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The influence of serial feeding of drinks at different temperatures on thermoregulatory responses during cycling

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ABSTRACT

In this study, we examined thermoregulatory responses to ingestion of separate aliquots of drinks at different temperatures during low-intensity exercise in conditions of moderate heat stress. Eight men cycled at 50% ($s = 3$) of their peak oxygen uptake ($\dot{V}O_{2peak}$) for 90 min (dry bulb temperature: 25.3°C, $s = 0.5$; relative humidity: 60%, $s = 5$). Four 400-ml aliquots of flavoured water at 10°C (cold), 37°C (warm) or 50°C (hot) were ingested after 30, 45, 60, and 75 min of exercise. Immediately after the 90 min of exercise, participants cycled at 95% $\dot{V}O_{2peak}$ to exhaustion to assess exercise capacity. There were no differences between trials in rectal temperature at the end of the 90 min of exercise (cold: 38.11°C, $s = 0.30$; warm: 38.10°C, $s = 0.33$; hot: 38.21°C, $s = 0.30$; $P = 0.765$). Mean skin temperature between 30 and 90 min tended to be influenced by drink temperature (cold: 34.49°C, $s = 0.64$; warm: 34.53°C, $s = 0.69$; hot: 34.71°C, $s = 0.48$; $P = 0.091$). Mean heart rate from 30 to 90 min was higher in the hot trial (129 beats · min^{-1}, $s = 7$; $P < 0.05$) than on the cold (124 beats · min^{-1}, $s = 9$) and warm trials (126 beats · min^{-1}, $s = 8$). Ratings of thermal sensation were higher on the hot trial than on the cold trial at 35 and 50 min ($P < 0.05$). Exercise capacity was similar between trials ($P = 0.963$). The heat load and debt induced by periodic drinking resulted in similar body temperatures during low-intensity exercise in conditions of moderate heat stress due to appropriate thermoregulatory reflexes.

Keywords: *Heat load and debt, exercise, body heat content, thermoregulation*

Introduction

Information on the thermoregulatory responses to the ingestion of drinks at different temperatures is limited, although cold solutions are commonly advocated as the ideal temperature for fluid replenishment. The current Position Stand of the American College of Sports Medicine (ACSM, 2007) recommended that fluids cooler than ambient temperature (between 15 and 22°C) be ingested during prolonged exercise in warm environments. Nutritional advice for military operations in hot environments from the US Army Research Institute of Environmental Medicine (2001) is similar to the recommendation from ACSM: they considered plain, cool water at temperatures of 15–22°C as the best drink for maintaining hydration status. The Position Statement of the National Athletic Trainers' Association (2000) encouraged a lower fluid temperature of between 10 and 15°C, although the evidence for this was not clearly presented.

These recommendations are partly based on studies that have shown an enhanced palatability of cool water compared with warm water, encouraging individuals to consume larger amounts (Armstrong, Hubbard, Szlyk, Matthew, & Sils, 1985; Szlyk, Sils, Francesconi, Hubbard, & Armstrong, 1989). Some early research also suggested that the gastric emptying rate of cool drinks was greater than that of warmer drinks (Costill & Saltin, 1974). However, drink temperature has little effect on fluid availability based on findings from resting studies employing both gastric emptying (McArthur & Feldman, 1989) and deuterium tracer techniques (Lambert & Maughan, 1992).

A more important effect of ingesting cold drinks may be to add a heat deficit to the body, thus slowing the rate of rise of core temperature that would otherwise occur in thermally stressful conditions. Costill and colleagues (Costill, Kammer, & Fisher, 1970) provided their participants with 100 ml of fluid at 10°C every 5 min for the first 100 min of a

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2-h treadmill run in a cool environment. They found that rectal temperature was about 0.8°C less than on a similar run where no fluid was given, but it is not clear whether this was an effect of fluid provision or of the heat deficit imposed by the ingestion of a very large volume of cold fluid. A field study by Dill and co-workers (Dill, Yousef, & Nelson, 1973), in which men walked slowly in desert heat for 2 h, showed that ingestion of a large volume (2.4 litres) of saline solution at 15°C reduced body temperature by about 1°C compared with control trials in which no fluid was allowed. Once again, however, the absence of an appropriate control trial meant that there was no indication of whether this was due to the fluid itself or to the imposition of a heat deficit resulting from the large intake of cold fluids. At around the same time, Gisolfi and Copping (1974) compared responses to 90–150 min of treadmill running in the heat (34°C) with no fluid intake or with ingestion every 20 min of 200 ml of water at 10°C or at body core temperature. They estimated that the reduction in rectal temperature attributable to the hypothermic effect of ingesting the cold drink was equal to about half of the observed 0.8°C difference in temperature between this trial and the trial in which no drink was given. In none of these studies was there any measure of exercise performance. In a recent study, Mundel and colleagues (Mundel, King, Collacott, & Jones, 2006) reported that rectal temperature and heart rate tended to be lower when ingesting drinks at 4°C versus drinks at 19°C, with a greater volume of the cool drink being consumed. A longer endurance time was recorded on the trial where cool drinks were ingested, which could reflect the reduced thermal stress, although there may be other effects of the greater amount of fluid ingested.

Some previous studies have shown that the ingestion of a large bolus of fluid at temperatures very different from the body temperature produced transient changes in thermoregulatory responses (Lee & Shirreffs, 2007; Wimer, Lamb, Sherman, & Swanson, 1997) and influenced thermal sensation during exercise (Lee and Shirreffs, 2007). When drinks were administered in smaller portions (Lovell, Pout, & Ryder, 2004), no significant differences in thermoregulatory responses between trials were observed when drinks at 4 and 50°C were ingested during 90 min of running at 60% peak oxygen uptake ($\dot{V}O_{2peak}$). The extent of thermoregulatory adjustments is likely to be dependent on the thermal load administered, and the rate of recovery of intragastric temperature will depend on the temperature of the drink, the volume consumed, and the thermal capacity of the solution. It has been speculated that repeated ingestion of drinks may not allow the temperature within the stomach to recover sufficiently (Leiper, 2001). The aim of the present study was to examine the effects of the repeated ingestion of drinks at different temperatures, provided in separate aliquots of 400 ml, on the thermoregulatory responses during low-intensity exercise undertaken in conditions of moderate heat stress.

Methods

Participants

Eight non-heat-acclimatized males volunteered to participate in this study, which was approved by the university's ethics advisory committee. The physical characteristics of the participants are listed in Table I. All participants 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 average monthly outdoor temperature was 12°C ($s = 3$). On the first laboratory visit, participants' height was measured to the nearest 0.005 m using a stadiometer and body mass was measured to the nearest 0.01 kg using a precision balance (Marsdens, London, UK). Skinfold thickness measurements were made at four sites (biceps, triceps, subscapular, and suprailiac) in triplicate using skinfold callipers (British Indicators, Model HSK-BI, UK) and the mean value was used to calculate total skinfolds. Body density was calculated according to the estimation of Durnin and Womersley (1974) with percent fat estimated using the equation of Siri (1956).

Peak aerobic capacity ($\dot{V}O_{2peak}$) was measured during a discontinuous incremental test on an

Table I. Participant characteristics (mean ± *s*).

	Age (years)	Mass (kg)	Height (m)	BSA (m^2)	BF (%)	$\dot{V}O_{2peak}$ ($litres \cdot min^{-1}$)	$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)
Mean	27 ± 4	70.9 ± 7.9	1.74 ± 0.05	1.85 ± 0.12	13.1 ± 2.6	3.8 ± 0.6	53.8 ± 6.2
Range	23–35	55.6–80.0	1.68–1.82	1.64–1.99	10.3–17.2	2.4–4.5	42.3–64.3

Note: BSA and BF denote body surface area (Dubois & Dubois, 1916) and body fat (Siri, 1956) respectively.

electromagnetically braked cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands). The test consisted of discontinuous graded exercise beginning at 100 W for 5 min with an increase of 25 or 50 W every 3 min thereafter until volitional exhaustion. The increment in workload was based on performance in the previous stage assessed by the experimenter and feedback from the participant. 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 (based on 220 beats per minute minus age), and (2) respiratory exchange ratio above 1.15 (ACSM, 2000). Heart rate was measured using short-range telemetry (Polar Vantage, Polar Electro Oy, Kempele, Finland). Based on the $\dot{V}O_2$–work rate relationship, the power outputs equivalent to 50 and 95% $\dot{V}O_{2peak}$ were calculated for use during the subsequent trials. After a short rest, the participants completed a ride to exhaustion at 95% $\dot{V}O_{2peak}$. During this ride and for the remaining trials, participants cycled on a Monark cycle erogmeter (Monark 874E, Monark Exercise AB, Sweden).

A second preliminary session was used to familiarize the participants with the experimental protocol and with the sensation of exercising to exhaustion at 95% $\dot{V}O_{2peak}$ after cycling for 90 min at 50% $\dot{V}O_{2peak}$. Four aliquots of 400 ml of flavoured water at a temperature of 50°C were consumed at 30, 45, 60, and 75 min during exercise to assess the participant's suitability in terms of his ability to ingest each aliquot within 2 min. This second ride at 95% $\dot{V}O_{2peak}$ to exhaustion performed prior to the first experimental trial should have reduced any learning effects that would influence performance in the subsequent main trials. During all familiarization and experimental trials, participants exercised at a constant, individually pre-determined power output equivalent to 50% of their $\dot{V}O_{2peak}$ followed by a constant, individually pre-determined power output equivalent to 95% of their $\dot{V}O_{2peak}$.

Experimental design

Participants performed three experimental trials, in which they ingested a cold (10°C), warm (37°C) or hot (50°C) drink in randomized order using an incomplete Latin square design. Heat debt and load were induced by the ingestion of drinks at 10°C and 50°C respectively. Drinks at temperatures of 10°C for the cold drink and 50°C for the hot drink were chosen because the former is generally perceived as ''cold'' and palatable to consume and the latter has been shown to be tolerable during exercise (Lee & Shirreffs, 2007; Lovell *et al.*, 2004). The warm drink at 37°C served as a control to observe the thermoregulatory responses associated with ingestion of the test drink without imposing a change in body heat content. Trials were separated by either 7 days or 14 days. Participants 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 prior to each trial. The experimental trials commenced in the morning at the same time for each participant to control for circadian variations in core temperature.

For each experimental trial, the participant reported to the laboratory after an overnight fast except for ingesting 500 ml of water 90 min before arriving at the laboratory. Upon arrival, a urine sample was collected before the participant put on a surgical gown and had his body mass recorded. A rectal probe (YSI UK Ltd., Hampshire, UK) was inserted 10 cm beyond the anal sphincter. The participant then put on underwear, shorts, socks, and shoes before skin thermistors (TSD202B, BIOPAC Systems Inc., UK) were attached to the skin of the chest, triceps, thigh, and calf on the right-hand side of the body using porous adhesive tape (3M, Loughborough, UK). Finally, a Polar Vantage heart rate transmitter was secured around each participant's chest. Weightings for skin temperature at four sites were applied as $0.3 \cdot$(skin temperatures of chest + arm) $+ 0.2 \cdot$(skin temperatures of thigh + calf) to compute mean skin temperature using the equation of Ramanathan (1964). Mean body temperature was estimated as $0.8 \cdot$(rectal temperature) $+ 0.2 \cdot$(mean skin temperature) (Stolwijk & Hardy, 1966), and total body heat content as $m_b \cdot c_p \cdot$(mean body temperature), where m_b is body mass (kg) and c_p is specific heat of the body, which was taken to be 3.47 $kJ \cdot {}^{\circ}C^{-1} \cdot kg^{-1}$ (Webb, 1995). Measurements of dry and wet bulb temperatures were made using a whirling hygrometer (York, UK) and relative humidity was deduced from a psychrometric table with known values of dry and wet bulb temperatures.

Immediately after collection of the resting baseline measures, participants mounted the cycle ergometer for the start of the 90-min exercise at 50% $\dot{V}O_{2peak}$ in the same laboratory. This transition took less than 30 s. Participants were asked to maintain a pedal cadence of 60 $rev \cdot min^{-1}$ throughout exercise. The 1.6 litres of drink was divided into four equal aliquots and consumed at 30, 45, 60, and 75 min of exercise. Each 400-ml drink (11 $mmol \cdot l^{-1}$ Na^+, $s = 1$; 2.0 $mmol \cdot l^{-1}$ K^+, $s = 0.1$; 56 $mOsmol \cdot kg^{-1}$, $s = 2$) consisted of 320 ml of tap water and 80 ml of a commercially available sugar-free orange cordial (Sainsbury, UK). Participants consumed each aliquot within 2 min. Drinks were placed in a thermostatically controlled water bath before ingestion.

Environmental data and heart rates were recorded every 5 min. Rectal and skin temperature measurements were acquired using the AcqKnowledge software (Biopac Systems Inc., UK) and recorded at 5-min intervals with a data acquisition system (Biopac Systems Inc., UK). Expired air was collected over a 1-min period every 30 min. Ratings of perceived exertion (Borg, 1973), thermal sensation [a 21-point scale ranging from ''unbearable cold'' (−10) to ''unbearable heat'' (+10) adapted from Parsons, 2003], and stomach fullness (Wu, Nicholas, Williams, Took, & Hardy, 2003) were recorded at 15-min intervals and 5 min after the onset of each ingestion during exercise. Wet bulb globe temperature (WBGT) was calculated as $0.1 \cdot (\text{dry bulb temperature}) + 0.7 \cdot (\text{wet bulb temperature}) + 0.2 \cdot (\text{globe temperature})$ (ACSM, 1996).

After 90 min of exercise, participants completed the exercise capacity test at an intensity of 95% $\dot{V}O_{2peak}$ at a cadence between 57 and 63 $\text{rev} \cdot \text{min}^{-1}$. The number of flywheel revolutions during the exercise capacity test was determined by a flywheel counter. Exhaustion was defined as the point when the participant was no longer able to maintain cycling cadence above 57 $\text{rev} \cdot \text{min}^{-1}$. Participants were given verbal encouragement by the same experimenter during the test. Time to exhaustion and the number of flywheel revolutions for the exercise capacity test were recorded, but this information was withheld from the participant until all participants had completed the study.

At the end of the exercise capacity test, all instrumentation was promptly removed and a complete post-exercise urine sample was obtained from the participant. Body mass was measured within 5 min of the end of exercise following 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 and urine production.

Urine and drink analyses

Urine and drink osmolality were determined by freezing-point depression (Osmomat 030, Gonotec, YSI, Farnborough, UK). Sodium and potassium concentrations of the drinks were determined via flame photometry (Corning 410C, New Jersey, USA). Chloride concentration was obtained by coulometric titration (PCLM 3, Jenway, Dunmore, Essex, 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 analysed in two phases, before and after ingestion of the first aliquot. A one-factor (drink temperature) analysis of variance (ANOVA) was performed to evaluate differences in the measured thermoregulatory variables at several instants (i.e. the pre-exercise value at 0 min, baseline value at 30 min, absolute rise of rectal temperature from 30 to 90 min, and post-exercise value at 90 min), and also to compare sweat loss and exercise capacity between trials. A two-factor (i.e. drink temperature and time) repeated-measures ANOVA was used to evaluate changes in the remaining measured variables over time (the time points were the same as for the sampling intervals described above). When a significant *F*-ratio was obtained, a paired Student's *t*-test with a Bonferroni adjustment was used to identify differences among treatment means. Selected relationships between parameters were also examined by Pearson product–moment correlation analysis. For clarity of presentation, the data in the Figures are reported as means and standard errors (s_x); in the text and Table I, they are presented as means and standard deviations (s). For all statistical analyses, the 0.05 level of significance was used.

Results

Environmental conditions

There were no differences in ambient temperature (25.4°C, $s = 0.4$; $P = 0.242$), wet bulb temperature (19.8°C, $s = 0.8$; $P = 0.415$), globe temperature (25.3°C, $s = 0.6$; $P = 0.295$) or relative humidity (60%, $s = 5$; $P = 0.878$) between trials. All trials were conducted in a small enclosed laboratory with negligible wind velocity. Wet bulb globe temperature was 21°C and the thermal stress was classified as ''moderate'' (ACSM, 1996).

Oxygen uptake

The 90 min of cycling elicited a mean $\dot{V}O_2$ of 1.9 $\text{litres} \cdot \text{min}^{-1}$ ($s = 0.3$; $P = 0.979$) on all trials, which corresponds to 50% ($s = 3$) of the participants' $\dot{V}O_{2peak}$.

Hydration status

All participants were considered euhydrated before the start of trials, as demonstrated by pre-exercise urine osmolality (335 $\text{mOsmol} \cdot \text{kg}^{-1}$, $s = 286$). Similar hydration status before each trial was indicated by the consistency of pre-exercise urine osmolality ($P = 0.903$) and body mass (70.7 kg, $s = 8.0$; $P = 0.999$).

There were no statistical differences in any of the measured variables before drinking, so the remaining

hour of exercise was used to assess the effect of drink temperature on the thermoregulatory responses. The 30th minute of exercise therefore served as the exercise baseline.

Rectal temperature

Participants commenced each exercise period with a similar rectal temperature on all trials (cold: 37.08°C, $s = 0.10$; warm: 37.17°C, $s = 0.18$; hot: 37.12°C, $s = 0.07$; $P = 0.686$) (Figure 1). At 30 min of exercise, before drink administration, there were no differences in rectal temperature between trials (37.75°C, $s = 0.23$; $P = 0.641$). Relative to the 30-min value, the increase in rectal temperature at the end of the 90-min exercise was similar between trials (cold: 0.42°C, $s = 0.19$; warm: 0.30°C, $s = 0.20$; hot: 0.46°C, $s = 0.22$; $P = 0.342$). At the end of the 90-min ride, there were no differences between trials in rectal temperature (cold: 38.11°C, $s = 0.30$; warm: 38.10°C, $s = 0.33$; hot: 38.21°C, $s = 0.30$; $P = 0.765$).

Mean skin temperature

There were no differences between trials in the mean skin temperature at rest (32.64°C, $s = 0.35$; $P = 0.482$) or at 30 min of exercise before drinking (34.34°C, $s = 0.61$; $P = 0.642$) (Figure 2). The average mean skin temperature after the start of drinking, between 30 and 90 min of exercise, tended to be influenced by drink temperature (cold: 34.49°C, $s = 0.64$; warm: 34.53°C, $s = 0.69$; hot: 34.71°C, $s = 0.48$; $P = 0.09$).

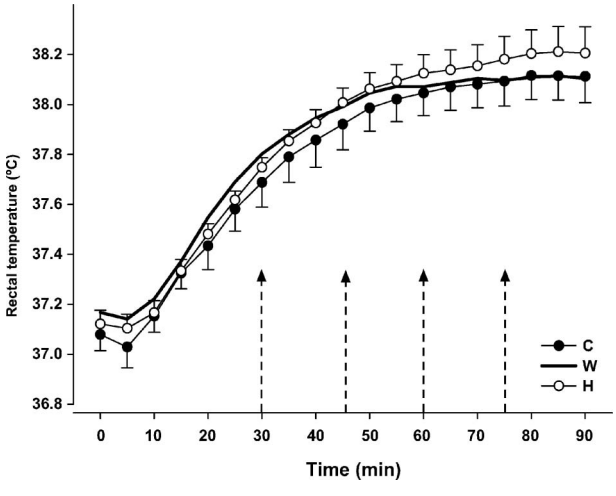

Figure 1. Rectal temperature (°C) during the three 90-min experimental trials (C = cold, W = warm, H = hot) at a constant, individually pre-determined power output equivalent to 50% $\dot{V}O_{2peak}$. Values are means and standard errors. Broken arrow denotes the ingestion of drink. There were no significant differences between trials.

Mean body temperature and total body heat content

The average mean body temperature from 30 to 90 min of exercise was 37.31°C ($s = 0.32$), 37.35°C ($s = 0.32$), and 37.42°C ($s = 0.23$) for the cold, warm, and hot trial respectively ($P = 0.749$). Table II illustrates the total body heat content and the change in total body heat content (ΔTBHC) with respect to the baseline measurement (30 min) during the three experimental trials. Total body heat content increased by 314 kJ ($s = 15$), 289 kJ ($s = 16$), and 314 kJ ($s = 17$) in the cold, warm, and hot trial respectively ($P = 0.714$).

Heart rate

There were no differences in heart rate between trials at rest (62 beats · min^{-1}, $s = 6$; $P = 0.273$) or at 30 min of exercise prior to fluid ingestion (122 beats · min^{-1}, $s = 7$; $P = 0.697$) (Figure 3). Mean heart rate was highest during the remaining 60 min of exercise in the hot trial (129 beats · min^{-1}, $s = 7$), intermediate in the warm trial (126 beats · min^{-1}, $s = 8$), and lowest in the cold trial (124 beats · min^{-1}, $s = 9$; $P < 0.05$). Taking 30 min as the baseline, a greater rise in heart rate was observed ($P < 0.05$) in the hot trial (10 beats · min^{-1}, $s = 4$) than in the cold trial (4 beats · min^{-1}, $s = 3$) at the end of the 90 min of exercise.

Urine and sweat losses

There was no effect of drink temperature on the volume of urine produced during exercise (cold: 246 ml, $s = 161$; warm: 277 ml, $s = 132$; hot: 213 ml, $s = 96$; $P = 0.629$). Mean sweat losses on the cold,

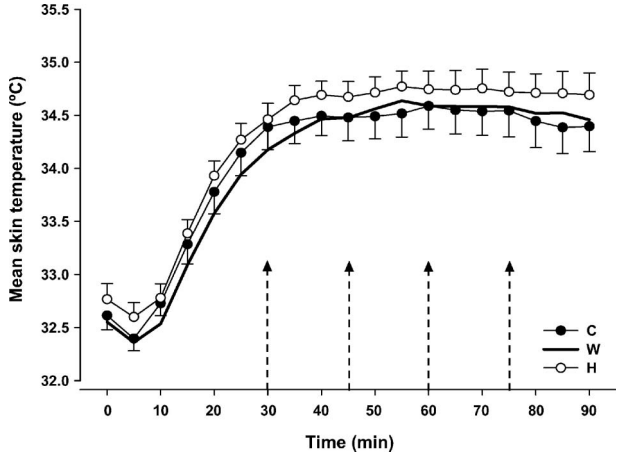

Figure 2. Mean skin temperature (°C) during the three 90-min experimental trials (C = cold, W = warm, H = hot) at a constant, individually pre-determined power output equivalent to 50% $\dot{V}O_{2peak}$. Values are means and standard errors. There were no significant differences between trials.

Table II. Total body heat content (TBHC, kJ) of the participants from 30 min onwards, change in body heat content relative to the 30-min value (ΔTBHC), and differences between the hot and cold trials (means values).

Trial	Time	30	45	60	75	90
Cold	TBHC	9156	9264	9351	9416	9470
	ΔTBHC relative to 30 min		*108*	*195*	*260*	*314*
Warm	TBHC	9134	9238	9314	9373	9423
	ΔTBHC relative to 30 min		*104*	*180*	*239*	*289*
Hot	TBHC	9129	9243	9323	9386	9443
	ΔTBHC relative to 30 min		*114*	*194*	*257*	*314*
	Differences between hot and cold trials		6	−1	−3	0
	P-value		0.338	0.887	0.742	0.988

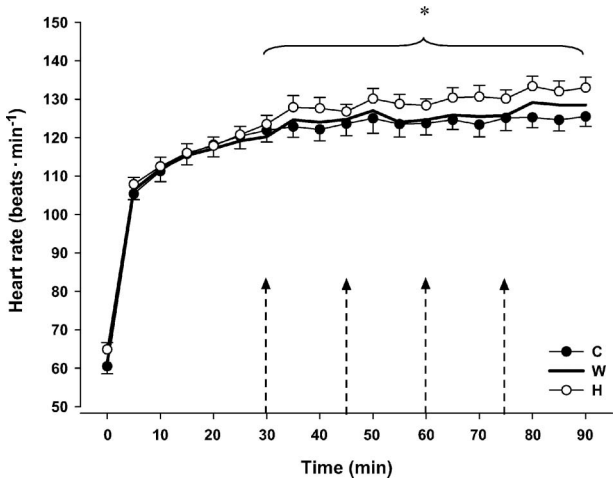

Figure 3. Heart rates (beats · min^{-1}) during the three 90-min experimental trials (C = cold, W = warm, H = hot) at a constant, individually pre-determined power output equivalent to 50% $\dot{V}O_{2peak}$. Values are means and standard errors. Mean heart rate was significantly higher between 30 and 90 min of exercise in the hot trial than in the warm or cold trials (*$P < 0.005$).

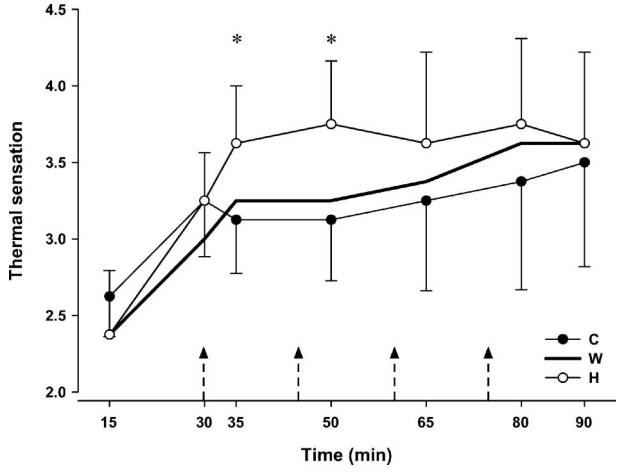

Figure 4. Ratings of thermal sensation during the three 90-min experimental trials (C = cold, W = warm, H = hot) where 0 = "neutral" and 4 = "most areas of the body feel hot". Values are means and standard errors. Ratings were higher at 35 and 50 min on the hot than on the cold trial (*$P < 0.05$).

warm, and hot trial were 1.09 litres ($s = 0.24$), 1.23 litres ($s = 0.31$), and 1.35 litres ($s = 0.38$) respectively ($P = 0.280$). When a pairwise comparison was made between the cold and hot trials, however, sweat loss was 0.26 litres ($s = 0.21$) higher in the hot trial ($P < 0.05$).

Subjective responses

Ratings of perceived exertion increased with time ($P < 0.01$) on all trials, with no differences between trials either before (11, $s = 2$; $P = 0.986$) or after the ingestion of drink from 30 to 90 min of exercise (12, $s = 2$; $P = 0.893$). Ratings of thermal sensation were higher on the hot than on the cold trial at 35 and 50 min ($P < 0.05$) (Figure 4). Subjective ratings of stomach fullness increased with time during exercise ($P < 0.05$), with no differences between trials from 30 to 90 min of exercise (10, $s = 2$; $P = 0.648$).

Exercise capacity

There were no differences in exercise capacity between trials (cold: 205 s, $s = 88$; warm: 213 s, $s = 74$; hot: 215 s, $s = 85$; $P = 0.963$).

Discussion

In this study, we examined the thermoregulatory responses to repeated ingestion of hot and cold drinks during prolonged low-intensity exercise in conditions of moderate heat stress. The consumption of 1.6 litres of water at 10°C should result in a fall in body temperature, whereas ingestion of the same volume of water at 50°C should result in an increase in body temperature. Based on the mean body mass of the participants of 70.9 kg ($s = 7.9$) and taking the heat capacity of human tissue to be 3.47 kJ · °C^{-1} · kg^{-1} (Aoyagi, McLellan, & Shephard, 1995), it would take about 246 kJ

($s = 27$) to elevate body temperature by 1°C. Assuming the heat capacity of the drinks to be the same as that of water ($4.18\ kJ \cdot °C^{-1} \cdot l^{-1}$), the energy required to warm or cool the drinks to body temperature, based on the equation of Nadel and Horvath (1969), is 181 and 87 kJ respectively. In the absence of any change in the other avenues of heat loss or gain, this should result in a difference of about 1.1°C ($s = 0.1$) in mean body temperature between the cold and hot trials. However, the observed mean body temperature and change in total body heat content after ingestion of drinks were similar in the cold and hot trials.

We have shown previously that the acute ingestion of one litre of cold (10°C) or hot (50°C) drinks in a single bolus during exercise at 53% $\dot{V}O_{2peak}$ resulted in appropriate thermoregulatory reflexes during exercise, but that there was also a sustained effect on body heat content (Lee & Shirreffs, 2007). In the present study, the total heat stimulus was greater because of the greater volume (1.6 litres) of fluid consumed, but this was applied over a longer period, as the drinks were consumed in four separate 400-ml aliquots. There was, however, no sustained effect on body heat content. It would appear that the human body is capable of eliciting appropriate thermoregulatory reflexes in response to an exogenous heat load or debt when drinks are ingested in separate aliquots of 400 ml during low-intensity exercise. The same may not apply during exercise of higher intensity when the rate of metabolic heat production is high (Dill *et al.*, 1973).

The repeated ingestion of 400 ml of liquids at different temperatures during exercise did not affect the rise in rectal temperature. In line with the present study, when drinks at 4 and 50°C were ingested (about 270 ml each) at six intervals during 90 min of running at 60% $\dot{V}O_{2peak}$, rectal temperature was found to be similar between the trials (Lovell *et al.*, 2004). Wimer *et al.* (1997) fed their participants approximately 750 ml of water after 62 min of exercise at the same intensity used in the present study followed by smaller portions of 300 ml at 80 and 100 min. They found that when compared with water at 38°C, the time-averaged increase in rectal temperature was about 0.1–0.2°C less for water at 0.5°C. In the study by Lovell *et al.* (2004), the lack of effect of temperature of ingested drinks on rectal temperature could be attributed at least in part to the small volume ingested at each of the six intervals, as this was based on the sweat loss incurred during a preceding no-fluid trial. In the study by Wimer *et al.* (1997), the attenuation of the exercise-induced increases in rectal temperature by drinking water at 0.5°C compared with water at 38°C was most apparent immediately after drinking the 750-ml large bolus at 62 min. If data from this initial measurement period are excluded from the statistical analyses by changing the baseline period from 62 min to 67.5–75 min, there was no significant effect of drink temperature on rectal temperature.

The evaporation of 1 g of sweat removes 2.5 kJ of heat from the body (Nadel & Horvath, 1969). The additional 0.26 litres ($s = 0.20$) of sweat in the hot trial relative to the cold trial, if it was all evaporated, would remove 650 kJ of heat, which is more than the 268 kJ difference in heat content between the two drinks. However, at the higher sweat rate a greater proportion of the sweat would be expected to drip from the body rather than being evaporated, which could explain the similar rectal temperature observed during exercise. Nadel and Horvath (1969) reported a slight decrease in skin temperature after ingesting ice cream at rest and Wimer *et al.* (1997) reported that the ingestion of water at 0.5°C during prolonged moderate-intensity recumbent cycling exercise elicited smaller increases in mean skin temperature than when water at 38°C was consumed. An immediate transient decrease in mean skin temperature has also been shown immediately after drinking a one-litre bolus of cold (10°C) drink (Lee & Shirreffs, 2007). Although there were no statistical differences in mean skin temperature between the drinks in the present study, the tendency ($P = 0.091$) for a higher mean skin temperature and an increase in heart rate on the hot trial is consistent with an increased skin blood flow. Heart rate was lower after the ingestion of cold drinks than hot drinks. These observations reinforce previous findings that ingesting cold water attenuates the increase in heart rate compared with ingesting the same amount of water at 37°C (Imms & Lighten, 1989; Lee & Shirreffs, 2007) or at 50°C (Lee & Shirreffs, 2007). However, other studies have found no differences in heart rate after ingesting drinks at temperatures of 4°C or 50°C (Lovell *et al.*, 2004) or at 0.5°C or 38°C (Wimer *et al.*, 1997).

Ratings of thermal sensation increase and decrease during heating and cooling of the skin independent of core temperature in the range from 37.9 to 38.5°C (Gibson, Redman, & Allan, 1980). This range is similar to the rectal temperatures reported in the present study and an increase in the ratings of thermal sensation followed the tendency for a higher mean skin temperature and increased heart rate in the hot trial.

There were no differences in exercise time to exhaustion between the three trials at the end of the 90-min ride. This is consistent with the similar ratings of perceived exertion across trials before the exercise capacity test. Furthermore, the ingestion of drinks at different temperatures did not alter rectal temperatures (~38.2°C) at the end of the 90-min ride at 50% $\dot{V}O_{2peak}$.

Based on the findings of the present study, we conclude that the human body is capable of maintaining body temperature by activating necessary thermoregulatory reflexes in response to the induced heat load or debt from ingestion of 400 ml of flavoured water at intervals during low-intensity endurance cycling under conditions of moderate heat stress.

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