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# Separate and combined effects of dehydration and thirst sensation on exercise performance in the heat

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**Using intravenous infusion, we separated the physiologic consequences of 3% body mass dehydration from the conscious awareness of fluid replacement on time trial (TT) performance in the heat. Eleven trained cyclists performed 90 min of steady-state (50% $\dot{V}O_{2peak}$) cycling followed by a self-paced 20-km TT in a hot–dry (35 °C, 10% relative humidity, wind speed 3.0 m/s) environment while euhydrated-not thirsty (EU-NT), euhydrated-thirsty (EU-T), dehydrated-not thirsty (DH-NT), or dehydrated-thirsty (DH-T). Thirst was manipulated by providing (NT) or withholding (T) *ad libitum* 35 °C water oral rinse. Distinct hydration states existed, with 0.4 ± 0.5% dehydration following the 20-km TT (EU) compared with 3.2 ± 0.6% in DH ($P < 0.001$). Greater perceived thirst existed in T (7 ± 2 on a 1–9 scale) than NT (4 ± 2, $P < 0.001$) after the TT. No significant differences in power output existed during the TT between hydration (EU 202.9 ± 36.5 W vs DH 207.0 ± 35.9 W, $P = 0.362$) and thirst conditions (NT 203.3 ± 35.6 W vs T 206.6 ± 36.8 W, $P = 0.548$), nor were there differences in completion time ($P = 0.832$) or pacing profile ($P = 0.690$). Within the range of up to 3% body mass loss, neither the physiologic effects from lowered hydration status nor the perception of thirst, separately or combined, affected sustained submaximal exercise performance in the heat for a healthy and fit population.**

One key ergogenic aid proposed for maintaining or enhancing endurance exercise performance in the heat has been maintaining adequate hydration (Sawka et al., 2007; Cheuvront & Kenefick, 2014), and fluid replacement may exert benefit through either allaying thirst or through decreasing physiologic strain. The physical act of drinking modifies an individual's perception of thirst (Figaro & Mack, 1997). Thirst plays an integral role in the body's homeostatic mechanism for fluid levels by acting as one of the key psychologic indicators to replenish lost fluids (McKinley, 2004), and can potentially influence the motivation for exercise. Specifically, thirst can be modulated by decreasing exercise intensity to prevent further fluid loss (Sawka & Noakes, 2007), such that impaired exercise performance in dehydrated subjects may be closely linked to the perception of thirst. In support, a meta-analysis by Goulet (2011) showed that time trial (TT) performance improved when subjects drank solely to attenuate thirst compared with drinking to completely replenish fluid loss or to not drinking at all. This meta-analysis further concluded that drinking according to thirst resulted in a mean power output increase of 5.2% compared with drinking below thirst sensation, and 2.4% compared with drinking above thirst sensation. Direct experimental evidence from the same laboratory indicated that half-marathon treadmill run speed and completion time in the heat were not different in trained runners drinking to thirst (3.1% body mass dehydration) or on an enforced schedule (1.3% dehydration) (Dion et al., 2013).

The proposal for maintaining near-euhydration has been developed based on studies with both acute dehydration and with prolonged hypohydration prior to exercise. In the former, a classic study by Montain and Coyle (1992) reported a progressive attenuation in heart rate (HR), core temperature, and stroke volume decrease with increasing (0, 20, 48, and 81% of sweat loss) oral fluid replacement during steady-state exercise in the heat. Hypohydration – a sustained state of lowered fluid balance – may increase resting HR and the rate of heat storage during exercise in both thermoneutral and hot environments (Cadarette et al., 1984; Buono & Wall, 2000; Cheuvront et al., 2005). Greenleaf and Castle (1971) observed rectal temperature ($T_{re}$) increases of 0.10 °C per 1% decrease in body mass during exercise at an ambient temperature of 24 °C, while Sawka et al. (1985) noted increases of 0.15°C per 1% hypohydration at 49°C. These factors, in addition to higher glycogen utilization and altered metabolic and central nervous system function (Distefano et al., 2013), interact with one another and may contribute to a degradation of aerobic exercise performance (Sawka et al., 2007).

Impaired performance with hypohydration is not a universal finding, however, with a meta-analysis by Goulet (2011) concluding that exercise-induced hypohydration of up to 4% body mass was not associated with a decrease in TT performance when compared with euhydrated conditions.

Study designs that manipulate hydration status through oral fluid ingestion are limited by altering both the physiologic hydration status and psychologic cues because of thirst perception and the lack of blinding to fluid balance. Recently, Wall et al. (2013) was the first study to provide a blinded state of hydration, via real or sham intravenous (IV) infusion during recovery from 3% exercise-heat dehydration. No differences in 25 km cycling TT performance were found with this blinded rehydration to 0, 2, or 3% body mass loss. However, neither oral fluid ingestion nor mouth rinse were provided during any of the hydration conditions, so it remains possible that the similar performance outcomes were driven by a consistent impairment from a strong psychologic state of thirst rather than a lack of effect from hydration status. Therefore, the purpose of this study was to investigate the separate and synergistic effects of hydration and thirst sensation on aerobic exercise performance. Hydration manipulation was done using a real or sham IV infusion to either maintain body mass within 0.5% of baseline (euhydrated), or allow the individual to enter a dehydrated state (≥ 2% body mass loss) over 90 min of submaximal and fixed-rate cycling, followed by a 20-km cycling TT. In addition, thirst sensation was manipulated by the presence or absence of a water mouth rinse. Our null hypothesis was that neither dehydration nor thirst, separately or in combination to 2–3% body mass loss, would impair voluntary exercise performance in hot environments.

## Materials and methods

### Participants

The experiment was approved by the Bioscience Research Ethics Board at Brock University (REB 12–139), and conformed to the latest revision of the Declaration of Helsinki. Eleven competitive male cyclists/triathletes were screened by a physician and provided written informed consent prior to participation. The mean ± (SD) age, height, body mass, body fat percentage, peak oxygen uptake ($\dot{V}O_{2peak}$), and peak power output were 33.6 ± 10.0 years, 180.3 ± 3.5 cm, 79.1 ± 10.1 kg, 12.4 ± 3.9%, 4.37 ± 0.67 L·min$^{-1}$, and 390 ± 35 W, respectively. Based on DePauw et al. (2013), participants would be classified as performance level 3 (scale of 1–5).

### Experimental design

Participants performed one familiarization and four randomized, double-blinded experimental trials in a hot–dry (35 °C, relative humidity 10%, wind speed 3.0 m/s) environmental chamber, with trials separated by 1 week to ensure proper recovery. Testing occurred June – October in Canada during the peak summer and early fall. No specific restrictions on training throughout the roughly five weeks of participation were placed on participants, but they were requested not to alter their training. Anecdotal feedback and informal review of training diaries suggested that training volume, patterns, and intensities were fairly stable. The experimental conditions were: euhydrated–not thirsty (EU-NT), euhydrated–thirsty (EU-T), dehydrated–not thirsty (DH-NT), and dehydrated–thirsty (DH-T). Euhydration (EU-NT; EU-T) was maintained by continuous IV infusion of isotonic saline (0.9% NaCl) with flow rate controlled by an electronic infusion pump set to match the rate of sweat loss measured during the familiarization trial. During dehydration trials (DH-NT; DH-T) participants were sham-instrumented with an identical IV configuration, and the technician performed similar movements and manipulations (e.g., checking the pump, massaging, and changing the saline bag) regardless of condition. In all conditions, saline bags were pre-warmed to 35 °C, with a small amount infused following IV line insertion to avoid conscious awareness of hydration condition. The IV pump was positioned behind the participant and the IV bag was covered with a black bag such that only the technician controlling the infusion pump was aware of the experimental condition, with both the participant and the lead researcher blinded to the hydration condition. The technician performed similar movements (e.g., checking IV line, monitoring infusion pump, massaging or changing saline bags) regardless of condition. Presence of thirst was manipulated by providing 35 °C water *ad libitum* for an oral rinse (EU-NT; DH-NT) or by denying water access (EU-T; DH-T).

The familiarization trial consisted of DH-T, but without any IV insertion or blood sampling, and this condition was chosen to measure the individual fluid loss and infusion requirements. EU and DH target ranges were within 0.5% and > 2% of baseline body mass, respectively.

### Experimental protocol

Participants ate a standardized breakfast (~ 592 kcal: 5 g fat, 66 g carbohydrate, 11 g protein) of 200 mL of juice and two commercial energy bars, consumed 2 h before testing. Upon arrival, participants voided their bladder and nude body mass was determined. Urine specific gravity was measured with a refractometer (PAL-10S, Atago, Tokyo, Japan). One catheter was then placed in an antecubital vein in each arm for blood sampling and IV saline infusion, respectively. Following instrumentation, participants entered the environmental chamber and sat quietly on the ergometer for 20 min before the first blood sample to normalize posture. Measurement time points for all variables are outlined in Fig. 1.

The protocol consisted of a 90 min steady-state (50% $\dot{V}O_{2\mathrm{peak}}$) exercise, followed by a 10-min rest and a self-paced 20-km TT. At the end of 90-min participants provided a urine sample and dressed weight before and after voiding. The self-paced 20-km TT was performed with no feedback other than distance completed every

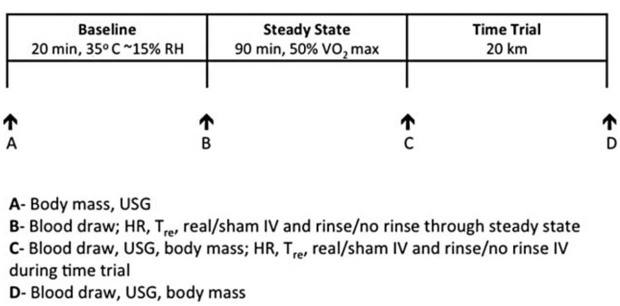


*Fig. 1.* Schematic of experimental protocol. HR, heart rate; IV, intravenous; RH, relative humidity; $T_{re}$, rectal temperature; USG, urine specific gravity.

1 km. After the TT, equipment was removed and participants towel dried and provided a final urine sample and nude body mass.

### Physiologic measurements

HR was measured beat-by-beat using a telemetric monitor (RS800CX, Polar Electro Oy, Finland). $T_{re}$ was measured with a flexible thermistor (Mon-A-Therm Core, Mallinkrodt Medical, St. Louis, Missouri, USA) inserted 15 cm beyond the anal sphincter, and $T_{re}$ was collected every second. Data for HR and $T_{re}$ are presented as 15-min averages during steady-state exercise and 2-km averages during the 20-km TT.

### Perceptual measurements

A set of four perceptual scales was displayed on the wall of the chamber directly in front of the participants. Participants were asked to provide numerical rankings from the scales based on how they currently felt. Rating of perceived exertion was reported on a 6–20 scale (Borg, 1982). Thermal comfort and thermal sensation were reported on 1–4 and 1–7 scales, respectively (Gagge et al., 1967). Thirst sensation was reported on a 1–9 scale (Kenefick et al., 2004).

### Blood processing and analyses

At each collection time point (Fig. 1), 10 mL of whole blood was drawn into ethylenediaminetetraacetic acid tubes and spun at 1500 g for 15 min (ZIPocrit, LW Scientific, Lawrenceville, Georgia, USA), with hematocrit then measured in triplicate. Plasma samples were separated into aliquots for measurement of plasma osmolality, stored in a freezer at −80 °C until use, then measured in triplicate by a vapor pressure osmometer (VAPRO5520, Westcor, Logan, Utah, USA).

### Statistic analyses

All data were confirmed for normal distribution prior to subsequent analysis. Between trial differences for all continuous variables measured at single time points were assessed using a one-way repeated measures analysis of variance (ANOVA). Data collected repeatedly over time were analyzed with a two-way (trial × time) repeated measures ANOVA and corrected for multiple comparisons with a Bonferroni correction. Power output during the TTs were analyzed over 2-km intervals, while $T_{re}$ and HR data were analyzed at $t = 0$ and 90 min of the 50% $\dot{V}O_{2peak}$, and 2-km intervals during the TT. Paired sample $t$-tests were performed to test significant main effects at specific time points. A Wilcoxon signed–rank test was used to compare all ordinal data (thirst, thermal comfort, thermal sensation, rating of perceived effort) at each time point (baseline and 90 min of 50% $\dot{V}O_{2peak}$, 5-km intervals during the TT). Data are presented as the mean ± SD. Statistical significance was set at $P < 0.05$. Cohen's $d$ effect sizes were calculated between trial pairings. Cohen's classification of effect size magnitude was used, whereby $d < 0.19$ = negligible effect; $d = 0.20$–$0.49$ = small effect; $d = 0.50$–$0.79$ = moderate effect and $d > 0.8$ = large effect (Cohen, 1988). All analyses were performed using the Statistical Package for the Social Sciences (SPSS) 20.0 statistic software package (SPSS, Inc., Chicago, Illinois, USA).

## Results

The IV protocol was successful in producing distinct hydration conditions (Table 1). During the two EU

Table 1. Body mass, urine-specific gravity, hematocrit, and plasma osmolality at baseline, after 90 min of 50% $\dot{V}O_{2peak}$ cycling, and after a 20-km time trial

| | EU-NT | | | EU-T | | | DH-NT | | | DH-T | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Base | End-90 | End-TT | Base | End-90 | End-TT | Base | End-90 | End-TT | Base | End-90 | End-TT |
| Mass (kg) | 80.19 ± 10.01 | 79.80 ± 9.98 | 79.92 ± 10.09 | 79.90 ± 9.71 | 79.53 ± 9.72 | 79.43 ± 9.81 | 80.11 ± 9.87 | 78.49 ± 9.82* | 77.59 ± 9.75* | 80.03 ± 9.62 | 78.38 ± 9.58* | 77.44 ± 9.29* |
| Urine specific gravity | 1.010 ± 0.007 | 1.013 ± 0.005 | 1.018 ± 0.002 | 1.011 ± 0.007 | 1.012 ± 0.006 | 1.016 ± 0.005 | 1.011 ± 0.008 | 1.015 ± 0.005 | 1.020 ± 0.005 | 1.009 ± 0.006 | 1.014 ± 0.005 | 1.021 ± 0.003 |
| Hematocrit (%) | 43.3 ± 2.1 | 42.3 ± 2.0 | 42.2 ± 2.4 | 43.5 ± 2.0 | 42.5 ± 1.9 | 42.5 ± 1.8 | 43.9 ± 1.9 | 44.7 ± 2.3* | 45.7 ± 2.1* | 44.0 ± 1.5 | 44.9 ± 1.9* | 46.1 ± 2.2* |
| Plasma osmolality ($mmol·kg^{-1}$) | 276.6 ± 12.4 | 283.5 ± 11.5 | 288.8 ± 12.6 | 283.9 ± 7.1 | 289.9 ± 7.0 | 295.4 ± 7.2 | 289.5 ± 8.4 | 295.2 ± 9.3 | 303.2 ± 9.9 | 280.7 ± 11.0 | 287.7 ± 10.1 | 295.1 ± 9.4 |

*DH significantly different from EU-NT and EU-T.

DH, dehydrated; EU, euhydrated; NT, not thirsty; T, thirsty.

conditions, body mass loss averaged 0.5 ± 0.4% after 90 min, significantly different from the two DH conditions of 2.1 ± 0.3% ($P < 0.001$), with no differences within EU or DH conditions. By the end of the 20 km TT, the disparity in hydration between EU and DH was heightened further, with final body mass losses of 3.2 ± 0.6% for DH compared with 0.4 ± 0.5% for EU ($P < 0.001$). This altered hydration is supported by significantly higher hematocrit in DH conditions both at 90 min (EU 42.4 ± 1.9%, DH 44.8 ± 2.1%, $P << 0.001$) and after the TT (EU 42.3 ± 2.1%, DH 45.9 ± 2.1%, $P << 0.001$). Both urine-specific gravity and plasma osmolality increased progressively over the 90 min of steady-state and 20-km TT cycling, but did not differ across the four experimental conditions. Importantly, participants were successfully blinded to the actual hydration conditions. In a debriefing questionnaire, participants correctly guessed their infusion condition in 27 out of the 44 trials (61%), but mean subject confidence was 54% (where 0 represented no confidence or no responses, and 100% represented absolute certainty).

Wide inter-individual variability existed across participants in their desire to satiate thirst via mouth rinsing, with some barely rinsing while others rinsed very frequently during NT trials. The number of mouth rinses ranged from 1 to 19 for the 90 min steady-state protocol and 2–20 for the 20-km TT, respectively. Nevertheless, the mouth rinse protocol was successful in eliciting distinct thirst conditions (Table 2), with NT and T thirst sensations of 3 ± 1 and 5 ± 2 respectively, at the end of the 90-min steady state ($P < 0.001$). Thirst sensation was greatly potentiated by the higher intensity of exercise during TTs, yet a significant difference in thirst was maintained across NT (4 ± 2) and T (7 ± 2, $P < 0.001$) after the 20 km TT. There were no differences in body mass changes or hydration indices across T and NT conditions.

No differences were evident in the HR and $T_{re}$ ($n = 9$ because of loss of data from slippage of rectal probes) responses over the 90-min hydration and thirst manipulations (Fig. 2). DH trials demonstrated both a higher HR and $T_{re}$ as the self-paced 20-km TT progressed compared with EU; however, no participant reached the ethically mandated termination thresholds despite the greater thermophysiologic strain. HR and $T_{re}$ did not differ between NT and T conditions during either the 90-min steady-state cycling or the TT, with no main or interaction effects observed (all $P > 0.05$). With the exception of thermal comfort, which was significantly more comfortable in the EU (3 ± 1) compared with the DH (4 ± 1) condition ($P = 0.039$) at the end of the 20-km TT, the blinded dehydration had minimal effects on subjective responses to the exercise (Table 2). Similarly, the presence or absence of mouth rinse did not influence rating of perceived exertion, thermal comfort, and thermal sensation between NT and T conditions (all $P > 0.05$) with the exception of thermal sensation, which

Table 2. Perceptual responses of thirst, thermal comfort, thermal sensation, and rating of perceived exertion at baseline, after 90 min of 50% $\dot{V}O_{2peak}$ cycling, and after a 20-km time trial

| | EU-NT | | | EU-T | | | DH-NT | | | DH-T | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Base | End-90 | End-TT | Base | End-90 | End-TT | Base | End-90 | End-TT | Base | End-90 | End-TT |
| Thirst | 1.6 ± 0.9 | 2.1 ± 1.1 | 4.1 ± 2.3 | 1.8 ± 1.0 | 4.5 ± 1.6‡ | 7.6 ± 1.4‡ | 1.7 ± 1.0 | 3.0 ± 1.4 | 4.5 ± 2.7 | 1.7 ± 0.8 | 4.7 ± 1.7‡ | 7.2 ± 2.0‡ |
| Thermal comfort | 1.3 ± 0.5 | 2.3 ± 0.6 | 3.3 ± 0.8 | 1.4 ± 0.7 | 2.2 ± 0.8 | 3.3 ± 0.8 | 1.4 ± 0.5 | 2.2 ± 0.8 | 3.5 ± 0.7* | 1.5 ± 0.7 | 2.2 ± 0.8 | 3.6 ± 0.7* |
| Thermal sensation | 4.8 ± 0.6 | 5.4 ± 1.0 | 6.0 ± 1.4 | 5.0 ± 0.6 | 5.5 ± 0.7 | 6.8 ± 0.4‡ | 4.9 ± 0.8 | 5.3 ± 0.8 | 6.5 ± 0.7 | 4.8 ± 0.8 | 5.5 ± 0.9 | 6.8 ± 0.4‡ |
| Rating of perceived exertion | \ | 11.2 ± 1.3 | 17.3 ± 1.8 | \ | 11.6 ± 1.6 | 18.0 ± 1.5 | \ | 11.6 ± 1.6 | 18.0 ± 1.5 | \ | 10.8 ± 1.5 | 18.2 ± 1.6 |

*DH significantly different from EU.

‡T significantly different from NT.

DH, dehydrated; EU, euhydrated; NT, not thirsty; T, thirsty.

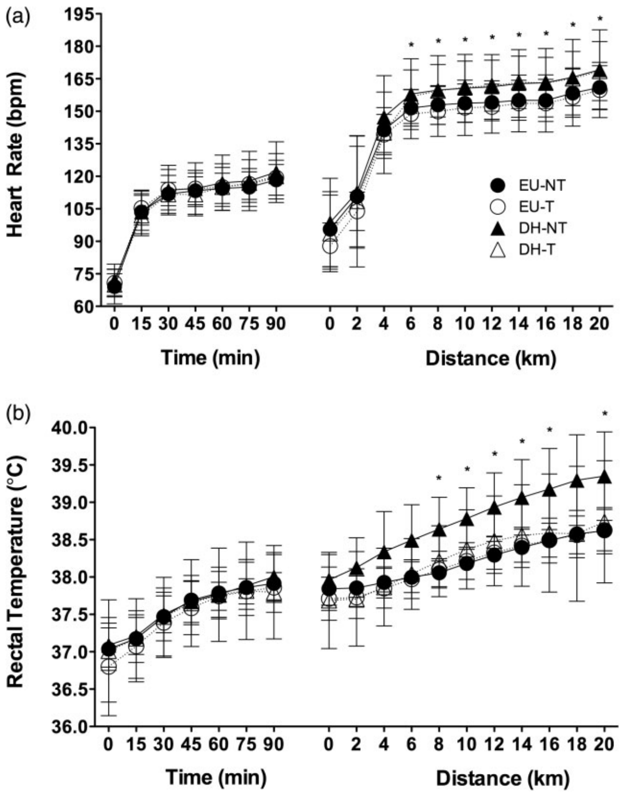


*Fig. 2.* (a) Heart rate ($n = 11$) and (b) rectal temperature ($n = 9$) responses to 90 min of 50% $\dot{V}O_{2\text{peak}}$ cycling and a 20-km time trial in hot (35 °C, 10% relative humidity) conditions. DH, dehydrated; EU, euhydrated; NT, not thirsty; T, thirsty. * DH significantly different from EU.

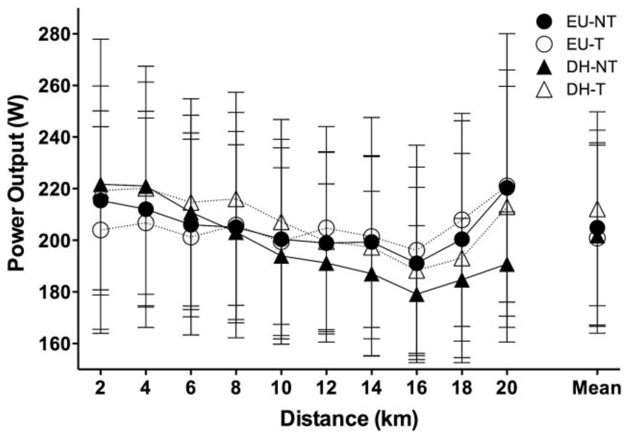


*Fig. 3.* Power output responses and completion time over a 20-km time trial in hot (35 °C, 10% relative humidity) conditions. DH, dehydrated; EU, euhydrated; NT, not thirsty; T, thirsty.

was significantly lower in the NT (6.3 ± 1.1) compared with the T (6.8 ± 0.4) condition ($P = 0.008$) at the end of the 20-km TT.

Power output at 50% $\dot{V}O_{2\text{peak}}$ was 116.4 ± 16.8 W, and by design was kept identical across all four experimental conditions. During the TT, no significant difference was evident in mean power output comparing across hydration (EU 202.9 ± 36.5 W vs DH 207.0 ± 35.9 W, $P = 0.362$) or thirst (NT 203.3 ± 35.6 W vs T 206.6 ± 36.8 W, $P = 0.548$) manipulations, nor were any observed across all four experimental conditions ($P = 0.890$, $d < 0.2$ or negligible for all comparisons, Fig. 3). A comparison of mean 20-km power output across a line of identity for hydration (EU vs DH) and thirst (NT vs T) is presented in Fig. 4. The lack of difference in power output is reflected in the TT completion times, with no significant difference across experimental conditions (EU-NT 2172 ± 155 s, EU-T 2180 ± 150 s, DH-NT 2185 ± 131 s, DH-T 2133 ± 142 s; $P = 0.832$). The largest difference across conditions was between DH-NT and DH-T at 52 s over ~ 2170 s (2.4% difference), and this resulted in a small effect size of 0.33.

## Discussion

The novel aspect of this study was employing either blinded sham or real IV infusion for hydration control, along with simultaneously manipulating thirst sensation by the withholding or the use of water mouth rinse. This design resulted in the separation and combination of both hydration and thirst sensation, and also permitted experimental conditions – dehydrated with no thirst sensation, euhydrated with thirst sensation – that had previously not been studied. The primary findings were that dehydration to ≥ 2% body mass loss elicited minimal thermal or cardiovascular effects during steady-state cycling; in contrast, thermophysiologic strain was elevated over the course of a 20-km self-paced cycling TT, yet remained below any level causing fatigue or exercise cessation. Furthermore, perceptual responses, mean power output, pacing strategy, and completion time over the 20-km TT was not influenced separately or synergistically by thirst sensations or hydration status, within a range down to slightly over 3% body mass loss at the end of the TT. These findings temper existing guidelines on fluid replacement during exercise in the heat (Sawka et al., 2007), which recommends maintaining hydration status within 2% of baseline for performance and health.

A critical aspect of truly understanding the effects of altered hydration on voluntary exercise performance is to isolate the physiologic consequences of hydration status from conscious awareness of the availability of fluid replacement. Public education over the past two decades has expounded that even mild dehydration is potentially dangerous, leading to an emphasis on maintaining fluid balance as close to euhydration as possible. This remains largely the case despite the modified 2007 American College of Sports Medicine Position Stand, which promotes 400–800 mL/h with the goal of maintaining hydration < 2% body mass loss (Sawka et al., 2007). The setting of such expectations makes it important to remove the conscious knowledge of hydration status as a confounding factor in pre-planning a mental performance template based on expected effects of an

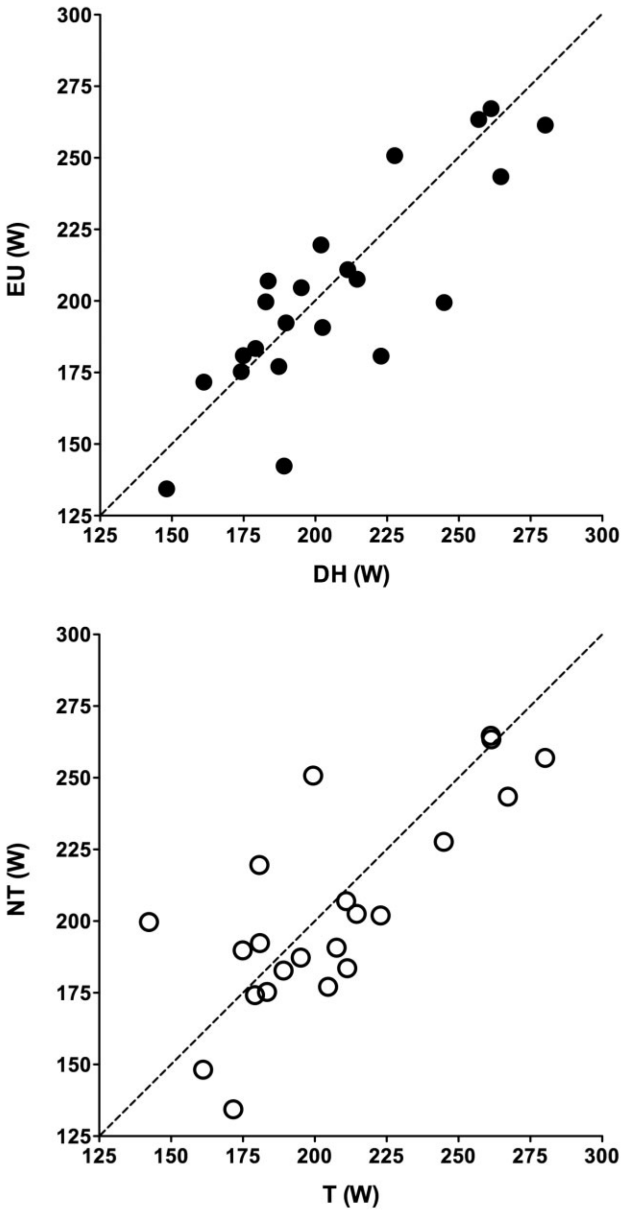


*Fig. 4.* Line of identity comparison of mean power output during a 20-km time trial in hot (35 °C, 10% relative humidity) conditions across hydration (DH, dehydration; EU, euhydration) and thirst (NT, not thirsty; T, thirsty) manipulations.

intervention (Eston, 2012). Paterson and Marino (2004) demonstrated that the expectation of exercise duration altered pacing strategy and ultimately TT performance, while Stone et al. (2012) improved cycling TT performance by deceptively racing participants against a faster-paced computer avatar. Similarly, unexpected changes in exercise duration during the course of a TT immediately altered RPE (Eston et al., 2012). The vast majority of hydration research has used oral ingestion for fluid manipulation (Montain & Coyle, 1992), such that both physiologic status and thirst perception are influenced at the same time and thus strongly intertwined. Our protocol took care to blind participants as much as possible from knowing whether it was a real or sham IV condition, with only ~ 60% correct estimates of hydration condition and ~ 50% confidence in their estimates.

To date, Wall et al. (2013) is the only study where participants performed self-paced or TT exercise while being blinded to their hydration status, with participants initially dehydrating to 3% body mass loss and then a hidden IV rehydrating them to 0%, 2%, and 3% body mass loss prior to a 25-km cycling TT. Our data support their finding that no differences were seen with hydration ranging from 0% to 3% body mass loss. In all conditions in Wall et al. (2013), oral fluid replacement was not provided, so it remains possible that the lack of differences across hydration conditions was due to a similar psychologic impairment from a strong thirst sensation. Rather than emphasizing drinking to control or maintain hydration status, an alternate proposal is that satiation of thirst sensation should be the goal of fluid replacement. Dion et al. (2013) tested treadmill half-marathon performance in the heat with a set rehydration regime to maintain < 2% body mass loss or else drinking to satisfy thirst (3.1% body mass loss), and reported no difference in performance time or pacing strategy. Our study thus extends the findings of Wall et al. (2013) and Dion et al. (2013) by exploring the separate and combined effects of thirst sensation with hydration as a driver for exercise. The present data suggest that, despite strong thirst sensations imposed by the lack of mouth rinse, the impact of such thirst sensation on central exercise drive may be overestimated. However, our protocol of mouth rinsing may have only transiently masked thirst by not permitting the swallowing of fluid. The oropharyngeal reflex is important in metering dipsogenic drive, with decreased arginine vasopressin response and thirst perception with oral drinking – with and without removal of ingested fluid through a nasogastric tube – compared with direct infusion of fluid into the stomach (Figaro & Mack, 1997). Further, Arnaoutis et al. (2012) observed prolonged time to exhaustion during ~ 20 min steady-state exercise with ingestion of ~ 100 mL of water compared with the same volume as mouth rinse. Thus, we must clarify that we altered thirst sensation through altering the sensation of dryness in the mouth rather than a physiologic alteration in actual thirst and dipsogenic drive; future research should explore controlling oropharyngeal stimulation through a gastric infusion/extraction protocol similar to that of Figaro and Mack (1997).

## Limitations

While IV infusion was critical to our goal of blinding hydration status, infusion does not exactly replicate the physiologic effects of oral fluid ingestion on fluid balance. Sweat glands draw fluid from the surrounding interstitial fluid, which is replenished firstly by the plasma and then, with continued sweat production and decreasing plasma volume, increasingly from the intracellular compartments. Our infusion protocol provided immediate maintenance of plasma volume without the time lag from gastric emptying and intestinal absorption, so IV likely differed from oral fluid in the magnitude of decrease in the intracellular fluid compartment, for example in muscle hydration. We pre-warmed the saline to 35 °C, which remained slightly below resting or exercising core temperature, and thus there is the slight potential for the infusion to act as a heat sink and alter thermoregulatory responses and heat storage. However, McLellan and Cheung (2000) calculated that 35 °C oral fluid ingestion did not significantly alter rates of heat storage during sustained low and high rates of metabolic heat production in the heat.

### Summary

In conclusion, we isolated dehydration separately from thirst sensation to investigate their independent and synergistic influences on self-paced exercise performance in the heat. Performance and pacing profile over a 20-km TT did not differ when starting at a dehydrated (> 2% body mass loss) compared with a euhydrated (< 0.5% body mass loss) state, culminating in a 3% body mass loss by the end of dehydrated TTs. Thirst sensation, manipulated by water mouth rinse, also did not influence TT performance either independently or when combined with hydration. Despite a total exercise duration of > 2 h in a hot environment, no participants terminated exercise after reaching the ethically mandated thresholds of 95% maximum HR or 40 °C $T_{re}$, and no illness or medical complications arose in any participant throughout the study. Thus, we conclude that exercise performance within the range of 2 h and up to 3% body mass loss are well-maintained in fit individuals.

## Perspectives

Previous research on the effects of hydration on exercise performance has largely utilized oral fluid replacement, but this can also affect thirst sensation and potentially psychological motivation. This is the first study to use real or sham IV infusion, combined with the presence or absence of *ad lib* plain water mouth rinse, to bypass conscious awareness of hydration status and to alter thirst sensation during exercise in the heat. During 90 min of moderate steady-state cycling, HR and core temperature did not differ between hydration conditions, but were significantly higher in dehydrated conditions during a 20-km self-paced cycling TT in hot (35 °C, 10% relative humidity) conditions. However, power output, 20-km TT completion times, and pacing profiles were not influenced by hydration status or thirst sensation either separately or in combination despite marked differences in hydration status and thirst sensation, even though body mass decreased by 3% following the dehydrated TTs. Therefore, we conclude that current guidelines advocating the importance of rehydration to maintain body mass loss within < 2% body mass during exercise in the heat as an ergogenic aid may be overly conservative in fit and trained populations.

**Key words:** Pacing, heat stress, ratings of perceived exertion, thermal perception, voluntary exercise.

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## Author contributions

S. S. C., C. L. W., and M. J. G. conceived and designed the study; S. S. C., G. W. M., M. M. M., P. J. W., and I. M. K. performed data collection; S. S. C., G. W. M., M. M. M., P. J. W., and C. L. W. analyzed and interpreted the data; S. S. C., G. W. M., and I. M. K. drafted the paper. All authors edited, revised, and approved the final version of the paper.

*Conflicts of interest:* The authors of this study declare that they have no conflicts of interest.

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