Utah, USA). Following recovery, participants then completed the first 3 sets of the cycling race simulation (detailed below) to become accustomed to the format, pacing and procedures used during the subsequent experimental trials. All testing was performed on a stationary air-braked cycle ergometer (Evolution bicycles, Geelong, Australia), connected to a customised computer program for determination of work/power output (Cyclemax, UWA, Australia). This (6 gear) ergometer allows for individual resistance and cadence choices, with resistance proportional to pedal rate as air is displaced from fan blades attached to the flywheel when the wheel turns. This variation in pedal rate and gearing reflects the type of resistance and convective conditions commonly experienced during road cycling races. Participants were then familiarised to the cognitive test (Serial Sevens) and all other equipment to be used during the experimental trials.

Cognitive Task (Serial Sevens)

A modified verbal version, based on the original Serial Sevens subtraction task used by Hayman [37], was assessed at 4 time points in each trial: baseline and following sets 2, 4 and 6 (end). The Serial Sevens task is a complex cognitive task designed to assess attention, concentration and working memory [38], with this modified version similar to that used by Kennedy and Scholey [39]. During this task, participants were presented with a randomly generated number (between 900-1000) and asked to count backwards (out loud) by 7 as quickly and as accurately as possible for 60 s. The task was scored as total number of subtractions made in this time (representing speed) and the number of incorrect responses (to represent accuracy). Participants were instructed that if they made a mistake they should carry on subtracting from the new number and subsequent responses were scored as positive if they were correct in relation to the new number.

Preliminary Procedures

Eight hours prior to the experimental trial, participants ingested a radiotelemetry pill (CorTemp, HQ, Inc., Palmetto, USA) for the measurement of gastrointestinal Tc and ingested 600 mL of water at least 1 h prior to arrival for pre-exercise hydration purposes. Upon arrival, a mid-stream urine sample was collected in a sterile container and 1 mL placed on the plate of a refractometer (TE-RM10SG, 1.000-1.070, Test Equip, Dandenong, Australia) to determine urine specific gravity (U_{SG}) to check that cyclists attended each trial in a similar euhydrated state (U_{SG}<1.020). Nude body-mass was then recorded on a digital platform scale (Model ED3300; Sauter Multi-Range, Ebingen, Germany) to the nearest 0.01 kg. A heart-rate (HR) monitor (Polar RS400, Finland) was fitted across the chest and skin thermistors (Skin Sensor SST-1, Physitemp Instruments Inc, Clifton, NJ, USA) taped on the sternum, right mid-anterior forearm and right mid-posterior calf to record Tsk by a computerised program (DASYLab Light, National Instruments, Ireland Resources Ltd). Mean Tsk was then calculated using the formula = (0.5 x $T_{sternum}$) + (0.14 x $T_{forearm}$) + (0.36 x T_{calf}) [40]. A capillary blood sample (finger prick) was then collected to measure blood lactate (BLa) concentration (Lactate Pro 2, Arkray KDK Corp., Kyoto, Japan). Baseline Tc and Tsk, HR, rating of perceived exertion (RPE; 6-20 scale) [41] and thermal sensation (TS; 0-8 scale) [42] were then recorded, and again every 5 min during the 30 min pre-cooling period.

Pre-cooling Interventions

Upon entering the climate chamber, participants immediately adopted one of four conditions (CG, CJ, CG+J or NC) for 30 min (20 min seated immediately followed by 10 min warm-up). The CG (CoreControl™, AVAcore Technologies, Ann Arbor, MI) was placed on the participant's dominant hand, encapsulating the hand surface area (wrist to fingertips). The gel CJ (Arctic Heat Products Pty Ltd, Queensland, Australia) was chosen for this study due to its common use in many Australian sports (e.g. football, rugby, hockey). The CJ has four anterior and posterior pockets containing crystals. As per manufacturer's instructions, the jacket was first soaked in water to activate the crystals to form a gel and then stored in a refrigerator. Prior to the cooling protocol, the CJ was placed in icy water (0-2°C) for 30 min then wrung out and worn over the participants cycling bib (participants wore bib shorts only). During the CG+J trial, participants adopted both cooling methods whereas during the control NC trial, the participant was seated with no cooling intervention.

Warm-up and Exercise Protocol (Cycling Race Simulation)

The 10 min of self-paced WUP (while still cooling or NC) included 3 x 5 s sprints performed at 70, 80 and 90% 'perceived' intensity. Then, the cycling protocol, comprising 6 sets (4 sets of 6 x 15 s sprints with varying recovery durations and 2 sets of 5 min maximal time trials; see Table 1) was performed. The sprints in sets 1 and 4 were separated by 45 s active recovery, and sets 2 and 5 by 15 s active recovery (all at 100 W). All sets were separated by 3 min of active recovery where participants also maintained a power output of 100 W. Active recovery was used to simulate a road-race where there are constant changes of tempo (hills/breakaways/being in the pack and relatively recovering) while proceeding in the race. Total cycling time was 43 min (excluding warm-up). This protocol was previously used by Brewer et al. [43] and modified from the cycling race simulation used by Vaile et al. [44]. During the trial, participants were only able to see the time left to complete each effort (which counted down and reset continuously) thus keeping the participant and the researcher blinded to their power output. Participants ingested 500 ml of water (23°C) throughout the trial. Performance measures, including total work (kJ) and mean power output (W), were determined for each individual sprint and time-trial set as well as across the entire trial. Immediately after each set Tc, Tsk, HR, RPE and TS were assessed, with the Serial Sevens and BLa only measured at the end of sets 2, 4 and 6. Participants then exited the chamber, were towel dried and nude body-mass was again measured to determine sweat loss (pre – post nude body-mass + fluid ingested).

Table 1: Cycling race simulation protocol (TT = time-trial).

Set	Activity	*Recovery	Time (min)
1	6 x 15 s sprints	45 s active recovery	6
2	6 x 15 s sprints	15 s active recovery	12
3	5 min TT	-	20
4	6 x 15 s sprints	45 s active recovery	29
5	6 x 15 s sprints	15 s active recovery	35
6	5 min TT	-	43

*3 min active recovery (100W) separated each set

Statistical Analysis

All data was analysed using SPSS Statistics Version 25.0 (IBM, Inc., New York, NY) and p-values $p<0.05$ were considered statistically significant. The effect of the four interventions on performance (cycling or cognitive) and physiological/perceptual variables (Tc, Tsk, HR, RPE, TS) were analysed using two-way (trial x time) repeated-measures ANOVAs across all time points, while one-way repeated-measures ANOVAs assessed baseline variables, performance trial totals, U_{SG}, sweat loss and environmental conditions. Where main or interaction effects occurred, follow-up post hoc comparisons using Bonferroni adjustments and paired sample t-tests were used to determine the location of any differences. In addition, inferential statistical analysis using Cohen's *d* effect sizes (ES) was calculated to determine the magnitude of these differences [45], with only moderate (0.50-0.80) to large (>0.80) ES reported. All values are expressed as mean ± standard deviation.

Results:

There was no difference in environmental conditions between trials or at any time point during all trials (35.0±0.6°C, p=0.693, 56.6±4.5% RH, p=0.319). Prior to exercise, participants' average U_{SG} status was 1.018±0.01, with this value being similar between trials (p=0.109). Blood lactate levels were also similar between trials at baseline (1.7±0.8 mmol.L^{-1}; p=0.296).

Pre-Cooling Period

For all trials, Tc was similar at baseline (~37.0±0.4°C, p=0.685; Figure 1) and remained relatively unchanged for the 20 min PRE-COOL period, with no significant differences or moderate-large ES recorded between trials at any time point (p=0.959). Once WUP commenced, a main effect for time (p<0.001) was seen for Tc, as values gradually rose in all trials to an average of 37.3±0.4°C; however, there were no significant differences or moderate to large ES between trials from 20-30 min (p=0.346).

In respect to Tsk, baseline values in all trials were similar (33.3-33.7°C, p=0.544; see Figure 2) with an interaction effect (p=0.001) seen as Tsk increased every 5 min across the PRE-COOL period in all trials (main effect for time p<0.001 and trial p=0.008). Specifically, over this 20 min period, Tsk was significantly lower for CJ and CG+J compared to CG at each 5 min time point from 5-20 min (p=0.002-0.022, *d*=0.77-1.01). Furthermore, moderate to large ES suggested a tendency for Tsk to be lower for the CJ compared to NC at every 5 min interval of the 20 min PRE-COOL period, with these values supported by significant p values recorded at the 10 and 15 min marks (CJ versus NC: *d*=0.67-0.85, p=0.033-0.056; 10 min p=0.040, 15 min p=0.033). Similarly for the CG+J trial, Tsk values tended to be lower than NC over the 20 min PRE-COOL period, with values being significant at 15 and 20 min (CG+J versus NC: *d*=0.51-0.97, p=0.005-0.120; 15 min p=0.026, 20 min p=0.005). Once the 10 min WUP commenced, Tsk continued to increased over time (p<0.001) and differ between conditions (p=0.003). After the first 5 min of PRE-COOL+WUP (25 min mark of overall cooling, see Figure 2), Tsk values remained lower in CJ and CG+J compared to CG (p=0.054, *d*=0.66 and p=0.021, *d*=0.79, respectively) and NC (p=0.052, *d*=0.81 and p=0.004, *d*=1.02, respectively). At the end of the 10 min PRE-COOL+WUP period, Tsk remained significantly lower for CJ and CG+J compared to NC (p=0.014, *d*=0.77 and p=0.015, *d*=0.64, respectively), while Tsk for CJ tended to be lower than CG (p=0.076, *d*=0.55).

Additionally, HR at baseline averaged 68±14 bpm across all trials (p=0.905) and remained relatively unchanged between trials at the end of the 20 min PRE-COOL period (72±15 bpm, p=0.580). Heart rate then increased over the PRE-COOL+WUP to an average of 124±20 bpm (p<0.001) at 30 min, but no significant differences occurred between trials (p=0.275). Ratings of TS at baseline were the same for all trials ('4 = comfortable', p=1.000). Once cooling (or NC) was applied, a significant interaction (p<0.001) and main effect for trial (p<0.001) indicated higher ('hotter') TS ratings for NC compared to all other trials at each 5 min interval over the 20 min PRE-COOL period (p=0.001-0.013, *d*=1.0-2.19; Figure 3), with TS ratings for CG also tending to be higher compared to CJ (p=0.070-0.217, *d*=0.68-0.99) and CG+J (p=0.024-0.070, *d*=0.79-1.12) across the same period. Thermal sensation then increased over the PRE-COOL+WUP period (p<0.001), remaining higher in NC compared to all other trials (p=0.003-0.015, *d*=0.1.26-1.85), while TS was higher in CG compared to CJ and CG+J; p=0.024-0.037, *d*=0.85-1.11).

Exercise Period

No significant differences or moderate-large ES were found between the four trials at any time point assessed (sets 1-6) for exercise performance (total work: p=0.345 or mean power: p=0.940; Table 2). Further, similar work and power outputs were maintained over the entire protocol, as no significant differences existed between trials for 'like' sets (1 vs. 4, work: p=0.897, power: p=0.965; 2 vs. 5, work: p=0.832, power: p=0.857; 3 vs. 6, work: p=0.558, power: p=0.626). Additionally, no significant difference was found between trials for the overall trial total work (p=0.103) or power (p=0.164).

Once exercise began, Tc continued to increase over the 6 sets (main effect for time p<0.001), peaking at an average of 38.8±0.4°C. This ~1.5°C rise occurred over 43 min, however no significant differences were seen between trials (p=0.082) following any of the 6 sets. However, moderate ES indicated that Tc in the CG+J trial tended to be lower after set 5 (38.4±0.3°C) compared to all other trials (~38.6°C; p=0.071-0.179, *d*=0.5-0.56), and lower than CJ following set 6 at trial completion (38.6±0.3°C v 38.9±0.4°C*;* p=0.080, *d*=0.58). Further, mean Tsk increased slightly by ~0.4°C (to 35.9±0.5°C) from the end of PRE-COOL+WUP to trial completion (set 6). No significant interaction (p=0.140) or main effects for time (p=0.061) or trial (p=0.814) were found for Tsk, but moderate ES did show that Tsk tended to be higher for CJ compared to CG+J in sets 4 (p=0.197, *d*=0.56) and 5 (p=0.154, *d*=0.55) and compared to CG in sets 5 (p=0.132, *d*=0.61) and 6 (p=0.071, *d*=0.64).

Heart rate increased over each successive set of the exercise protocol, peaking after the time-trials (sets 1-3: ~158 to ~174 bpm, sets 4-6: ~165 to ~180 bpm; main effect for time p<0.001), although no significant differences in HR were found between trials after each set (p=0.610). Ratings of TS also increased over the exercise protocol, from '5 = warm' to '7 = very hot' (p<0.001); with a main effect for trial (p=0.002), which specifically saw higher values for NC compared to CG (p=0.025-0.050, *d*=0.56-0.58), CJ (p=0.007-0.053, *d*=0.58-1.04) and CG+J (p=0.005-0.006, *d*=1.20-1.22) following the first two sets. Furthermore, RPE values also increased in a steady manner from the commencement of exercise to the end of the exercise protocol (8 to 19; p<0.001), with no significant differences found between trials upon exercise completion (RPE: 19±1='extremely hard'; p=0.224). Blood lactate levels increased rapidly with exercise (p<0.001), however responses were not significantly different between trials at any time point (p=0.652) with final BLa values reaching 18.7±4.7 $mmol.L^{-1}$. Finally, moderate-large ES indicated that a greater sweat loss occurred for NC (1.79±0.33 kg, 2.42% body-mass loss) compared to all other trials (1.53-1.60 kg, 2.07-2.16% body-mass loss; p=0.085, *d*=0.55-0.88).

For the Serial Sevens cognitive task, only a significant main effect for time occurred (p<0.001), as performance on the task (total amount of numbers subtracted) improved from baseline (~20 subtractions) to the end of exercise (~24 subtractions), with no significant interaction found for trials at any point during the protocol (p=0.843). Additionally, participants made an average error of ~1 number each time the task was performed, but this was not different over time or between trials (p=0.999).

Discussion

The purpose of this study was to assess the effects of practical pre-cooling methods (hand and torso cooling alone and combined) compared to NC on subsequent cycling and cognitive performance in heat. While the CJ and CG+J resulted in reduced Tsk and TS during pre-cooling compared to CG and NC, no significant differences or moderate to large ES were found between trials for subsequent exercise or cognitive performance. Overall, these results do not support our hypotheses.

Pre-cooling Period

During the 30 min pre-cooling period, the cooling modalities had little effect in either decreasing Tc or limiting its rise (across WUP) compared to NC. This is similar to previous findings where no effect of cooling on Tc was seen when pre-cooling was undertaken with a CJ alone while resting in heat (34.3-37.0°C, 41-50% RH) [46,47] or when a CJ was worn during an active WUP in heat (35.0°C, 44% RH) [10]. In our study it was expected that the addition of WUP during pre-cooling would have resulted in an increased flow of cooler blood (as a result of using the cooling modalities, specifically CJ and CG+J) from the skin to core, with this ultimately reducing Tc compared to NC prior to exercise commencement. Possibly, attempting to reduce Tc using cooling modalities that only cover sections of the body (as opposed to CWI) may not be consistently successful when Tc is within a normal resting range (~36.5-37.5ºC) [48] or when exposed to heat.

The Tsk values in the current study were lower during the initial 20 min resting period in the CJ and CG+J trials compared to NC, but then similarly increased over time in all trials. This outcome is supported by other studies that performed pre-cooling (20-40 min) with a CJ in heat (34.3-37.0°C, 41-50% RH) whilst resting and reported significantly lower Tsk for the CJ compared to control, with Tsk increasing slightly over the duration of the pre-cooling period in all trials [46,47]. Across the 10 min PRECOOL+WUP period, Tsk values in the current study again increased over time in all trials, yet remained lower for CJ and CG+J compared to NC, similar to results seen in previous studies utilising a CJ during an active WUP in heat [9,10,47]. Despite the use of cooling modalities, the slight increase in Tsk during rest and WUP for all trials found here most likely reflect the overwhelming effects of a hot environment on the body surface. Furthermore, it has been suggested that wearing the CJ whilst resting may result in vasoconstriction (with a concomitant decrease in blood flow), consequently reducing heat exchange between the CJ and the core but enabling some heat exchange from the skin to the CJ to occur, thus resulting in a reduction in Tsk (but not Tc) when compared with control [12]. When worn during the WUP, the two CJ trials continued to mediate localised skin cooling (heat exchange between the jacket and the skin) compared to NC, with the expectation that cooled blood would result in a lower Tc due to an increase in blood flow as a result of the active WUP [9]. However this did not occur here possibly due to reasons noted earlier. Furthermore, the significantly lower Tsk found here in the two CJ trials compared to the CG alone may be due to the greater BSA covered by the CJ compared to the CG (CJ ~17% versus CG ~1% [17]), as well as the fact that mean Tsk is calculated from measurements at various sites on the body, with greater emphasis placed on the sternal measurement, an area directly covered by the CJ.

In respect to Tc and Tsk results for the CG, no published studies to date have assessed the effect of this modality on Tc and Tsk responses during pre-cooling with or without a WUP in heat. Consequently, the results found here suggest that this cooling method has no impact on the rise in Tc and Tsk when used prior to exercise or during a 10 min active WUP in heat. Possibly, the combination of the minimal BSA covered by the CG and a lack of effect of the CG on Tc that is within a normal resting range may partly explain these results, although further studies are required to confirm or refute these findings.

While not surprising, our results do show that the cooling provided by CJ and CG+J also improved (reduced) TS, as participants 'felt' significantly hotter in NC during the entire 30 min pre-cooling period in heat. The lower TS scores associated with CJ and CG are supported by other studies that reported lower TS results associated with the use of a CJ during a WUP compared to NC [9,10,47], with no previous studies assessing TS during WUP using a CG.

Exercise Performance

Previous studies have reported significant improvements in subsequent maximal running and cycling endurance performance [9-12,47] following pre-exercise reductions in Tc and/or Tsk as a result of wearing a CJ (compared to NC) during pre-cooling and a WUP in heat. Our results contrast with the majority of this research, as no improvements in subsequent exercise performance were found here following pre-cooling with the CJ or CG (either alone or in combination), compared to NC. This result is likely due to similar Tc values being found between all trials following pre-cooling, despite lower Tsk values (for the CJ trials) and improvements in TS (for all cooling trials) leading into exercise, compared to NC.

Of relevance, Schlader et al. [49] proposed that lower Tsk and TS values (compared to a control) could influence self-selected exercise intensity, resulting in greater power output during the initial stages of cycling in heat, however no effect was found here. Although participants did report feeling 'cooler' in cooling trials compared to NC following the first two sets of exercise, the lower TS values were not enough to translate into performance benefits in these or later sets (likely due to similar Tc and Tsk). It is also possible that once exercise commenced in our study the airflow generated from the bike fan could have limited the previous Tsk cooling effects seen during the pre-cooling period, as no further differences in Tsk were found for the CJ trials (compared to NC) once exercise commenced. The effect of the bike fan replicates convection conditions that would typically be encountered during outdoor road cycling (high ecological validity), therefore the pre-cooling interventions used here may be more beneficial in sporting scenarios where wind doesn't offer the same convective skin cooling effect as that typically seen with cycling.

As the overall work and mean power output did not differ between the cooling and NC trials here, the magnitude of any cooling effect produced appears insufficient to promote any change in exercise performance. Our findings are similar to those by Quod et al. [46] who reported a reduction in Tsk, but not Tc (compared to NC) following CJ pre-cooling, with no improvement found for subsequent 40 min cycling time-trial performance. Further, Stannard et al. [50] also reported that pre-cooling with a CJ (compared to NC) resulted in no significant differences between trials for Tc or subsequent 10 km running time-trial performance. Overall, these results infer that pre-exercise Tc needs to be reduced (compared to NC) for subsequent exercise performance to have the best prospects of improvement. Of further consideration is the type of exercise used following pre-cooling. Specifically, the effects of pre-cooling on prolonged activity generally show greater benefit for submaximal (continuous) exercise than maximal repeated-sprint activity (as summarised in Bongers et al. [51]). For example, when wearing a CJ (for 5-20 min) prior to prolonged repeated-sprint cycling and running protocols in heat (30-80 min in duration), no significant improvements in subsequent performance were reported [21,52-54]. This contrasts to the significant performance improvements seen during prolonged continuous cycling and running following pre-cooling compared to no-cooling [9-13]. These differences may be because prolonged repeated-sprint performance elicits greater thermoregulatory and physiological strain than submaximal endurance activity [19], which in turn may limit the effects of pre-cooling.

With regard to the CG, this was the first study to assess Tc/Tsk responses in a pre-cooling capacity (30 min). No effect was found for subsequent exercise performance when compared to NC, so it is likely that (similar to CJ) pre-exercise Tc needs to be lower than control for any subsequent performance benefits to occur after using a CG. Interestingly, wearing the CG during walking [15] and cycling [16] exercise in heat has been found to attenuate the rise in Tc and extend exercise time compared to NC, but using this method during exercise is impractical in most sporting scenarios. Additionally, using the CG for 10 min following 60 min of exercise-induced hyperthermia reduced Tc by 0.4ºC and improved subsequent 3 km time trial performance by 20 s in heat (~31ºC) compared to NC in wheelchair tennis athletes [55]. Therefore, while a CG was not beneficial for the population of athletes or repeated-sprint cycling activity used in this study, whether this form of pre-cooling could provide a benefit in sporting populations that have impaired thermoregulatory ability [56] and face logistical challenges (e.g. wheelchair athletes) requires further investigation.

Sweat Loss and Cognitive Function

Here, greater sweat loss occurred in NC, indicating a greater degree of dehydration (2.42% body-mass loss) compared to all other trials (2.07-2.16%), for the same rise in Tc. The lower sweat loss found in the cooling trials is likely due to the delayed onset of sweating promoted by pre-cooling [57]. Of relevance, exercise-induced fatigue and dehydration (decreases in body-mass >2%) following prolonged exercise in heat has previously shown impairments in complex cognitive ability [30-32]. In regard to our cognitive performance results (specifically working memory), no decrement on the Serial Sevens task was seen throughout or at the completion of exercise in all trials, although participants were moderately dehydrated (as mentioned above) and fatigued (mean HR: 180 bpm, RPE: 19 = 'very, very hard', TS: 7 = 'very hot'). Specifically, task performance (speed and accuracy) improved (total number of correct subtractions with no change in errors made) during and following exercise compared to baseline in all trials. This contrasts with our hypothesis as it was thought that strenuous exercise in heat would impair cognitive performance, as an increased heat load (elevated Tc) impairs complex task performance at a lower Tc than simple/less attention demanding tasks [58]. Small increases in Tc (up to 38.2°C) have been linked to improved complex cognitive performance [33,59,60], possibly due to exercise-induced arousal [61], coupled with higher levels of blood adrenaline caused by exercise [62]. These factors have previously been described to explain improvements in complex decisional tasks following acute exercise [63] and could explain the similar improvements over time seen here. Of relevance, impairments in complex task performance have been shown to manifest when Tc exceeds >39.0°C [64,65], suggesting that a greater hyperthermic state during exercise (Tc of 38.8°C achieved here) would have had to occur before cognitive performance decrements may have been seen.

Importantly, the Serial Sevens task is a complex cognitive test that assesses attention, working memory maintenance and manipulation [38]. By maintaining or improving working memory capacity (as seen here), it would be expected that attention would be improved, thus enhancing the ability to block out distractions during sporting events [28]. The comparable cognitive scores found between all trials here is most likely a reflection of the similar Tc values recorded at the end of pre-cooling.

Conclusion

In summary, the combined method of pre-cooling (CG+J) was similar in effect to the CJ alone in reducing Tsk and TS prior to exercise and during a WUP (in heat); however, this did not translate into improved subsequent cycling performance, most likely because Tc was unaffected by use of these cooling modalities. Further, no benefit of the CG alone was found on cooling rates or subsequent exercise performance. Notably, working memory performance improved in all trials, indicating complex cognitive function was not negatively affected during prolonged high intensity exercise in heat.

Practical Applications:

Based on these findings, when determining pre-cooling strategies to implement prior to prolonged exercise performance in hot and humid conditions (such as that anticipated of the 2020 Tokyo Olympic Games), athletes and practitioners could consider the following:

- As the aim of pre-cooling is to lower Tc prior to exercise, the use of practical methods such as a CJ and CG were unable to do this, nor did precooling with these devices improve subsequent performance in a trained cycling population prior to high intensity endurance exercise in heat.
- Use of more effective pre-cooling methods or multiple methods used together to cover greater body surface area may be required to achieve reductions in Tc, hence delay the rise during exercise in heat and improve endurance exercise performance.
- While reductions in Tsk and TS were evident following pre-cooling with the CJ, CG and CG+J, this did not improve subsequent repeated-sprint performance. However, these physiological responses to cooling with a CJ and/or CG may be beneficial for improving performance in submaximal endurance events.
- Pre-cooling with the CG, CJ and CG+J did not improve complex cognitive performance during a simulated cycle road race in heat (35.0°C and 56.6% RH) compared to a no-cooling trial. However highly trained athletes were able to

maintain successful cognitive functions (i.e. decision-making) when in a markedly hyperthermic state (Tc of 38.8°C).

Disclosure statement

The authors have no conflict of interest to declare.

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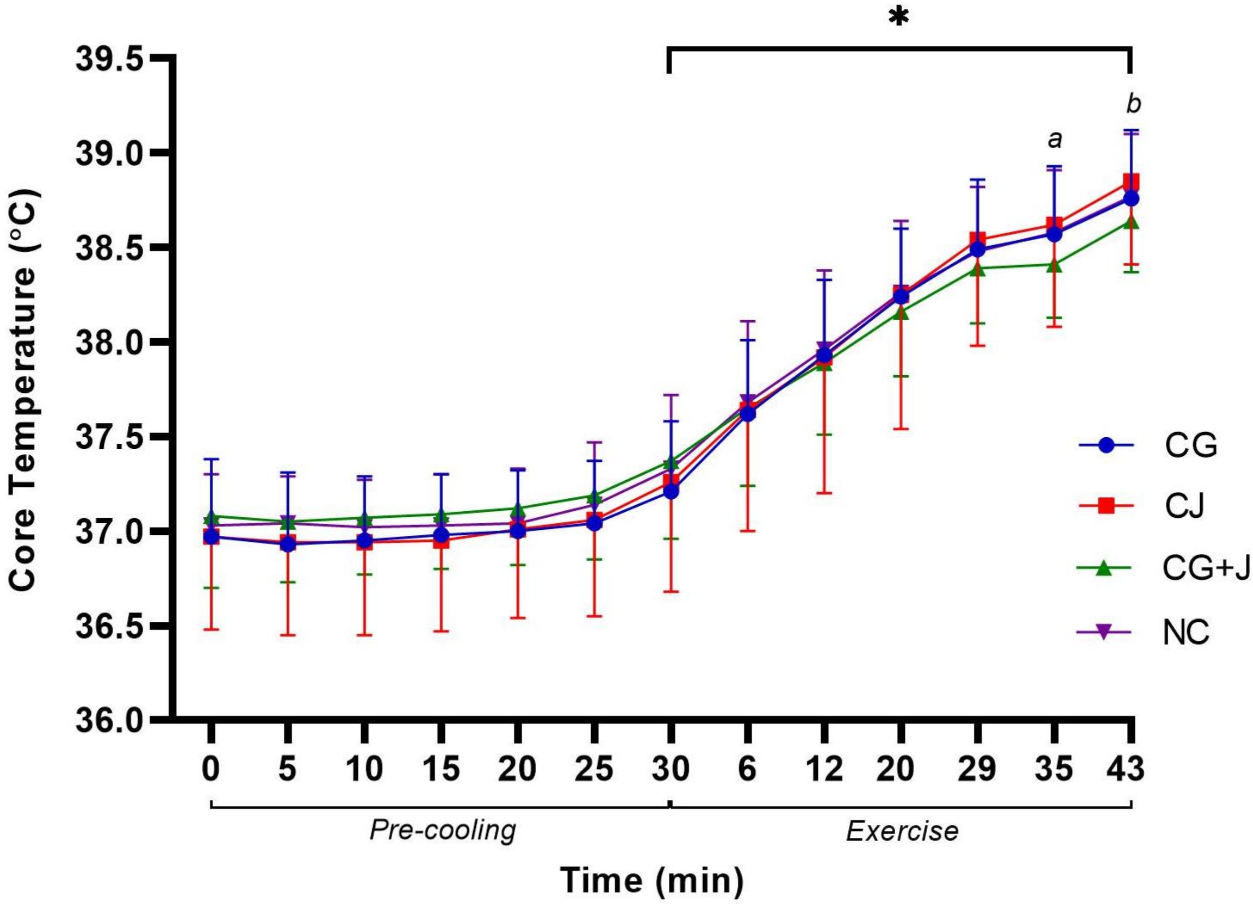
Table 2. Total Work (kJ) and Mean Power Output (MPO; Watts) recorded during the simulated cycling race protocol following a 30 min pre-cooling period using a cooling glove (CG), cooling jacket (CJ), cooling glove and jacket (CG+J) or no cooling (NC) (n=10).

	CG		**CJ**		**CG+J**		**NC**	
	Work	**MPO**	**Work**	**MPO**	**Work**	**MPO**	**Work**	**MPO**
Set 1	51.3 ± 7.9	570.4 ± 88.5	51.9 ± 6.4	577.4 ± 70.9	51.2 ± 6.8	568.9 ± 75.5	51.0 ± 7.7	567.5 ± 85.5
Set 2	47.6 ± 6.4	528.3 ± 69.7	48.1 ± 5.6	533.1 ± 60.1	46.6 ± 6.4	517.1 ± 69.6	46.5 ± 7.5	515.0 ± 80.2
Set 3	95.8 ± 18.2	316.7 ± 55.2	100.8 ± 17.5	333.0 ± 52.7	97.1 ± 17.0	320.6 ± 50.2	98.3 ± 17.5	325.5 ± 53.8
Set 4	51.4 ± 8.2	569.7 ± 88.0	51.9 ± 7.9	575.7 ± 84.5	51.1 ± 7.5	567.9 ± 83.3	50.4 ± 7.9	559.0 ± 85.3
Set 5	45.9 ± 6.8	510.4 ± 77.5	46.8 ± 6.6	520.3 ± 73.4	45.7 ± 6.7	508.2 ± 75.0	45.0 ± 7.4	499.7 ± 82.4
Set 6	96.9 ± 14.5	322.7 ± 47.7	100.4 ± 14.2	339.3 ± 41.7	100.0 ± 17.4	333.2 ± 57.9	97.3 ± 15.9	324.4 ± 82.4
Trial total	388.9 ± 51.0	469.7 ± 60.6	400.1 ± 50.8	479.8 ± 56.4	391.7 ± 51.4	469.3 ± 56.6	388.6 ± 54.3	465.2 ± 63.4

No significant differences ($p>0.05$) or moderate-large ES were noted for any data.

Figure 1: Mean (±SD) core temperature responses (°C) during the 30 min pre-cooling period (20 min PRE-COOL, 10 min PRE-COOL+WUP) and 43 min exercise protocol (n=10).

CG: cooling glove, CJ: cooling jacket, CG+J: cooling glove and jacket, NC: no cooling.



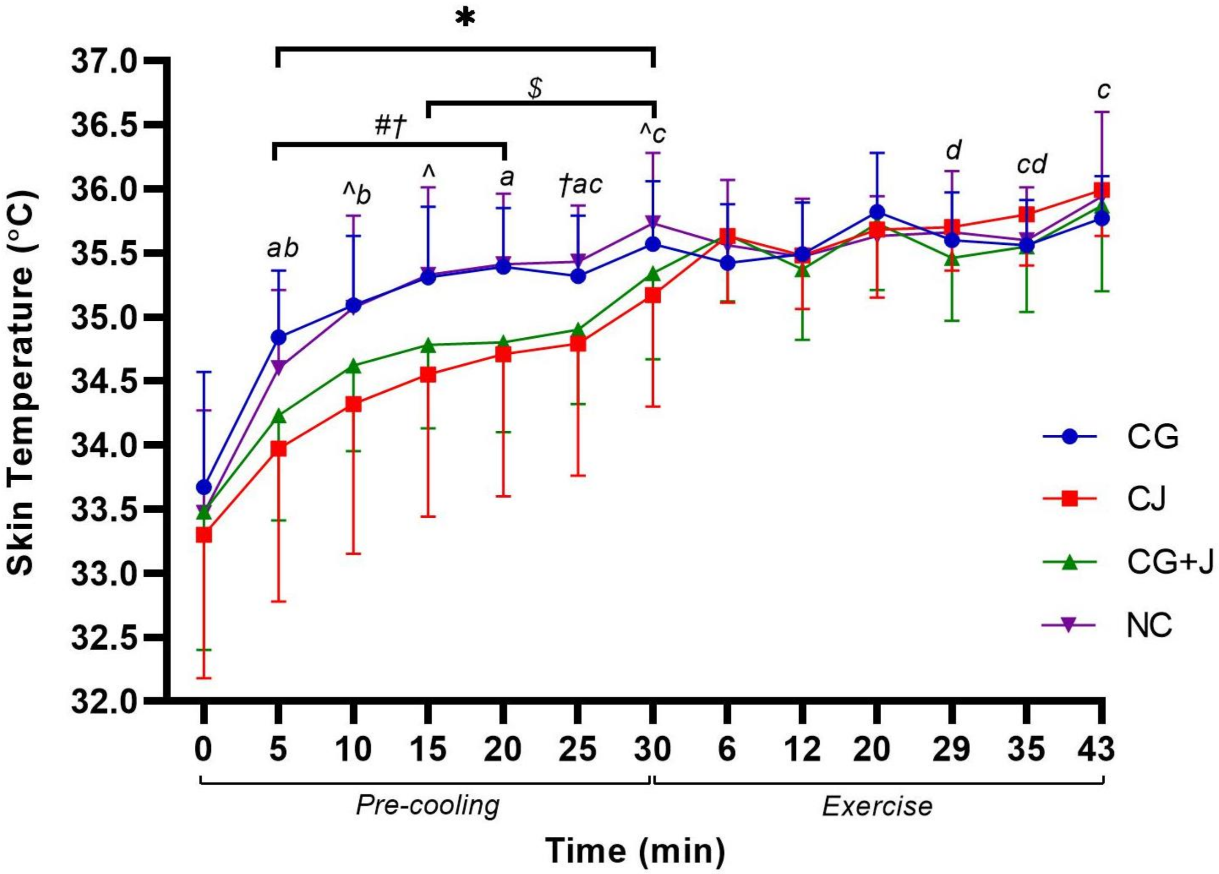
*Main effect (time); significantly different from preceding time point (p<0.001)

[a] Moderate ES for CG+J v all trials (*d*=0.50-0.56)

[b] Moderate ES for CG+J v CJ (*d*=0.58)

Figure 2: Mean (±SD) skin temperature responses (°C) during the 30 min pre-cooling period (20 min PRE-COOL, 10 min PRE-COOL+WUP) and 43 min exercise protocol (n=10).

CG: cooling glove, CJ: cooling jacket, CG+J: cooling glove and jacket, NC: no cooling.



* Main effect (time); significantly different from preceding time point (p<0.001)

Significant difference for CJ vs. CG (p=0.002-0.022)

† Significant difference for CG+J vs. CG (p=0.002-0.022)

^ Significant difference for CJ vs. NC (p=0.014-0.040)

$ Significant difference for CG+J vs. NC (p=0.004-0.026)

[a] Moderate-large ES for CJ vs. NC (*d*=0.52-0.81)

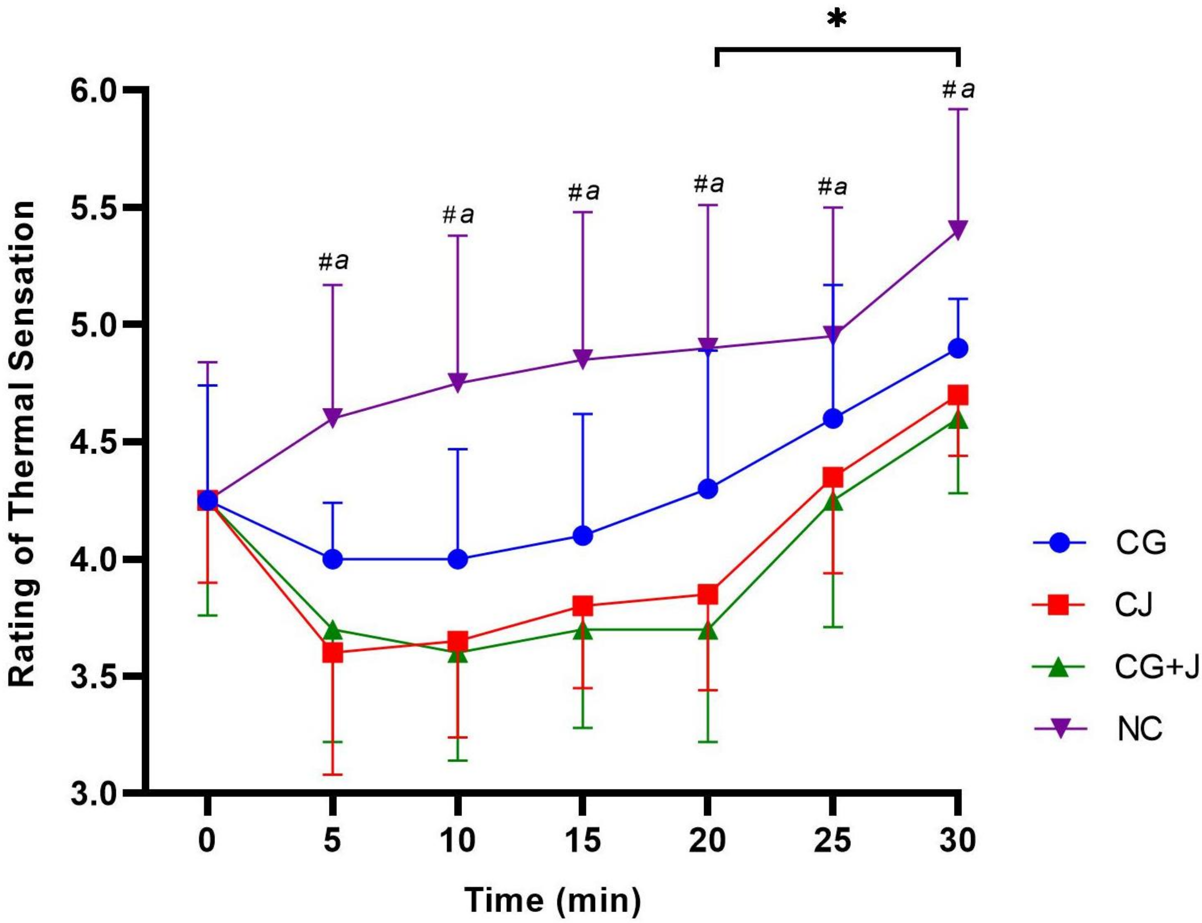
[b] Moderate ES for CG+J vs. NC (*d*=0.51-0.66)

[c] Moderate ES for CJ vs. CG (*d*=0.55-0.66)

[d] Moderate ES for CG+J vs. CJ (*d*=0.55-0.56)

Figure 3: Ratings of thermal sensation (mean±SD) during the 30 min pre-cooling period (20 min PRE-COOL, 10 min PRE-COOL+WUP) (n=10).

CG: cooling glove, CJ: cooling jacket, CG+J: cooling glove and jacket, NC: no cooling.



*Main effect (time); significantly different from preceding time point (p<0.001)

[#] Significant difference for CG, CJ and CG+J vs. NC (p=0.001-0.015)

[a] Moderate-large ES for CJ and CG+J vs. CG (*d*=0.68-1.12)