

Effects of body cooling on aerobic exercise capacity under combined heat stress and mental fatigue

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ABSTRACT

This study examined the effects of body cooling on thermoregulatory and perceptual responses during exercise under combined heat stress and mental fatigue. Seven moderately trained males completed three randomized trials: thermoneutral (22°C, CON), hot (35°C, HOT), and hot with cooling (35°C, COOL). Participants performed a cognitive task during 45 min of cycling at 50% maximal oxygen uptake ($\text{VO}_{2\text{max}}$), followed by exercise at 75% $\text{VO}_{2\text{max}}$ until exhaustion. In COOL, participants ingested ice slurry (1.25 g/kg body mass every 5 min for 30 min) and wore an ice vest starting 40 min before exercise. Absolute time to exhaustion was shorter in HOT (441 ± 83 s) than in CON (623 ± 153 s) and COOL (571 ± 198 s), although differences were not statistically significant. Exploratory analysis showed a smaller reduction in time to exhaustion relative to CON in COOL than in HOT ($92.7 \pm 22.9\%$ vs. $73.9 \pm 21.3\%$). The increase in rectal temperature from baseline to exercise onset was lower in COOL than HOT. Mental fatigue increased following the cognitive task in all trials, with no differences among trials, and objective cognitive performance was unchanged. These findings suggest that cooling reduced thermal strain but did not significantly improve absolute aerobic exercise capacity.

Keywords: sports medicine; ice slurry; ice vest; time to exhaustion; core temperature; AX-CPT.

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INTRODUCTION

Exposure to hot environments places considerable strain on both physiological and psychological systems during exercise (Flouris & Schlader, 2015), particularly in aerobic exercise, repeated sprint performance and team sports performed in hot conditions (Girard et al., 2015). Elevated core (T_c) and skin temperatures (T_{sk}) have been repeatedly identified as major limiting factors to endurance performance, primarily via reduction in central nervous system drive, increased cardiovascular strain and an elevated perception of effort (Gonzalez-Alonso et al., 1999; Maughan & Shirreffs, 2004). Additionally, prolonged cognitive load leading to mental fatigue has emerged as a critical modulator of endurance exercise tolerance, independent of overt physiological strain (Marcora et al., 2009). Metanalyses have demonstrated small to medium negative effects of experimentally induced mental fatigue on subsequent endurance performance (Brown et al., 2020; Giboin & Wolff, 2019).

More recently, interest has grown in the combined impact of heat stress and mental fatigue (Naito et al., 2024; Otani et al., 2017; Van Cutsem, De Pauw, et al., 2017). Otani et al. (2017) demonstrated that heat-stress-induced increases in T_c and T_{sk} , produced by upper-chest warm-water immersion in a seated position during cognitive tasks (CT) in healthy young adults, reduced subsequent aerobic exercise capacity compared with mental fatigue alone. In addition, Naito et al. (2024) reported that, in highly trained athletes, a protocol combining mental fatigue induction with hyperthermia (elevations in both T_c and T_{sk}) induced by upper-chest warm-water immersion resulted in a significantly shorter time to exhaustion (TTE) than a condition involving elevated T_{sk} alone (with lower T_c) under mental-fatigue conditions. Interestingly, although mental fatigue, as measured using a visual analogue scale, increased in both conditions, its magnitude did not differ between trials, suggesting that the additional decrement in performance was driven mainly by T_c elevation rather than by greater cognitive fatigue per se.

During exercise in the heat, single cooling strategies, such as ice-slurry ingestion or a cooling vest, have consistently been shown to alleviate thermal strain, enhance perceptual comfort, and improve endurance performance by delaying the onset of heat-related fatigue (Bongers et al., 2017; van de Kerkhof et al., 2024). Furthermore, cooling interventions have been reported to support cognitive functioning, particularly in complex domains such as working memory and executive control (Saldaris et al., 2020). A recent review suggests that combining internal and external cooling methods, such as ice-slurry ingestion and a cooling vest, may produce a greater core-to-skin temperature gradient and provide additive or synergistic advantages by simultaneously targeting multiple body regions, thereby producing greater reductions in T_c and perceptual strain than single-method approaches (Bongers et al., 2020).

Given these findings, an important research gap remains: although internal and external cooling strategies are well established for mitigating thermal and perceptual strain during exercise in the heat, their effectiveness when athletes experience heat stress and mental fatigue concurrently has not been systematically investigated. In many endurance and team-sport settings, athletes must sustain prolonged cognitive engagement, including pacing, decision-making, and tactical awareness, while exposed to thermal stress, which may exacerbate performance decline. Under these dual-stressor conditions, cooling may be relevant not only for reducing thermal strain but also for maintaining functional capacity while cognitive and physical demands occur concurrently. However, whether cooling can modify cognitive and endurance responses when heat stress and mental fatigue are experienced simultaneously remains unclear. Effective thermal-management strategies are increasingly relevant because athletes may be required to perform under challenging environmental conditions, highlighting the need for practical approaches that reduce thermal strain while maintaining physical and cognitive function.

Therefore, the present study aimed to investigate the effects of a body cooling intervention before and during exercise on thermoregulatory and perceptual responses, as well as aerobic exercise capacity, under combined heat stress and mental fatigue. It was hypothesized that body cooling under combined heat stress and mental fatigue would attenuate thermal strain and perceived exertion, thereby prolonging subsequent time to exhaustion compared with heat exposure alone.

METHODS

Participants

Eight non-heat-acclimatized moderately trained male athletes were recruited for this study. However, one participant withdrew due to experience mild dizziness in the experimental trial. Therefore, seven non-heat-acclimatized moderately trained male athletes (age: 22 ± 1 years, height: 174.8 ± 8.3 cm, body mass [BM]: 72.25 ± 11.2 kg, maximal oxygen uptake [$\text{VO}_{2\text{max}}$]: 46.2 ± 4.6 mL/kg/min) participated in this study. Participants were categorized according to “tier 3” as moderately trained by a previous study (McKay et al., 2022). All the participants were non-smokers and normotensive, had no known autonomic dysfunction or cardiovascular disease, and were not taking any medications.

The study protocol was approved by the institutional ethics committee (Permission number: 23-1-64), and all participants provided written informed consent before participation. The study complied with the latest version of the Declaration of Helsinki and was conducted according to international standards.

Preliminary measurements

To determine the $\text{VO}_{2\text{max}}$, on their first visit to the laboratory, each participant performed a progressive exercise test by cycling ergometer (Powermax VIII, Combi, Japan) at room temperature (22°C and 50% relative humidity [RH]). Their height and BM were measured to the nearest 0.1 cm and 10 g, respectively (TBF-210, Tanita Co., Japan). The initial stage load was set at 60 W and was increased by 20 W/min until participants reached exhaustion to measure their $\text{VO}_{2\text{max}}$. Respiratory gases were measured every 30 s during the test using a pre-calibrated automatic gas analyser (AE-310s, Minato Medical Science, Japan). Heart rate (HR) was monitored continuously via telemetry using an HR monitor (RC3 GPS, Polar, Finland). The test was considered valid if two of the following three criteria were met: 1) oxygen consumption reached a plateau, 2) HR remained within 5% of the predicted maximum ($220 - \text{age}$), or 3) the respiratory exchange ratio was above 1.10 (Kalapotharakos et al., 2011).

Experimental protocols

The participants completed three trials in a randomized and partially counterbalanced order: thermoneutral trial (22°C , CON), hot trial (35°C , HOT), and hot trial with cooling intervention (35°C , COOL). Relative humidity was maintained at approximately 50%, and no external airflow was applied during the trials. All experimental trials were separated by at least 48 h to avoid an order effect and commenced at the same time to control for circadian variations in T_{c} . To avoid the influence of natural heat acclimatization, all trials were conducted during the winter season.

Throughout the study period, all participants were asked to maintain their normal lifestyle habits, including their physical activity and nutritional habits. During the 24-h period before the experimental trial, the participants were instructed to refrain from strenuous exercise and the consumption of alcohol, caffeine, and nutritional supplements. Each participant arrived at the laboratory after an overnight fast and refraining from consuming any type of beverage for 2 h.

Upon arrival at the laboratory, participants practiced the CT before the first experimental trial. After urine samples were collected, and BM was measured in the nude, the participants were dressed in shorts and athletic shoes for all trials. The intrinsic clothing insulation value for this ensemble was 0.08 clo (ASHRAE, 2005). The participants were fitted with measuring equipment and asked to perform CT for 45 min to induce mental fatigue while performing 50 $\text{VO}_{2\text{max}}$ cycling exercise (45-min CT with exercise) under each trial. Perceptual responses were collected before and after the 45-min CT with exercise.

After a 5-min rest, participants performed the cycling exercise at an intensity equivalent to 75% $\text{VO}_{2\text{max}}$ until reaching voluntary exhaustion (TTE). The participants were asked to maintain a pedal cadence of 60 rev/min throughout the exercise. Exhaustion was defined as being unable to maintain 60 rev/min for 5 s. Standardized instructions were provided before exercise, and no verbal encouragement was given during any trial to avoid influencing performance. After the exercise, the participants dried themselves with a towel and were weighed again to determine BM before urine sample collection (Figure 1). Participants were instructed to refrain from consuming any beverages from the onset of exercise until the final urine sample collection.

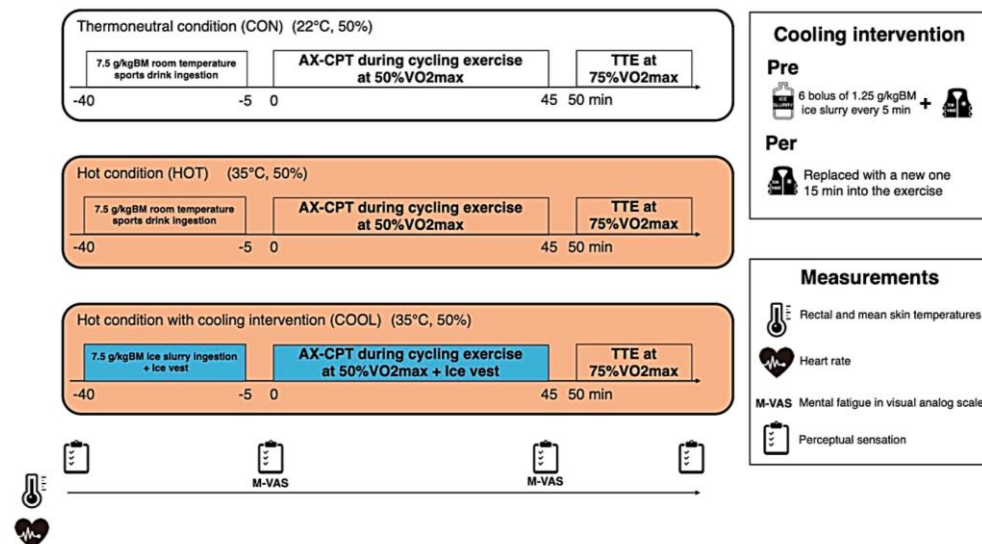


Figure 1. Schematic representation of the experimental protocol.

Cognitive task (CT)

Mental fatigue was induced using a computerized CT, specifically the AX-continuous performance task (AX-CPT), as previously delineated (Marcora et al., 2009). Previous studies have shown that AX-CPT results in a substantial decrease in the proportion of correct responses without any change in blood glucose levels, thereby suggesting that the mental fatigue induced by this test originates from cognitive function (Brownsberger et al., 2013; Marcora et al., 2009). Moreover, previous research has shown that even a 10-min AX-CPT can induce mental fatigue (Dallaway et al., 2022). It is notable that the longer the task, the greater the mental fatigue. Accordingly, we attempted to enhance the mental fatigue for participants by employing the 45-min AX-CPT (480 trials), when the combination of fixation, cue and probe times for each task was taken into consideration. Task parameters and visual depictions of the AX-CPT are presented in Figure 2.

Briefly, in the AX-CPT, participants made a target response (index finger button press) to the probe letter X only if it was preceded by the cue letter A. All cues and non-target probes require non-target responses

(middle finger button press). Target sequence trials are frequent and set up a prepotent tendency to make a target response when the probe letter X occurs. As a result, non-target sequence trials where any non-A cue (collectively called B-cues) is presented and followed by a probe letter X required the most cognitive control. The frequency of occurrence was 70% AX, 10% AY, 10% BX, and 10% BY, respectively.

CT performance was assessed using reaction time, lapses of attention, and accuracy by standard psychology software (Multi-PAS2, DKH, Japan). Attention lapses correspond to the number of trials with a reaction time longer than 2000 ms (Lopes et al., 2020). Response accuracy was the proportion of correct responses. Mental fatigue was characterized by an increase in reaction time, an increase in lapses of attention, and/or a decrease in accuracy (Lopes et al., 2020).

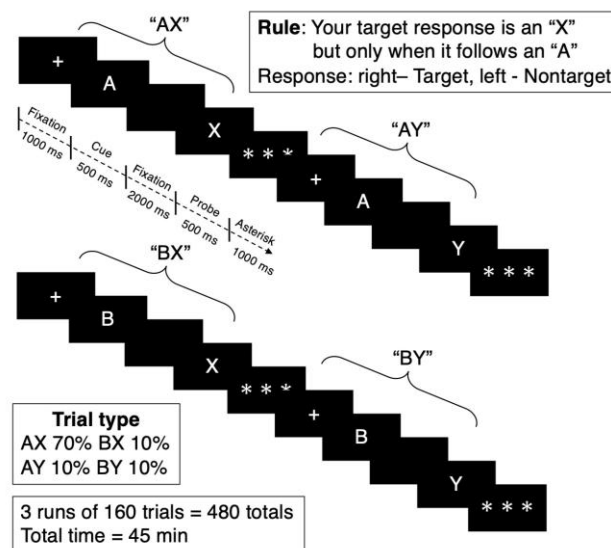


Figure 2. Schematic representation of the AX-CPT protocol.

Body cooling strategy

An ice vest (Cold Charge Vest, Mizuno, Japan: 1.9 kg), designed to cool the neck, upper body, back, and lateral torso, was used in this study. Gel-based ice packs (approximately -1°C) were pre-frozen and inserted into the ice vest. The ice vest was kept in a freezer until immediately before cooling and was replaced with a new one after being worn for 1 h. Participants wore the ice vest from 40 min before exercise throughout the 45-min CT with exercise. Participants ingested 1.25 g/kg BM of commercially available ice slurry (Pocari Sweat Ice Slurry, Otsuka Pharmaceutical, Japan) every 5 min for 30 min in the COOL trial. In the CON (22°C) and HOT (35°C) trials, participants ingested a room-temperature sports drink (Pocari Sweat, Otsuka Pharmaceutical, Japan) following the same ingestion schedule as the COOL trial.

Measurements

Throughout the three trials, rectal temperature (Tre) was obtained using a disposable rectal thermistor (ITP010-11, Nikkiso-Therm Co., Ltd., Japan) that was self-inserted approximately 150 mm into the rectum. The relative change in Tre was calculated using the value at -40 min (prior to the cooling intervention) as the baseline. HR was monitored continuously via telemetry using an HR monitor (H10, Polar, USA) affixed to the chest. Four temperatures (chest, upper arm, thigh, and calf) were also recorded via iButtons® (Thermocron SL type; KN Laboratory, Japan) affixed with hypoallergenic polyacrylate adhesive tape. The Tsk was calculated using the following formula from Ramanathan (1964):

$T_{sk} = 0.3 \times (\text{chest temperature}) + 0.3 \times (\text{upper arm temperature}) + 0.2 \times (\text{thigh temperature}) + 0.2 \times (\text{calf temperature})$.

The core-to-skin temperature gradient was calculated using the following formula:

Core-to-skin temperature gradient = $T_{re} - T_{sk}$.

Urine specific gravity (USG) was measured using a refractometer (PAL-09S, Atago, Japan) before and after exercise. Nude BM to the nearest 10 g was measured using a weighing scale (BC-316, Tanita, Japan) before and after the trial. Total sweating loss (TSL) was calculated using the following formula:

$TSL = BM \text{ before the trial} - BM \text{ after the trial} + \text{ingestion volume}$.

Dehydration was calculated using the following formula:

$\text{Dehydration} = (BM \text{ before cooling} - BM \text{ after all-out}) / BM \text{ before cooling} \times 100$.

Self-reported mental fatigue was measured using a visual analogue scale (M-VAS) before and after the 45-min task. The M-VAS has been shown to provide a valid and reliable method for assessing various psychological constructs (Marcora & Staiano, 2010). Participants were asked to indicate their perceived level of mental fatigue (from not at all fatigued to completely exhausted) by placing a mark on a 100-mm line (Van Cutsem, De Pauw, et al., 2017; Van Cutsem, Marcora, et al., 2017).

Subjective thermal sensation (TS; 9-point scale ranging from 1 = “very cold” to 9 = “very hot”) (International Organization for Standardization [ISO], 2019) and comfort (TC; 7-point scale ranging from 1 = “very uncomfortable” to 7 = “very comfortable”) (Gagge et al., 1967) were recorded before and after both the 45-min CT with exercise and TTE. The rating of perceived exertion (RPE; 15-point scale) (Borg, 1982) was recorded before and after the TTE.

Statistical analysis

Descriptive data are presented as mean $\pm$ standard deviations (SD). Statistical analyses were performed using IBM SPSS Statistics 28 (IBM Corp., Armonk, NY, USA). TTE was the primary performance outcome, with HOT vs. CON and COOL vs. HOT representing the primary comparisons. Other outcomes were considered secondary. Normality and homogeneity of variance were assessed using the Shapiro–Wilk and Levene’s tests, respectively. For repeated-measures analyses, sphericity was assessed using Mauchly’s test, with Greenhouse–Geisser correction applied when violated.

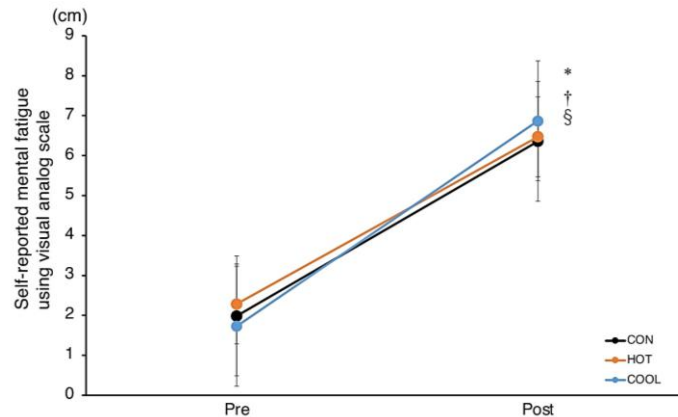
TTE was analysed using one-way repeated-measured ANOVA, and physiological variables (T_{re} and T_{sk}) using two-way repeated-measured ANOVA (trial $\times$ time). Significant ANOVA effects were followed by paired t-tests with adjustment for multiple comparisons. Perceptual sensations (TS, TC, and RPE) and CT (reaction time, lapses, accuracy) were analysed using Friedman’s test, followed by Wilcoxon signed-rank tests for pairwise comparisons when appropriate. Statistical significance was set at $p < .05$.

Given the small sample size, analyses were considered exploratory, with emphasis on effect magnitude and precision. For ANOVA, partial eta squared (η_p^2) was calculated and interpreted as small (.01), moderate (.06), or large (.14) (Cohen, 1988).

RESULTS

CT performance

There were no significant differences among trials in reaction time ($d = 0.03$ – 0.43), lapses of attention ($d = 0.00$ – 1.22), or accuracy ($d = 0.00$ – 1.12) at any assessment point (Table 1; $p > .05$). M-VAS scores increased after the 45-min CT with exercise in all trials ($p < .001$), although there were no significant differences among trials (Figure 3; $p > .05$, $d = 0.19$ – 0.57).



Note. CON = control condition; HOT = hot condition; COOL = cooling condition; VAS = visual analogue scale. Trial: $p = .910$, $\eta_p^2 = .02$; time: $p = .001$, $\eta_p^2 = .85$; trial $\times$ time: $p = .467$, $\eta_p^2 = .12$. * $p < .05$ compared with Pre within the CON condition. † $p < .05$ compared with Pre within the HOT condition. § $p < .05$ compared with Pre within the COOL condition.

Figure 3. The self-reported mental fatigue using visual analogue scale under the three experimental trials.

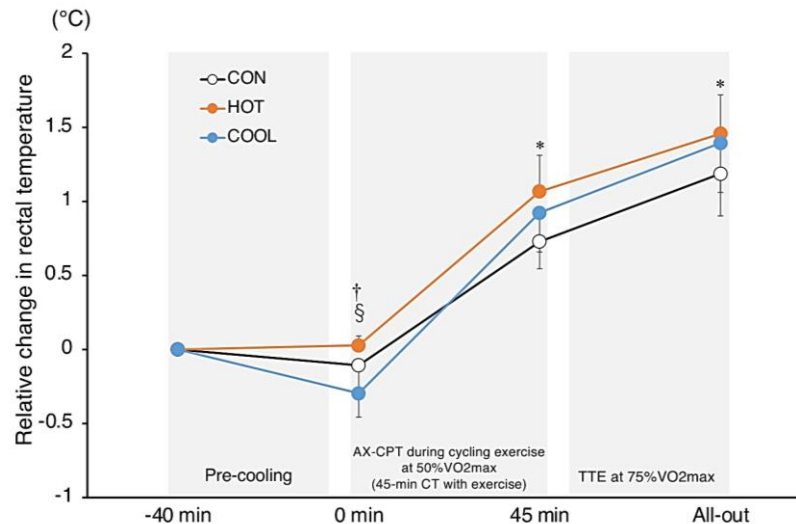
Table 1. Cognitive task performance across experimental trials.

	Time	CON	HOT	COOL	Effect size d	ANOVA, p values (η_p^2)		
		Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD		Trial	Time	Interaction
Reaction time (sec)	15 min	0.487 $\pm$ 0.141	0.423 $\pm$ 0.159	0.431 $\pm$ 0.158	0.05–0.43			
	30 min	0.412 $\pm$ 0.168	0.417 $\pm$ 0.152	0.393 $\pm$ 0.161	0.03–0.15	.06 (.38)	.001 (.82)	.10 (.27)
	45 min	0.410 $\pm$ 0.164	0.393 $\pm$ 0.146	0.383 $\pm$ 0.134	0.07–0.18			
Lapses of attention	15 min	16 $\pm$ 15	10 $\pm$ 6	3 $\pm$ 2	0.53–1.22			
	30 min	3 $\pm$ 6	7 $\pm$ 8	2 $\pm$ 2	0.22–0.86	.357 (.16)	.213 (.22)	.234 (.20)
	45 min	2 $\pm$ 2	3 $\pm$ 2	2 $\pm$ 1	0.00–0.50			
Accuracy (%)	15 min	85 $\pm$ 15	92 $\pm$ 15	97 $\pm$ 2	0.47–1.12			
	30 min	97 $\pm$ 4	91 $\pm$ 18	98 $\pm$ 2	0.32–0.55	.356 (.16)	.258 (.20)	.213 (.21)
	45 min	98 $\pm$ 2	97 $\pm$ 2	97 $\pm$ 2	0.00–0.50			

Note. Values are means $\pm$ SDs.

Thermoregulatory responses

The change in T_{re} at the onset of 45-min CT with exercise was lower in the COOL trial compared to the CON and HOT trials (Figure 4; $p < .05$). In the CON trial, the 45-min CT with exercise resulted in a lower change in T_{re} compared to the HOT trial ($p < .05$), and this difference in the change in T_{re} remained until the all-out. There were no significant differences in the change in T_{re} during exercise between the COOL trial and the CON ($p = .27$) or HOT ($p = 1.00$) trials. At rest, T_{sk} was similar between trials (Table 2). T_{sk} at the onset of 45-min CT with exercise was lower in the COOL trial compared to the HOT trial ($p < .05$). The core-to-skin temperature gradient at the onset of 45-min CT with exercise was wider in the COOL trial than that in the HOT trial (Table 2; $p < .05$). T_{sk} and core-to-skin temperature gradient in the CON trial were showed significant differences compared to the HOT or COOL trials from onset of 45-min CT with exercise to all-out ($p < .05$).



Note. Values are means $\pm$ SDs. CON = thermoneutral condition; HOT = hot condition; COOL = hot condition with cooling intervention. Main effects were observed for trial ($p = .003$, $\eta_p^2 = .63$) and time ($p < .001$, $\eta_p^2 = .96$), with a significant trial $\times$ time interaction ($p < .001$, $\eta_p^2 = .48$). * $p < .05$ for CON versus HOT. † $p < .05$ for CON versus COOL. § $p < .05$ for HOT versus COOL.

Figure 4. Change in rectal temperature relative to the -40-min baseline across the three experimental trials.

Table 2. Physiological and perceptual responses across experimental trials.

	Time	CON	HOT	COOL	ANOVA, p values (η_p^2)		
		Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD	Trial	Time	Interaction
Rectal temperature (°C)	-40 min	36.82 $\pm$ 0.28	36.79 $\pm$ 0.30	36.95 $\pm$ 0.30			
	0 min	36.71 $\pm$ 0.29	36.82 $\pm$ 0.29	36.65 $\pm$ 0.34			
	45 min	37.54 $\pm$ 0.16	37.86 $\pm$ 0.24*	37.87 $\pm$ 0.11*	.011 (.53)	.001 (.96)	.001 (.48)
	All-out	38.00 $\pm$ 0.21	38.25 $\pm$ 0.22*	38.35 $\pm$ 0.32*			
Skin temperature (°C)	-40 min	30.15 $\pm$ 1.08	30.70 $\pm$ 0.45	30.68 $\pm$ 0.68			
	0 min	31.18 $\pm$ 0.52	35.03 $\pm$ 0.39*	34.15 $\pm$ 0.40*†			
	45 min	33.96 $\pm$ 0.63	36.95 $\pm$ 0.21*	36.77 $\pm$ 0.23*	.001 (.94)	.001 (.99)	.001 (.71)
	All-out	33.74 $\pm$ 0.65	36.88 $\pm$ 0.43*	36.86 $\pm$ 0.54*			
Core-to-skin temperature gradient (°C)	-40 min	6.67 $\pm$ 1.26	6.10 $\pm$ 0.40	6.27 $\pm$ 0.63			
	0 min	4.83 $\pm$ 0.36	1.99 $\pm$ 0.49*	2.50 $\pm$ 0.28*†			
	45 min	3.59 $\pm$ 0.61	0.91 $\pm$ 0.31*	1.11 $\pm$ 0.16*	.001 (.93)	.001 (.98)	.001 (.68)
	All-out	4.26 $\pm$ 0.59	1.37 $\pm$ 0.43*	1.49 $\pm$ 0.28*			
Heart rate (bpm)	-40 min	70 $\pm$ 9	68 $\pm$ 6	70 $\pm$ 5			
	0 min	72 $\pm$ 5	74 $\pm$ 9	73 $\pm$ 5			
	45 min	140 $\pm$ 10	159 $\pm$ 10	156 $\pm$ 10*	.001 (.74)	.001 (.99)	.001 (.56)
	All-out	182 $\pm$ 13	191 $\pm$ 5	190 $\pm$ 5			
Thermal sensation	-40 min	3.3 $\pm$ 0.5	6.6 $\pm$ 0.5*	6.4 $\pm$ 0.5*			
	0 min	3.0 $\pm$ 0.6	6.6 $\pm$ 0.5*	4.3 $\pm$ 1.3†			
	45 min	6.1 $\pm$ 2.3	7.7 $\pm$ 0.5	6.6 $\pm$ 1.4	.001 (.84)	.001 (.82)	.001 (.44)
	All-out	7.1 $\pm$ 1.6	8.6 $\pm$ 0.5*	7.3 $\pm$ 2.4			
Thermal comfort	-40 min	5.4 $\pm$ 1.0	4.3 $\pm$ 1.0*	4.0 $\pm$ 1.2*			
	0 min	4.9 $\pm$ 1.1	3.9 $\pm$ 0.7	4.7 $\pm$ 0.8†			
	45 min	3.0 $\pm$ 0.8	2.9 $\pm$ 0.9	3.1 $\pm$ 0.7	.043 (.41)	.001 (.75)	.130 (.23)
	All-out	3.0 $\pm$ 1.0	2.1 $\pm$ 0.9*	2.1 $\pm$ 1.9			
Rating of perceived exertion	-40 min	6.7 $\pm$ 1.3	6.4 $\pm$ 1.1	6.6 $\pm$ 1.5			
	0 min	6.7 $\pm$ 1.3	6.4 $\pm$ 1.1	6.6 $\pm$ 1.5			
	45 min	13.9 $\pm$ 2.5	13.3 $\pm$ 2.4	13.5 $\pm$ 2.3	.752 (.05)	.001 (.97)	.898 (.06)
	All-out	19.7 $\pm$ 0.5	19.9 $\pm$ 0.4	19.9 $\pm$ 0.4			

Note. Values are means $\pm$ SDs. CON = thermoneutral condition; HOT = hot condition; COOL = hot condition with cooling intervention. * $p < .05$ for CON versus HOT or COOL. † $p < .05$ for HOT versus COOL.

HR

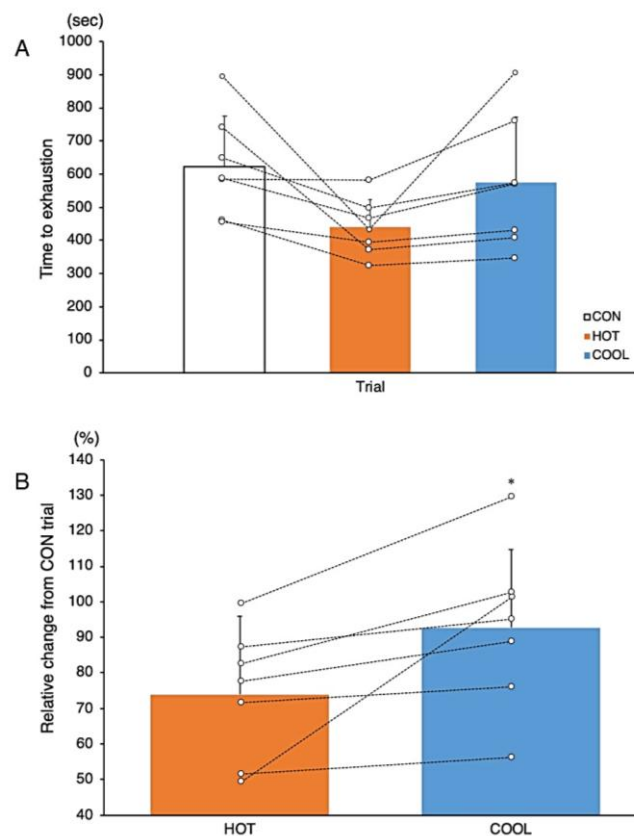
HR was higher in the HOT or COOL trials than in the CON trial after the 45-min CT with exercise, although there were no significant differences in HR at exhaustion between trials (Table 2; $p > .05$).

Body water composition

There were no significant differences in USG both before (CON: 1.021 ± 0.005 , HOT: 1.019 ± 0.008 , COOL: 1.020 ± 0.007 ; $p > .05$, $d = 0.16$ – 0.33) and after (CON: 1.014 ± 0.005 , HOT: 1.015 ± 0.004 , COOL: 1.019 ± 0.007 ; $p > .05$, $d = 0.22$ – 0.82) trials. The TSL was higher in the HOT trial (1284 ± 354 g) than in the CON (756 ± 237 g; $p = .002$, $d = 1.75$) or COOL (1072 ± 258 g; $p = .04$, $d = 0.68$) trial. Dehydration was higher in the HOT trial ($1.03 \pm 0.41\%$) than in the CON ($0.30 \pm 0.29\%$; $p = .001$, $d = 2.06$) or COOL ($0.75 \pm 0.40\%$; $p = .04$, $d = 0.69$) trial.

Perceptual scales

At rest, TS was lower and TC was higher in the CON trial compared to the HOT or COOL trials (Table 2; $p < .05$). At the onset of 45-min CT with exercise, TS was lower and TC was higher in the COOL trial compared to the HOT trial ($p < .05$). There were no significant differences in TS and TC after the 45-min CT with exercise, albeit TS was lower and TC was higher in the CON trial compared to the HOT at all-out. There were no significant differences in RPE between trials (Table 2; $p > .05$).



Note. Lines represent the raw data of individual participants ($n = 7$). No significant differences in absolute time to exhaustion (TTE) were observed among trials (Panel A; trial effect: $p = .08$). Panel B presents TTE relative to the CON trial under the HOT and COOL conditions. * $p = .03$. CON = thermoneutral condition; HOT = hot condition; COOL = hot condition with cooling intervention.

Figure 5. Time to exhaustion across the three experimental trials: (A) absolute time to exhaustion and (B) time to exhaustion relative to CON.

TTE

Mean time to exhaustion was 441 ± 83 s in HOT, 623 ± 153 s in CON, and 571 ± 198 s in COOL, with no significant differences among trials (Figure 5A; $p > .05$). The effect size for CON compared with HOT was $d = 0.91$, 90% CI [0.04, 1.78]; the effect sizes for CON compared with COOL and HOT compared with COOL were $d = 0.43$, 90% CI [-0.34, 1.78], and $d = -0.54$, 90% CI [-1.32, 0.25], respectively. Time to exhaustion relative to CON was $73.9 \pm 21.3\%$ in HOT and $92.7 \pm 22.9\%$ in COOL, with a statistically significant difference between HOT and COOL, $p = .03$, $d = 1.08$, 90% CI [0.15, 2.01] (Figure 5B).

DISCUSSION

The present study investigated the effects of body cooling on physiological, perceptual, and cognitive responses during exercise performed under combined heat stress and mental fatigue. The main findings were that the cooling intervention attenuated increases in T_{re} and T_{sk} and improved thermal comfort, while subjective mental fatigue and CT performance were not significantly affected. Although no statistically significant differences in absolute TTE were observed among trials, an exploratory analysis of relative changes in TTE showed a smaller reduction in the COOL trial than in the HOT trial. Thus, while the primary analysis did not demonstrate a significant effect of cooling on absolute endurance performance, the exploratory findings suggest that body cooling may have the potential to attenuate heat-related reductions in aerobic exercise capacity under combined thermal and mental load.

The thermoregulatory findings align with previous work showing that cooling interventions effectively reduce T_{c} and T_{sk} and delay the onset of hyperthermia during exercise in the heat (Siegel & Laursen, 2012; Stevens et al., 2017). Both internal cooling via ice slurry ingestion and external cooling using an ice vest contribute to maintaining a greater core-to-skin temperature gradient, which increases the thermal gradient between the body core and the skin, enhancing conductive heat transfer and thereby facilitating heat dissipation. Consistent with earlier studies (Cheuvront et al., 2010; Choo et al., 2019), the present data demonstrated that the cooling intervention can provide additive effects on thermal strain reduction. Indeed, TSL and dehydration in the COOL trial were lower than in the HOT trial, suggesting that the cooling intervention may have contributed to attenuating fluid loss during exercise. The improvement in perceptual comfort and reduction in thermal sensation further support the psychophysiological benefits of cooling. Collectively, the reduction in thermal strain and perceptual burden may have contributed to the partial preservation of endurance performance despite concurrent cognitive loading. However, because absolute TTE did not differ significantly among trials, this potential performance benefit should be interpreted cautiously.

Importantly, the absence of a cognitive benefit despite clear reductions in thermal strain suggests a dissociation between thermal relief and cognitive performance. The present cooling intervention reduced T_{re} and T_{sk} and improved thermal comfort, yet these changes were not accompanied by improvements in reaction time, lapses of attention, accuracy, or subjective mental fatigue. This pattern suggests that reducing peripheral and systemic thermal strain alone may not be sufficient to alter cognitive performance when hyperthermia remains moderate and the cognitive demands of the task are insufficient to reveal performance decrements. Previous studies have similarly reported limited effects of cooling on basic cognitive performance despite reductions in thermal strain or TS (Cowe et al., 2024; Cowe et al., 2025; Saldaris, Landers, Lay, et al., 2019). In contrast, beneficial effects of cooling on cognition have been reported under more severe hyperthermic conditions and during tasks requiring higher-order executive function or working memory (Tyler & Sunderland, 2011). Thus, the cognitive effects of cooling may depend on both the magnitude of thermal strain and the cognitive demands imposed by the task. Under the present experimental conditions, cooling appears to have provided thermal and perceptual relief without substantially altering cognitive

function. This dissociation suggests that any potential effects of cooling on exercise tolerance may operate primarily through physiological and perceptual mechanisms rather than through changes in cognitive performance.

The present study found that the AX-CPT increased self-reported mental fatigue, but this increase was not accompanied by detectable changes in reaction time, lapses of attention, or accuracy. Importantly, there were no significant differences in subjective mental fatigue between trials, suggesting that the degree of perceived mental fatigue was broadly comparable across experimental conditions. This finding is consistent with previous studies (Naito et al., 2024; Otani et al., 2017; Valenza et al., 2020), suggesting that mental fatigue induced by prolonged CT is not necessarily exacerbated by elevated ambient temperature or moderate hyperthermia. These findings suggest a dissociation between subjective mental fatigue and objective cognitive performance, with the present protocol primarily influencing perceived fatigue rather than measurable cognitive performance. Nevertheless, mental fatigue has been proposed to increase RPE and thereby impair endurance performance within a psychobiological framework (Marcora et al., 2009; Pageaux & Lepers, 2018; Van Cutsem, De Pauw, et al., 2017). In the present study, however, RPE did not differ significantly between trials. Contemporary models of endurance regulation propose that exercise performance is governed by the integration of multiple physiological, sensory, affective, and cognitive inputs that contribute to the regulation of exercise effort and tolerance (Pageaux et al., 2014; Tucker, 2009; Venhorst et al., 2018). Within this framework, thermal strain and mental fatigue may represent partially distinct sources of physiological and psychological load that can converge on the processes regulating exercise effort and tolerance. Schlader et al. (2011) demonstrated that thermal perception is closely associated with exercise capacity in the heat and suggested that changes in Tsk can influence the regulation of exercise intensity. Consistent with this concept, perceptual cooling strategies such as menthol application have been reported to reduce thermal discomfort and improve time to exhaustion and perceptual responses during exercise in the heat, despite limited effects on Tc (Barwood et al., 2020). In the present study, cooling reduced Tre and Tsk and improved thermal comfort, indicating that the thermal and peripheral perceptual components of the exercise burden were attenuated. However, these changes were not accompanied by a significant reduction in RPE or an improvement in absolute TTE. This dissociation suggests that improvements in thermal perception do not necessarily translate into proportional changes in the overall perception of effort or endurance capacity. Rather than indicating that peripheral thermal feedback alone determines exercise tolerance, the present findings are consistent with an integrative model in which thermal perception represents one of multiple inputs contributing to the regulation of exercise effort.

From a practical standpoint, the present findings suggest that body cooling may be a useful strategy for maintaining physiological stability and perceptual comfort during exercise in hot environments. However, although the present study incorporated a cognitively demanding task to induce mental fatigue, the cognitive assessment did not represent sport-specific cognitive or tactical performance. Therefore, while the findings may have relevance to exercise performed under combined thermal and cognitive demands, implications for pacing, tactical decision-making, or sport performance should be considered hypotheses rather than direct evidence. The practical implementation of cooling may also depend on the characteristics of the sport and the opportunities available for cooling. For example, in many team sports requiring rapid decision-making, such as soccer or rugby, wearing a cooling vest during competition may not be practical. In such contexts, pre-cooling before competition or cooling during scheduled breaks may be more feasible. More broadly, cooling strategies can be considered according to when they can be implemented, including pre-cooling before exercise, per-cooling during exercise or competition, and recovery-based cooling during breaks or between bouts. The choice among these approaches may depend on the demands of the sport and the opportunities available for cooling without interfering with performance. Importantly, the present study cannot

determine whether the observed physiological and perceptual effects translate into improved sport-specific performance or how long the effects of pre-cooling persist after its application. Future research should therefore examine the duration of cooling effects and whether different cooling strategies provide meaningful benefits for sport-specific cognitive, tactical, and performance outcomes across different sporting contexts.

Limitations

In previous studies (Marcora et al., 2009; Van Cutsem, De Pauw, et al., 2017), participants were provided with motivational incentives to ensure a consistently high level of effort throughout experimental trials. In contrast, the present study did not include any explicit motivational intervention in order to prioritize participant safety and minimize the risk of heat-related illness due to excessive exertion under heat stress. Notably, one participant experienced heat-related symptoms (mild dizziness) in the HOT trial and was subsequently excluded from analysis. While this approach ensured participant safety, the absence of a motivational control may have contributed to variability in exercise performance. Future research could consider implementing controlled motivational interventions or standardized encouragement protocols to balance participant safety with consistent effort, particularly in hot environments.

Second, the AX-CPT was performed concurrently with cycling, resulting in a combined cognitive-and-physical task. Therefore, the present design cannot fully separate the effects of mental fatigue from the physiological and cognitive effects of exercise itself, nor determine the independent effects of mental fatigue or its interaction with heat stress and cooling. Accordingly, the findings should be interpreted in the context of exercise performed concurrently with a cognitive task. Future studies incorporating cognitive-only, exercise-only, and combined conditions would help clarify the independent and interactive effects of cognitive load and physical exercise under heat stress.

Third, the cooling intervention combined an external cooling vest with internal ice-slurry ingestion. Therefore, the present study cannot determine the independent contribution of either cooling strategy or whether their effects were additive or interactive. Although the total fluid volume and sports drink composition were matched across conditions, with a portion of the sports drink provided as ice slurry in the COOL condition, the thermal and sensory characteristics of the ingested fluid necessarily differed between conditions. Thus, potential sensory and expectancy effects associated with the cooling intervention cannot be completely excluded, and participants could not be adequately blinded to the intervention. Accordingly, the present findings should be interpreted as the effects of a combined cooling package rather than the independent effect of either cooling method. Future studies using a four-condition design (control, ice slurry alone, cooling vest alone, and combined cooling), with matched fluid volume and nutritional composition and an appropriate thermal placebo where feasible, would help clarify the individual and combined effects of internal and external cooling.

The final sample size was $n = 7$ because one participant withdrew due to mild dizziness during the HOT trial. The small sample size may have limited the statistical power to detect differences, particularly for trial $\times$ time interactions and endurance performance. Therefore, the present findings should be interpreted as exploratory, and the nonsignificant results should not be taken as evidence for the absence of an effect. Future studies with larger sample sizes are warranted to confirm the present findings.

CONCLUSIONS

In conclusion, body cooling attenuated the increases in T_{re} and T_{sk} and improved thermal comfort during exercise under combined heat stress and mental fatigue but did not significantly affect subjective mental

fatigue or CT performance. Absolute TTE did not differ significantly among trials. Although an exploratory analysis of relative TTE indicated a significant difference between the HOT and COOL trials, this finding should be interpreted cautiously because the relative values were derived from the same absolute TTE data using CON as a common denominator. Therefore, the present findings do not provide sufficient evidence that body cooling improves or preserves aerobic exercise capacity under combined thermal and mental load. Further studies with larger samples are needed to clarify this potential effect.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows:

Conceptualisation: Takashi Naito. Methodology: Hirotsugu Morinaga, Mariko Nakamura. Formal analysis: Takashi Naito, Tatsuya Saito. Investigation: Yohei Takai, Nobuhiko Akazawa. Data curation: Takashi Naito, Tatsuya Saito, Hirotsugu Morinaga, Mariko Nakamura. Writing – original draft: Takashi Naito. Writing – review & editing: Takashi Naito, Tatsuya Saito, Hirotsugu Morinaga, Mariko Nakamura. Supervision: Yohei Takai, Nobuhiko Akazawa.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

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