

# Cold Drink Ingestion Improves Exercise Endurance Capacity in the Heat

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## ABSTRACT

LEE, J. K. W., S. M. SHIRREFFS, and R. J. MAUGHAN. Cold Drink Ingestion Improves Exercise Endurance Capacity in the Heat. *Med. Sci. Sports Exerc.*, Vol. 40, No. 9, pp. 1637–1644, 2008. **Purpose:** To investigate the effect of drink temperature on cycling capacity in the heat. **Methods:** On two separate trials, eight males cycled at  $66 \pm 2\%$   $\dot{V}O_{2\text{peak}}$  (mean  $\pm$  SD) to exhaustion in hot ( $35.0 \pm 0.2^\circ\text{C}$ ) and humid ( $60 \pm 1\%$ ) environments. Participants ingested three 300-mL aliquots of either a cold ( $4^\circ\text{C}$ ) or a warm ( $37^\circ\text{C}$ ) drink during 30 min of seated rest before exercise and 100 mL of the same drink every 10 min during exercise. Rectal and skin temperatures, heart rate, and sweat rate were recorded. Ratings of thermal sensation and perceived exertion were assessed. **Results:** Exercise time was longer ( $P < 0.001$ ) with the cold drink ( $63.8 \pm 4.3$  min) than with the warm drink ( $52.0 \pm 4.1$  min). Rectal temperature fell by  $0.5 \pm 0.1^\circ\text{C}$  ( $P < 0.001$ ) at the end of the resting period after ingestion of the cold drinks. There was no effect of drink temperature on mean skin temperature at rest ( $P = 0.870$ ), but mean skin temperature was lower from 20 min during exercise with ingestion of the cold drink than with the warm drink ( $P < 0.05$ ). Heart rate was lower before exercise and for the first 35 min of exercise with ingestion of the cold drink than with the warm drink ( $P < 0.05$ ). Drink temperature influenced sweat rate ( $1.22 \pm 0.34$  and  $1.40 \pm 0.41$   $\text{L}\cdot\text{h}^{-1}$  for the cold and the warm drink, respectively;  $P < 0.05$ ). Ratings of thermal sensation and perceived exertion ( $P < 0.01$ ) during exercise were lower when the cold drink was ingested. **Conclusion:** Compared with a drink at  $37^\circ\text{C}$ , the ingestion of a cold drink before and during exercise in the heat reduced physiological strain (reduced heat accumulation) during exercise, leading to an improved endurance capacity ( $23 \pm 6\%$ ). **Key Words:** DRINK TEMPERATURE, CORE TEMPERATURE, PREEXERCISE COOLING, THERMOREGULATION

The debilitating effects of heat stress on the ability to perform prolonged strenuous exercise are well established. During exercise in a hot environment, a substantial rise in body core temperature ( $T_c$ ) is often linked with the onset of fatigue (13,30). Fluid replacement before and during prolonged exercise in the heat has been shown to be effective in reducing the elevation of  $T_c$  (33) and in extending endurance capacity (26). These studies typically involved a trial with fluid replacement and another no-fluid trial serving as control, so the benefits were likely to be attributed to the hydration effects of fluids consumed. However, Dill et al. (11) investigated the effect of drinking large volumes (2.4 L) of cold ( $15^\circ\text{C}$ ) saline on physiological responses to 2 h of walking in desert heat ( $37$ – $47^\circ\text{C}$ ) and found that  $T_c$  was reduced relative to a trial where no drinks were allowed by approximately  $1^\circ\text{C}$ . There was no apparent difference in thermoregulatory responses, and this temperature differential is close to the value calculated from the heat deficit imposed by ingestion of the cold fluid.

Gonzalez-Alonso et al. (13) showed that lowering initial esophageal temperature by water immersion for 30 min before exercise and attenuating the rise in esophageal temperature by wearing a water-perfused jacket during exercise have separate beneficial effects in extending cycling time to exhaustion in the heat. Although precooling maneuvers such as exposure to cold air and water immersion can be effective in increasing tolerance to exercise in conditions of heat stress, they are impractical in the athletic, occupational, and military fields due to problems regarding time and equipment required to achieve sufficient body cooling to improve exercise performance (25).

There is some evidence in the literature that the temperature of ingested drinks will influence body temperature, with implications for the risk of heat illness and for performance. Gisolfi and Copping (12) showed that ingestion of cold water during running resulted in a smaller rise in rectal temperature ( $T_{re}$ ) during prolonged treadmill running in the heat than was observed when the same volume of water was ingested at body normal  $T_c$ . They also showed that ingestion of the fluid was more effective during exercise than that in the preexercise period. We have shown more recently that, when compared with the ingestion of 1.2 L of hot drinks ( $50^\circ\text{C}$ ), ingestion of the same volume of cold drinks ( $4^\circ\text{C}$ ) at rest resulted in a reduction in  $T_{re}$  of  $0.7^\circ\text{C}$  (23). Ingestion of 1.2 L of cold drinks during exercise at  $60\%$   $\dot{V}O_{2\text{peak}}$  was effective in reducing the rise of  $T_{re}$  by  $0.3^\circ\text{C}$  at the end of exercise

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relative to a trial where the same volume of hot drinks was consumed (23). No measure of performance was made in any of these studies (11,12,23), however. The effect of drinking cold water (4°C) on endurance capacity in the heat was recently reported by Mundel et al. (29) who found that the ingestion of cold drinks, compared with drinks at 19°C (control), extended mean cycling (65%  $\dot{V}O_{2peak}$ ) time to exhaustion in the heat (34°C) from 55 to 62 min. However, the results are difficult to interpret because an *ad libitum* drinking schedule was used, resulting in subjects consuming significantly more cold fluids (about 1.3 L·h<sup>-1</sup>) compared with drinks at 19°C (about 1.0 L·h<sup>-1</sup>). More recently, Lee and Shirreffs (21) have shown that ingestion of a single large (1 L) bolus of hot or cold fluid after 30 min of a 90-min exercise period influenced subsequent thermoregulatory and cardiovascular responses but did not influence performance in a brief bout of high-intensity cycling performed immediately after the 90-min steady-state exercise.

The present study aimed to investigate the effects of ingesting cold drinks on the thermoregulatory responses and endurance capacity during prolonged exercise in a hot environment. It was hypothesized that the ingestion of cold drinks, compared with the ingestion of drinks of similar volume at normal  $T_{re}$ , before and during exercise would reduce the physiological strain ( $T_{re}$ , heart rate), resulting in an extended exercise time to exhaustion in the heat.

## METHODS

**Subjects.** Eight non-heat-acclimatized males volunteered to participate in this study, which was approved by the University Ethical Advisory Committee. The physical characteristics (mean  $\pm$  SD and range) of the subjects are listed in Table 1. All subjects completed a health history screening questionnaire and were considered moderately active, participating in recreational sport activities. They gave their written informed consent to participate and retained the right to withdraw from the study at any time.

**Preliminary measurements.** All experiments were conducted when the mean  $\pm$  SD monthly outdoor temperature was  $4 \pm 2^\circ\text{C}$ , and thus, subjects were not acclimated to a warm environment. On the first visit, subjects attended the laboratory where their height was obtained to the nearest 0.5 cm using a stadiometer and body mass to the nearest 0.01 kg using a floor weighing scale (CFW-150K; Adam Equipment Co Ltd., Milton Keynes, UK). Skinfold thickness measurements were taken at four sites (biceps, triceps, subscapular, and suprailiac) in triplicate using skinfold callipers (Model HSK-BI; British

Indicators, West Sussex, UK), and the mean value was used to calculate total skinfolds. Body fat content was estimated as described in our previous paper (21).

Peak aerobic capacity ( $\dot{V}O_{2peak}$ ) was measured during a discontinuous incremental test on an electromagnetically braked cycle ergometer (Gould Corival 300, Groningen, The Netherlands). The test consisted of a discontinuous graded exercise beginning at 100 W for 5 min and with an increase of 25 or 50 W for every 3 min thereafter until volitional exhaustion. The increment in workload was based on performance in the previous stage assessed by the experimenter and on feedback from the subject. Stages were separated by approximately 5 min of rest. The test was considered valid if the following two criteria were met: 1) heart rate within 10% of the predicted maximum and 2) respiratory exchange ratio above 1.15 (2). Heart rate was measured using short-range telemetry (Polar Vantage; Polar Electro Oy, Kempele, Finland). On the basis of the  $\dot{V}O_{2work}$  rate relationship, the power output equivalent to 65%  $\dot{V}O_{2peak}$  was calculated for use during the subsequent trials. After a short rest, subjects completed a ride at 65%  $\dot{V}O_{2peak}$  to exhaustion in the heat. On the second visit, a minimum of 1 wk later, subjects were familiarized with the experimental instrumentation and the sensation of cycling at 65%  $\dot{V}O_{2peak}$  to exhaustion in the heat for the second time. During this session, each subject ingested 900 mL ( $3 \times 300$  mL aliquots) of flavored water at 20°C during the final 30 min of the preexercise rest period followed by 100 mL of the same drink every 10 min during exercise. Therefore, two rides at 65%  $\dot{V}O_{2peak}$  to exhaustion in the heat were completed by each subject before the first main trial to minimize potential learning effects.

**Experimental design.** Subjects completed two experimental trials, ingesting either the cold (4°C) or the warm (37°C) drinks in a randomized order using a Latin square design. The temperatures of the drinks were chosen at 4°C for the cold drink and 37°C for the warm drink because the former is similar to that of drinks typically kept in a household refrigerator and has been shown to be effective in decreasing  $T_{re}$  (23) and the latter served as a control to observe the physiological responses associated with ingestion of fluid without imposing a heat load or a heat deficit. Trials were carried out on the same day of the week, separated by 7 or 14 d. Subjects were asked to record their diet for 48 h before the first experimental trial and to repeat this same diet before subsequent trials. They were also requested to avoid strenuous activity and to refrain from alcohol for 24 h before each trial. The experimental trials commenced in the morning at the same time for each subject to control for circadian variations in  $T_{re}$ .

TABLE 1. Subject characteristics (mean  $\pm$  SD).

	Age (yr)	Mass (kg)	Height (m)	BSA (m <sup>2</sup> )	BF (%)	$\dot{V}O_2$ (L·min <sup>-1</sup> )	$\dot{V}O_2$ (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )
Mean	22	66.8	1.75	1.81	12.5	3.9	57.8
SD	4	7.3	0.08	0.14	2.4	0.6	5.6
Range	18–29	54.0–75.8	1.62–1.85	1.56–1.98	9.2–15.4	3.0–4.7	51.0–65.8

BSA and BF denote body surface area and body fat, respectively.

For each experimental trial, the subject reported to the laboratory after an overnight fast with the exception of ingesting 500 mL of water 90 min before arriving at the laboratory. On arrival, a urine sample was collected before the subject's nude body mass was recorded. A rectal probe (YSI UK Ltd., Hampshire, UK) was self-inserted 10 cm beyond the anal sphincter. The subject then put on underwear, shorts, socks, and shoes before skin thermistors (YSI UK Ltd.) were attached to the skin of the chest, triceps, thigh, and calf on the right-hand side of the body using Transpore medical tape (3M, Loughborough, UK). Finally, a heart rate transmitter was secured onto each subject. Weightings for skin temperature at four sites were applied as  $0.3 \times (\text{chest temperature} + \text{arm temperature}) + 0.2 \times (\text{thigh temperature} + \text{calf temperature})$  to compute mean skin temperature ( $T_{sk}$ ) using the equation of Ramanathan (35). Mean body temperature was estimated as  $0.65 T_{re} + 0.35 T_{sk}$  at rest and  $0.8 T_{re} + 0.2 T_{sk}$  during exercise (38). Total body heat content was calculated from the body mass, the mean body temperature, and the specific heat of body tissue as described previously (21).

After this, subjects sat on a chair for 45 min (a 15-min equilibrium period followed by a 30-min intervention period) in the testing laboratory, which was maintained at 27°C with relative humidity of 20%. Aliquots of flavored water (300 mL) were administered at the beginning and after 10 and 20 min of the intervention period when resting. Each 300-mL aliquot ( $8 \pm 1 \text{ mmol}\cdot\text{L}^{-1} \text{ Na}^+$ ,  $1.3 \pm 0.1 \text{ mmol}\cdot\text{L}^{-1} \text{ K}^+$ ,  $37 \pm 2 \text{ mOsm}\cdot\text{kg}^{-1}$ ) was made up of 60 mL of a commercially available sugar-free orange cordial (Sainsbury, UK) and 240 mL of tap water. During the resting period, subjects ingested each 300-mL aliquot within 2 min. Immediately after the resting period, subjects entered the environmental chamber (35°C with a relative humidity of 60%) to commence cycling at 65%  $\dot{V}O_{2peak}$  to exhaustion. There was a 2-min interval between entering the chamber and beginning of exercise. Subjects were asked to maintain a pedal cadence of 70 to 90 rpm throughout the exercise. Subjects ingested 100 mL of the same treatment drink every 10 min during exercise, with each 100-mL aliquot being consumed within 1 min. Drinks were placed in a thermostatically controlled water bath (SN6735; Laboratory Thermal Equipment, Greenfield, UK) before ingestion.

Environmental data were recorded every 15 min. Rectal and skin temperatures and heart rate were recorded every 5 min and at the point of exhaustion. Expired air was collected into Douglas bags over a 1-min period every 20 min during exercise. The air was subsequently analyzed via a Servomex 1440 carbon dioxide and oxygen analyzer (Servomex, Crowborough, UK), and calculations were made using the assumptions of the Haldane transformation (34). Ratings of thermal sensation (a 21-point scale ranging from unbearable cold [-10] to unbearable heat [+10] adapted from Parsons (32)) were recorded at 10-min intervals starting from 10 and 5 min during the resting

period and exercise, respectively. Ratings of perceived exertion (6) were made at 10-min intervals during exercise, starting at 5 min. These subjective ratings were also assessed at the cessation of exercise. Wet bulb globe temperature (WBGT) was calculated as  $(0.1 \times \text{dry bulb temperature}) + (0.7 \times \text{wet bulb temperature}) + (0.2 \times \text{globe temperature})$ . Globe temperature was assumed to be the same as dry bulb temperature because all experiments were conducted in an enclosed room so no significant radiant heat load was present. Wet bulb temperature was deduced using a psychometric table with known values of dry bulb temperature and relative humidity (Zeal Ltd., London, UK).

Exhaustion was defined as the point when the subject was unable to maintain cycling cadence above 60 rpm despite verbal encouragement by the experimenter. Time to exhaustion was recorded, but this information was withheld from the subject until all subjects had completed the study. At the end of the ride, all instrumentation was promptly removed, and a postexercise urine sample was obtained from the subject. For this urine sample, as for the pre-exercise sample, subjects were asked to empty their bladder as fully as possible and to collect the entire volume in a container provided. Body mass was measured within 10 min of the end of exercise after the removal of any unevaporated sweat with a towel. Sweat loss was estimated from the differences in body mass before and after each trial, corrected for fluid intake, urine production, respiratory water loss, and substrate exchange (27). Urine and drink osmolality were determined by freezing point depression (Osmomat 030; Gonotec, YSI, Farnborough, UK).

**Statistical analyses.** All statistical computations were performed using the Statistical Package for Social Sciences version 12.0. Except for the environmental parameters, all measurements were analyzed in two phases—at rest and during exercise. Student's paired *t*-test was used to evaluate differences in the measured physiological variables at a single time point, absolute change of  $T_{re}$  during rest, sweat rate, and exercise time to exhaustion between trials. A two-factor (i.e., drink temperature and time) repeated-measures ANOVA evaluated the changes in the remaining measured variables over time (the number of time points computed was in accordance with the reported sampling intervals described earlier). When a significant *F*-ratio was obtained, a Student's paired *t*-test, with a Bonferroni adjustment, isolated differences among treatment means. Figures are illustrated as means  $\pm$  SEM for clarity of presentation, and all other data are presented as means  $\pm$  SD. For all statistical analyses, the 0.05 level of significance was used.

## RESULTS

### Environmental conditions and hydration status.

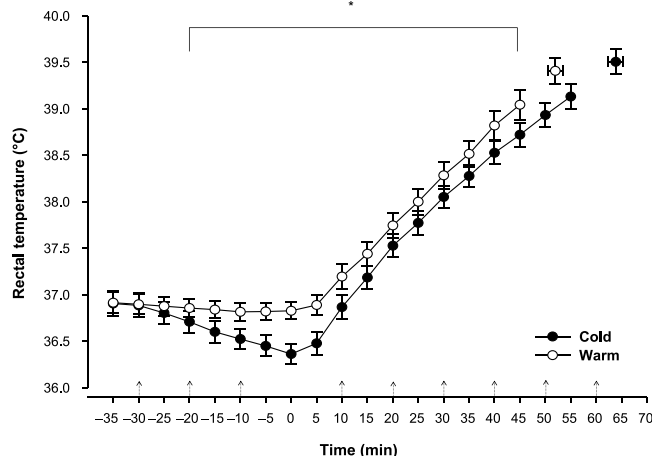
There were no differences in mean ambient temperature between trials during the resting ( $27.0 \pm 0.3^\circ\text{C}$ ;  $P = 0.625$ ) and the exercise ( $35.0 \pm 0.2^\circ\text{C}$ ;  $P = 0.760$ ) periods. Mean relative humidity was similar between trials during the resting ( $22 \pm 4\%$ ;  $P = 0.571$ ) and the exercise ( $60 \pm 1\%$ ;

$P = 0.340$ ) periods. All trials were conducted in a small enclosed laboratory with negligible wind velocity. WBGT was  $30^{\circ}\text{C}$  during exercise, and the thermal stress was classified beyond “high risk” ( $\text{WBGT} > 28^{\circ}\text{C}$  (1)). All subjects were considered euhydrated before each trial as demonstrated by preexercise urine osmolality ( $525 \pm 308 \text{ mOsm}\cdot\text{kg}^{-1}$ ). Similar hydration status before each trial was indicated by the consistency between trials of urine osmolality ( $P = 0.966$ ) and body mass ( $P = 0.641$ ).

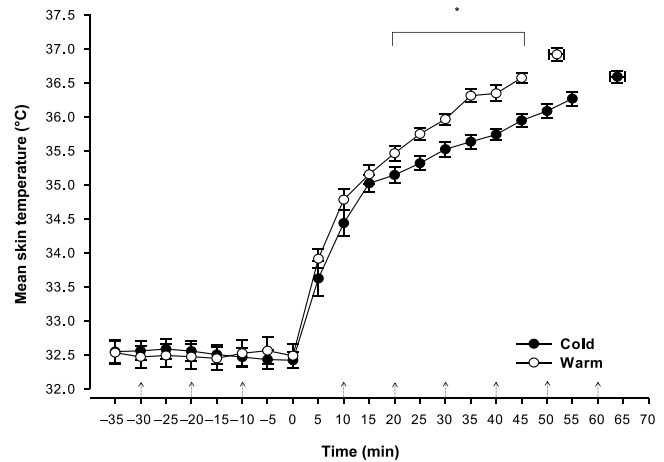
**Cycling times to exhaustion.** There was no trial order effect on cycling time to exhaustion ( $P = 0.752$ ). Subjects cycled longer ( $P < 0.001$ ) with the ingestion of the cold drink ( $63.8 \pm 4.3 \text{ min}$ ) than with the warm drink ( $52.0 \pm 4.1 \text{ min}$ ). When comparison was made against the warm drink, subjects cycled for  $23 \pm 6\%$  (range =  $16\text{--}34\%$ ) longer ( $11.9 \pm 2.8 \text{ min}$ , range =  $9.3\text{--}17.1 \text{ min}$ ;  $P < 0.001$ ) with the ingestion of cold drink.

**Oxygen uptake ( $\dot{V}\text{O}_2$ ).** The cycling exercise elicited a mean  $\dot{V}\text{O}_2$  of  $2.5 \pm 0.4 \text{ L}\cdot\text{min}^{-1}$  ( $P = 0.275$ ), which corresponds to  $66 \pm 2\%$  of the subjects'  $\dot{V}\text{O}_{2\text{peak}}$  in both trials and a mean respiratory exchange ratio of  $0.97 \pm 0.03$  ( $P = 0.613$ ) in both trials.

**Rectal temperature ( $T_{\text{re}}$ ).** During the resting period immediately before drinking (time point  $-30 \text{ min}$ ), there was no difference in  $T_{\text{re}}$  between trials ( $36.9 \pm 0.3^{\circ}\text{C}$ ;  $P = 0.858$ ; Fig. 1). At the end of the resting period, the ingestion of the cold drink caused  $T_{\text{re}}$  to fall by  $0.5 \pm 0.1^{\circ}\text{C}$  to  $36.4 \pm 0.3^{\circ}\text{C}$  ( $P < 0.001$ ).  $T_{\text{re}}$  remained relatively unchanged at  $36.8 \pm 0.3^{\circ}\text{C}$  after the ingestion of the warm drink ( $P = 0.098$ ). During exercise, mean  $T_{\text{re}}$  was lower when subjects ingested the cold drink ( $37.7 \pm 0.4^{\circ}\text{C}$ ) than when they ingested the warm drink ( $38.0 \pm 0.4^{\circ}\text{C}$ ;  $P < 0.001$ ).  $T_{\text{re}}$  increased continuously during exercise



**FIGURE 1— $T_{\text{re}}$  ( $^{\circ}\text{C}$ ) during the two experimental trials. Mean values and SEM are shown. Arrow denotes when drink was ingested. At the end of the resting period, ingestion of cold drinks decreased  $T_{\text{re}}$  ( $P < 0.001$ ), and  $T_{\text{re}}$  remained relatively unchanged with the ingestion of warm drinks ( $P = 0.098$ ). During exercise, mean  $T_{\text{re}}$  was significantly lower (\*) with ingestion of the cold drinks than with the warm drinks ( $P < 0.05$ ) from  $-20 \text{ min}$  until  $45 \text{ min}$  of exercise.**



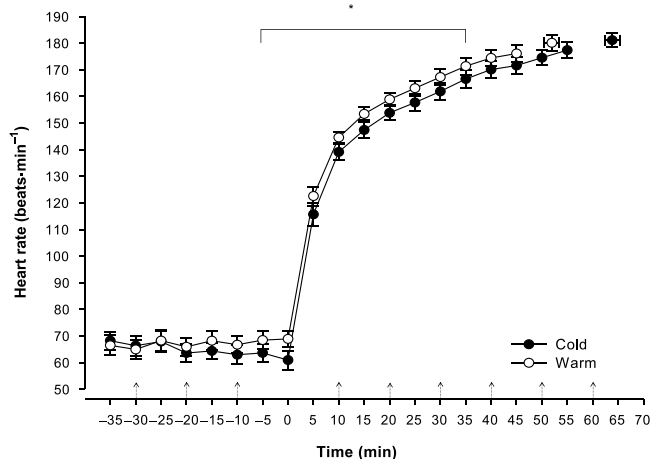
**FIGURE 2— $T_{\text{sk}}$  ( $^{\circ}\text{C}$ ) during the two experimental trials. Mean values and SEM are shown. Arrow denotes when drink was ingested. At rest, drink temperature had no effect on average  $T_{\text{sk}}$  ( $P = 0.870$ ). During exercise,  $T_{\text{sk}}$  was lower (\*) from  $20 \text{ min}$  onward with the ingestion of cold drinks than with warm drinks ( $P < 0.05$ ).**

( $P < 0.001$ ) and reached a similar value of  $39.5 \pm 0.4^{\circ}\text{C}$  at exhaustion in both trials ( $P = 0.104$ ). The rate of rise at each interval ( $5 \text{ min}$ ) was similar in both trials ( $0.25 \pm 0.05^{\circ}\text{C}\cdot 5 \text{ min}^{-1}$ ;  $P = 0.720$ ).

**Mean skin temperature ( $T_{\text{sk}}$ ).** There was no difference in  $T_{\text{sk}}$  between trials during the resting period before drinking (time point  $-30 \text{ min}$ ;  $32.5 \pm 0.5^{\circ}\text{C}$ ;  $P = 0.430$ ; Fig. 2). During the resting period, there was no effect on  $T_{\text{sk}}$  after ingesting either drink ( $32.5 \pm 0.5^{\circ}\text{C}$ ;  $P = 0.870$ ). During exercise, the ingestion of the cold drink was more effective in attenuating the rise of  $T_{\text{sk}}$  with the value being significantly lower ( $P < 0.01$ ) from  $20 \text{ min}$  onward when ingesting the cold drink than with the warm drink. There was no significant difference in  $T_{\text{sk}}$  at the point of exhaustion between the trials (cold drink =  $36.6 \pm 0.2^{\circ}\text{C}$ ; warm drink =  $36.9 \pm 0.3^{\circ}\text{C}$ ;  $P = 0.083$ ).

**Mean body temperature and total body heat content.** During the resting period, before drinking, there was no difference in mean body temperature ( $35.4 \pm 0.3^{\circ}\text{C}$ ;  $P = 0.611$ ) or total body heat content ( $8168 \pm 896 \text{ kJ}$ ;  $P = 0.800$ ) between trials. The mean body temperature was lower ( $P < 0.05$ ) for the last  $15 \text{ min}$  of rest and the first  $45 \text{ min}$  of exercise with the ingestion of the cold drink than with the ingestion of the warm drink. As compared with the ingestion of the warm drink, total body heat content was lower ( $P < 0.05$ ) after the ingestion of the cold drink from time point  $-10$  to  $45 \text{ min}$ . At exhaustion, there were no differences between trials in mean body temperature (cold drink =  $38.9 \pm 0.3^{\circ}\text{C}$ ; warm drink =  $38.9 \pm 0.4^{\circ}\text{C}$ ;  $P = 0.701$ ) and total body heat content (cold drink =  $8987 \pm 1024 \text{ kJ}$ ; warm drink =  $8993 \pm 1032 \text{ kJ}$ ;  $P = 0.812$ ).

**Heart rate.** There was no difference in heart rate between trials before fluid ingestion (time point  $-30 \text{ min}$ ) during the resting period ( $66 \pm 10 \text{ beats}\cdot\text{min}^{-1}$ ;  $P = 0.265$ ; Fig. 3). Heart rate was lower with the ingestion of the cold



**FIGURE 3**—Heart rate (beats·min<sup>-1</sup>) during the two experimental trials. Mean values and SEM are shown. *Arrow* denotes when drink was ingested. Heart rate was lower (\*) with the ingestion of cold drinks 5 min before the end of the resting period to 35 min of exercise compared with the ingestion of warm drinks ( $P < 0.05$ ).

drink 5 min before the end and at the end of the resting period compared with ingestion of the warm drink ( $P < 0.01$ ). At the end of the resting period, heart rate decreased to  $61 \pm 10$  beats·min<sup>-1</sup> ( $P < 0.01$ ) after ingesting the cold drink and increased to  $69 \pm 9$  beats·min<sup>-1</sup> ( $P < 0.05$ ) after the ingestion of the warm drink. Heart rate remained lower with the ingestion of the cold drink than with the warm drink until 35 min during exercise ( $P < 0.05$ ). There was no difference in heart rate between trials at exhaustion ( $181 \pm 8$  beats·min<sup>-1</sup>;  $P = 0.573$ ).

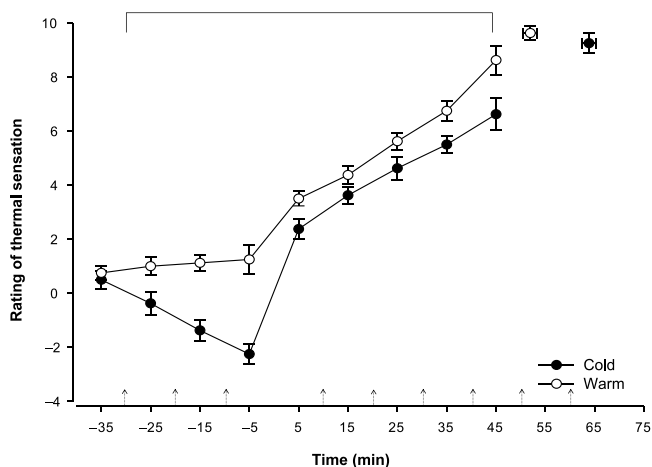
**Sweat rate and fluid balance.** Postexercise urine volume was similar ( $P = 0.226$ ) on both trials: volume was  $205 \pm 105$  mL on the cold drink trial and  $179 \pm 104$  mL on the warm drink trial. Estimated sweat rate during exercise

(27) was lower with the ingestion of the cold drink than with the warm drink amounting to  $1.22 \pm 0.34$  and  $1.40 \pm 0.41$  L·h<sup>-1</sup>, respectively ( $P < 0.05$ ). Net body mass loss during exercise was small and amounted to  $0.2 \pm 0.6\%$  with the cold drink and  $0.2 \pm 0.5\%$  with the warm drink.

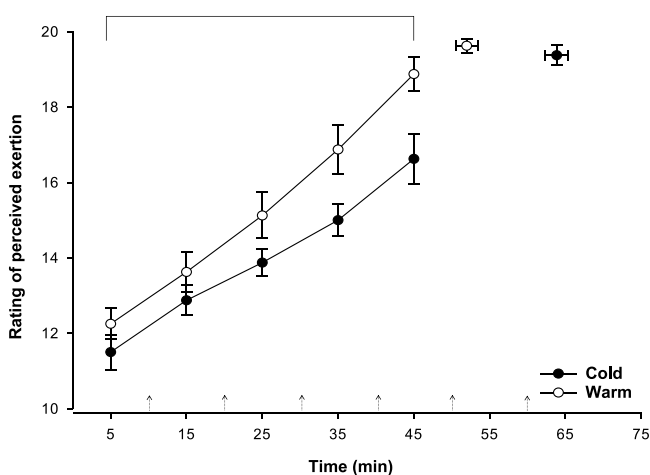
**Ratings of thermal sensation and perceived exertion.** Ratings of thermal sensation were similar between trials 5 min before drinking (time point -35 min) during the resting period ( $1 \pm 1$ ;  $P = 0.516$ ; Fig. 4). Ratings of thermal sensation were lowered to  $-2 \pm 1$  ( $P < 0.01$ ) after the ingestion of the cold drink at 5 min before the end of the resting period (time point -5 min), whereas ratings of thermal sensation remained unchanged after the ingestion of the warm drink ( $1 \pm 2$ ;  $P = 0.407$ ). This effect persisted throughout exercise, such that mean ratings of thermal sensation were significantly lower with the ingestion of the cold drink ( $5 \pm 1$ ) than with the warm drink ( $6 \pm 1$ ;  $P < 0.001$ ). Similarly, ratings of perceived exertion were lower ( $P < 0.01$ ) during exercise when subjects ingested the cold drink ( $14 \pm 1$ ) than when they ingested the warm drink ( $15 \pm 1$ ; Fig. 5). At exhaustion, ratings of thermal sensation ( $9 \pm 1$ ;  $P = 0.081$ ) and perceived exertion ( $20 \pm 1$ ;  $P = 0.170$ ) were similar between trials.

## DISCUSSION

The main findings from the present study were that ingestion of a cold drink (4°C) compared with a drink at a normal body temperature (warm; 37°C) before and during prolonged cycling exercise reduced the physiological strain ( $T_{re}$ , heart rate) and resulted in a longer cycling time to exhaustion (by 11.9 min; 23%) in a hot and humid environment. This suggests that ingesting cold drinks before and during exercise was effective in extending the



**FIGURE 4**—Ratings of thermal sensation during the two experimental trials. Mean values and SEM are shown. *Arrow* denotes when drink was ingested. Mean rating of thermal sensation was lower (\*) with the ingestion of cold drinks than with warm drinks ( $P < 0.001$ ).



**FIGURE 5**—Ratings of perceived exertion during the two experimental trials. Mean values and SEM are shown. *Arrow* denotes when drink was ingested. Mean rating of perceived exertion was lower (\*) during exercise with the ingestion of cold drinks than with warm drinks ( $P < 0.01$ ).

exercise time before subjects reached the high  $T_c$  that often limits endurance performance in the heat. These findings therefore add substance to those of Mundel et al. (29), who showed that mean cycling time to exhaustion at 65%  $\dot{V}O_{2peak}$  in the heat (34°C) was increased from 55 min when drinking water at a temperature of 19°C *ad libitum* during exercise to 62 min when drinking cold water (4°C). However, the results are difficult to interpret because the *ad libitum* drinking schedule resulted in subjects consuming significantly more cold fluids (about 1.3 L·h<sup>-1</sup>) compared with drinks at 19°C (about 1.0 L·h<sup>-1</sup>). The extended cycling time with ingestion of cold drinks could therefore be attributed, at least in part, to the greater volume of fluid consumed (10).

There is growing evidence that a high  $T_c$  *per se* ( $\geq 40^\circ\text{C}$ ) may contribute to the subjective decision to terminate endurance exercise in the heat (13,14). Gonzalez-Alonso et al. (13) demonstrated that subjects fatigue at the same esophageal temperature ( $\sim 40.1^\circ\text{C}$ ) at the end of cycling at 60%  $\dot{V}O_{2peak}$  in a hot environment (40°C) despite differences in initial esophageal temperature (35.9 vs 37.4°C) induced by immersing subjects in water of different temperatures for 30 min. Likewise, Hasegawa et al. (14) have reported similar  $T_{re}$  ( $\sim 39.1^\circ\text{C}$ ) between precooling (water immersion) and control treatments at the end of cycling in the heat (32°C) at 80%  $\dot{V}O_{2peak}$ . In the present study,  $T_{re}$  reached a similar mean value of 39.5°C (range = 39.0–40.0°C) at exhaustion after ingesting the cold (4°C) and warm drinks (37°C) with a rise of 0.25°C every 5 min on both trials. These observations are consistent with previous studies that have reported that the reduction in  $T_{re}$  produced by precooling largely determines the absolute  $T_{re}$  increase above baseline temperature without changing the rate of rise during exercise (13,40). In contrast, when cold drinks were consumed only during exercise and not before so that no preexercise cooling took place (21,22), we found that there was no meaningful difference in  $T_{re}$  between trials, regardless of whether the drink was consumed as one large bolus at a single time point (21) or in smaller volumes consumed at intervals during the exercise (22), similar to the current study. Taken together, these data suggest that the preexercise cooling induced by drinking before exercise had a significant influence on the outcome of the current study.

Precooling the human body by exposure to cold air (20) or partial immersion in cold water (41) has been shown to be beneficial in creating a greater heat sink in peripheral tissues for metabolically produced heat. Imms and Lighten (18) reported that drinking approximately 1 L of water at 7°C while resting in a semirecumbent position in a temperate environment ( $\sim 27^\circ\text{C}$ ) resulted in a maximum reduction of 0.61°C in aural temperature compared with the control subjects who consumed the same volume of drinks at 37°C. We have also previously shown that the ingestion of 1.2 L of cold drinks (4°C) at rest was effective in lowering  $T_{re}$  by 0.7°C over a 1-h period (23). In the present study, the

ingestion of 900 mL of cold drinks (4°C) during the resting period lowered  $T_{re}$  by 0.5°C over 30 min. It is possible that this may have been sufficient to improve performance without further drinking during exercise, but the current study cannot determine this for certain. Gisolfi and Copping (12) reported that consuming 1 L of warm or cold water during a treadmill run in the heat (34°C, 42% relative humidity) was more effective in preventing a marked rise in  $T_{re}$  than drinking the same volume of water 30 min before the run. They also reported that these different interventions did not significantly affect the sweat rate during exercise: this is in contrast to the observation in the present study that the lower  $T_c$  induced by ingestion of cold water had the effect of reducing the sweating rate in the present study.

The effect of ingesting cold drinks in lowering  $T_{re}$  during the resting period before exercise mimics previous precooling experiments that have shown to be effective in reducing  $T_c$  before completing an exercise capacity test (25). In the present study, the lower  $T_{re}$  observed during exercise is most likely due to the effect of ingestion of cold drinks during the preexercise resting period, and the preexercise fall in  $T_c$  may explain some of the apparent discrepancies between the current study and the other findings in the literature. Our previous experiments have shown that the ingestion of cold (4°C) or cool (10°C) drinks during exercise, in aliquots of even larger volume (1–1.6 L) than those given in the present study, had only a small effect ( $\sim 0.1$ – $0.3^\circ\text{C}$  (21,23)) or no effect on  $T_{re}$  (22) during low-intensity cycling (50–60%  $\dot{V}O_{2peak}$ ) when compared with the ingestion of the same volume of drinks at 50°C. Similarly to Lee and Shirreffs (21), Wimer et al. (42) reported that, compared with the ingestion of approximately 1350 mL of water at 38°C, the ingestion of drinks at 0.5°C during exercise reduced the rise in  $T_{re}$  by  $\sim 0.14^\circ\text{C}$  at the end of 2-h recumbent cycling at 51%  $\dot{V}O_{2peak}$ . However, in contrast to these observations, Dill et al. (11) found that drinking large volumes (2.4 L) of cold (15°C) saline during 2 h of low-intensity (6 km·h<sup>-1</sup>) walking in desert heat (37–47°C) reduced  $T_c$  relative to a trial where no drinks were allowed. The observed reduction was close to the calculated 1°C induced by the heat deficit, suggesting that the temperature differential was due to the imposed heat deficit rather than any effect on thermoregulatory function. The low intensity of exercise may have allowed the responses to be closer to those seen with drinking at rest. Finally, Gisolfi and Copping (12) found that the reduction in  $T_{re}$  that resulted from giving 200 mL of cold (10°C) water every 20 min during treadmill running in the heat was about twice as great (0.8°C) as was calculated from the heat deficit applied. They ascribed this discrepancy to the better maintenance of hydration status and therefore better cardiovascular function when the water was ingested.

A greater capacity for heat storage after precooling would allow a greater margin for metabolic heat production lessening the strain on the thermoregulatory system compared with the control conditions (5,20). In the present

study, the lower heart rate and  $T_{sk}$  when cold drink was ingested are consistent with previous studies that have reported the attenuation of heart rate and skin blood flow during exercise after precooling compared with control conditions (13,20).

By creating a heat deficit via precooling, probably the onset of heat dissipation mechanisms was delayed hence lengthening the time required to reach sweating threshold. The average sweating rate was lower by about  $0.18 \pm 0.18 \text{ L}\cdot\text{h}^{-1}$  with the ingestion of the cold drink than with the warm drink. This observation extends the findings from previous experiments that demonstrated a significantly delayed onset of sweating after precooling (41) and a decrease in sweat rate during exercise compared with the control treatment (14,20). It is important to recognize, however, that not all studies have shown a significant reduction in sweat rate after precooling (5,9). In any case, dehydration should not be a limiting factor to the cycling time to exhaustion in the present study, given that the amount of net body mass loss during exercise was minimal (cold drink =  $0.2 \pm 0.6\%$ ; warm drink =  $0.2 \pm 0.5\%$ ) and would be insufficient to induce strain or impair performance during prolonged exercise (7,9).

The evidence for a reduced physiological strain, that is, heart rate and  $T_{re}$ , in response to ingestion of the cold drink compared with the ingestion of the warm drink is supported by the decreased subjective strain reported by our subjects. After ingesting the cold drink, ratings of thermal sensation were lower at the end of the resting period and throughout the exercise. A heat dissipation response to an internal heat load with no elevation in hypothalamic temperature has been reported in sheep (36), indicating the possible presence of thermosensitive receptors located within the abdominal cavity. There is little or no information in humans, but there is evidence from other species for the presence of thermoreceptors in the mouth, esophagus, and abdominal viscera (16), the abdominal cavity (36), the spinal cord (17), and the muscle (4). This observation extends the findings of Wilson et al. (41) who showed that by delaying the autonomic heat dissipation mechanisms during exercise, thermal strain on the cardiovascular system was reduced leading to an improvement in thermal comfort. During exercise, the reduced physiological strain in response to ingestion of the cold drink seems to maintain the motivation to continue cycling as reflected by the lower ratings of perceived exertion after the ingestion of the cold drink compared with the warm drink.

It is sometimes difficult to put previous precooling maneuvers to practical use in athletic, occupational, or military settings due to the problems related to time and the equipment required to cool the body sufficiently to improve endurance capacity (25). Precooling by exogenous means such as exposure to cold air (20) or immersion in water (13) causes substantial decreases in skin temperature and induces a certain degree of thermal discomfort during the precooling period. Precooling by the ingestion of cold drinks, as per

the protocol used in this study, creates a heat sink that decreases  $T_{re}$  while minimizing the disadvantages of an increased metabolic heat production and perceived thermal discomfort. Taking into account that skin temperature is a major input to the overall ratings of thermal sensation and comfort (15), the relatively constant  $T_{sk}$  at rest after the ingestion of cold drinks in the present study may be linked to the fact that the subjects did not experience any thermal discomfort (from  $\sim 0$  = "neutral" to 2 = "some areas of body feel cold").

It might be argued that ingestion of the cold drink would lead to a faster rate of gastric emptying of the ingested fluid (8,39) and therefore faster absorption in the small intestine and a better maintenance of vascular volume, thus accounting for the lower heart rate on this trial. This effect seems to be related to the change in intragastric temperature produced (24,39). Not all studies have shown this effect, and a cold ( $12^\circ\text{C}$ ) drink resulted in a slowing of the initial rate of gastric emptying relative to a control drink at  $37^\circ\text{C}$  when a volume of 500 mL was ingested, but there was no difference between drinks when a smaller volume (200 mL) was administered (3). In contrast to these findings, however, McArthur and Feldman (28) showed that the rate of emptying of a 360-mL drink of coffee was not different when this was ingested at 4, 37, or  $58^\circ\text{C}$ . Lambert and Maughan (19) also showed that the rate of deuterium accumulation in the plasma, which is influenced by both gastric emptying and intestinal absorption, was similar after ingestion of deuterium-labeled drinks at a temperature of 4 or  $50^\circ\text{C}$ . Further support for the idea that the responses observed in this study were not mediated by differences in fluid availability comes from the absence of any difference between trials in urine volume after exercise. The absence of any difference in  $\dot{V}\text{O}_2$  or substrate use also suggests that metabolic factors, such as differential rate of use of muscle glycogen, did not account for the performance difference observed. In any case, there is ample evidence that muscle glycogen availability does not influence exercise of this intensity and duration when the ambient temperature is high (31).

## CONCLUSIONS

The present study has demonstrated that ingestion of cold fluids before and during exercise can attenuate the increase in  $T_{re}$  that occurs during exercise at 66%  $\dot{V}\text{O}_{2\text{peak}}$  in a hot uncompensable environment. Cold drinks are also effective in extending the cycling time to exhaustion in the heat. Unlike conventional precooling maneuvers, often criticized due to their impracticality, an improved endurance capacity with precooling via drinking cold fluids seems attractive, taking into account that hydration before and during an endurance activity, especially in hot environments, is widely advocated (37).

The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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