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Hypohydration impairs endurance exercise performance in temperate but not cold air

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Cheuvront, Samuel N., Robert Carter III, John W. Castellani, and Michael N. Sawka. Hypohydration impairs endurance exercise performance in temperate but not cold air. *J Appl Physiol* 99: 1972–1976, 2005. First published July 14, 2005; doi:10.1152/jappphysiol.00329.2005.— This study compared the effects of hypohydration (HYP) on endurance exercise performance in temperate and cold air environments. On four occasions, six men and two women (age = 24 ± 6 yr, height = 170 ± 6 cm, weight = 72.9 ± 11.1 kg, peak O_2 consumption = 48 ± 9 ml·kg⁻¹·min⁻¹) were exposed to 3 h of passive heat stress (45°C) in the early morning with [euhydration (EUH)] or without (HYP; 3% body mass) fluid replacement. Later in the day, subjects sat in a cold (2°C) or temperate (20°C) environment with minimal clothing for 1 h before performing 30 min of cycle ergometry at 50% peak O_2 consumption followed immediately by a 30-min performance time trial. Rectal and mean skin temperatures, heart rate, and ratings of perceived exertion measurements were made at regular intervals. Performance was assessed by the total amount of work (kJ) completed in the 30-min time trial. Skin temperature was significantly lower in the cold compared with the temperate trial, but there was no independent effect of hydration. Rectal temperature in both HYP trials was higher than EUH after 60 min of exercise, but the difference was only significant within the temperate trials ($P < 0.05$). Heart rate was significantly higher at 30 min within the temperate trial (HYP > EUH) and at 60 min within the cold trial (HYP > EUH) ($P < 0.05$). Ratings of perceived exertion increased over time with no differences among trials. Total work performed during the 30-min time trial was not influenced by environment but was less ($P < 0.05$) for HYP than EUH in the temperate trials. The corresponding change in performance (EUH – HYP) was greater for temperate (–8%) than for cold (–3%) ($P < 0.05$). These data demonstrate that 1) HYP impairs endurance exercise performance in temperate but not cold air but 2) cold stress per se does not.

dehydration; thermoregulation; environment

PERSONS EXERCISING IN COLD WEATHER can incur substantial fluid losses (6) and are commonly advised to maintain hydration to avoid cold injury and sustain performance. Despite these assertions, recent research shows that hypohydration (HYP; reduced body water) does not increase the risk of hypothermia or peripheral cold injury (23, 24). Similarly, HYP in excess of 2% body mass impairs endurance exercise performance in hot and temperate environments with the magnitude of effect largest in the heat (4, 30). The extent to which this is true in cooler environments is unknown, but there is evidence that the mechanisms for HYP-mediated fatigue in warmer environments are blunted in the cold and may therefore have less impact.

Hyperthermia and cardiovascular strain are two major factors implicated in the genesis of HYP-mediated endurance

exercise fatigue in hot and temperate environments (4). Both the independent and combined effects of hyperthermia and hypovolemia on cardiovascular strain dynamics in the heat have been elegantly described (9–11, 28). Recent examination of the same parameters during exercise in cooler environments (3–8°C) indicates that core temperature elevations associated with HYP are significantly reduced (9, 17). Tachycardia is also attenuated and stroke volume and cardiac output better preserved during progressive dehydration up to 4% of body mass during both moderate (50% maximal O_2 uptake) (17) and more intense (72% maximal O_2 uptake) (9) exercise cold stress. Taken together, cardiovascular strain attributed to hyperthermia and hypovolemia in warm and hot climates is blunted in cooler conditions, which may preserve endurance exercise performance.

Although multiple meteorological variables can influence endurance exercise success (32), performances typically improve as air temperatures decline (32, 33). Laboratory (7) and field data (32, 33) support an “optimal” air temperature threshold near 12°C; above or below this temperature, performance is relatively impaired (7). Endurance performance limitations in hot environments are well documented (21, 31), but evidence during exercise cold stress is complicated by the comparison reference temperature (7), wearing heavily insulated clothing (25), and possibly the choice of an open-ended endurance exercise task (1, 7, 25). The best explanation for fatigue offered by cold performance studies also implicates factors other than cardiovascular strain or O_2 uptake as performance limiting. Competitive endurance athletes appear to perform at a high level coincident with significant body water losses in cool environments (4), but few studies have manipulated hydration state to experimentally compare the impact of HYP on performance in cold vs. more temperate conditions. Those that have are difficult to interpret due to the absence of true control conditions (18) or wearing heavily insulated clothing (27).

The purpose of this study was to compare the effects of HYP on endurance exercise performance in temperate and cold air. Our hypothesis was that cold air would mitigate the decrement in performance attributable to HYP in a temperate environment. A combination of air motion and low air temperatures was used to induce cold stress beyond previous studies but without exceeding cold injury thresholds. In addition, a close-ended exercise task was selected to reduce the influence of cold-stress tolerance on performance.

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METHODS

Subjects

Eight healthy volunteers (age = 24 ± 6 yr, height = 170 ± 6 cm, weight = 72.9 ± 11.1 kg, body fat $22 \pm 6\%$) participated in this study and completed all phases of experimentation. Subjects (6 men, 2 women) were physically active and moderately fit [peak $\dot{V}O_2$ consumption ($\dot{V}O_{2\text{ peak}}$) = 48 ± 9 ml·kg⁻¹·min⁻¹]. Subjects were provided informational briefings and gave voluntary and informed written consent to participate. Investigators adhered to AR 70-25 and U.S. Army Medical Research and Materiel Command Regulation 70-25 on the use of volunteers in research and the appropriate Institutional Review Boards approved this study.

Preliminary Procedures

Each subject's $\dot{V}O_{2\text{ peak}}$ was measured using an incremental cycle ergometer protocol with continuous gas-exchange measurements (TrueMax, ParvoMedics, Sandy, UT). The calculated workload at 50% $\dot{V}O_{2\text{ peak}}$ was validated during 30 min of steady-state cycling 1 day later. The ergometer used (Lode Excalibur Sport, Lode, Groningen, The Netherlands) allows pedal rate-independent (hyperbolic) and -dependent (linear) modes of cycling. Individual linear factors (LF) were calculated [$W = LF \times (\text{rpm})^2$] for each subject to reflect a 50% $\dot{V}O_{2\text{ peak}}$ exercise intensity at a pedal cadence of 60 rpm. The linear factor setting provided room to increase work output during the time trial before reaching maximal sustainable workloads, which were estimated from $\dot{V}O_{2\text{ peak}}$ testing at ~ 100 rpm. Practice trials included 30 min of steady-state cycling (50% $\dot{V}O_{2\text{ peak}}$), followed immediately by a 30-min performance time trial. Three practice sessions were used to reduce training and learning effects (8, 13). Elapsed time was displayed, and the total work (kJ) completed in 30 min was given as feedback for motivation to improve with each subsequent practice ride. Experimental test scenarios were the same as those used in practice except that subjects were blinded to all test parameters but elapsed time. Semi-nude body mass (shorts only) was measured after voiding and before breakfast each morning for 10-days to establish a normal individual baseline body mass for euhydration (EUH) assessment on test days. All experimentation began within 3 days of completing preliminary procedures.

Experimental Procedures

A counterbalanced 2×2 (hydration \times environment) experimental design was employed. Each was separated by at least 48 h. Experiments were conducted at the same time of day, and women were tested in the follicular phase of their menstrual cycle to control for circadian and ovulatory fluctuations in body temperature. On the morning of each trial, body mass was measured with an electronic precision balance scale (Toledo 1D1 accuracy ± 20 g, Worthington, OH) for comparison against within-subject 10-day averages, and a 10-ml venous blood sample was collected for serum osmolality determination. A standardized breakfast was provided, after which subjects rested in a seated position for ~ 1 h before moving to a hot room (45°C, 50% relative humidity, 1 m/s air speed) for 3 h of passive heat exposure with (EUH) or without (HYP) fluid replacement. A 2-h recovery period followed in which a shower was permitted and a small snack was provided (200 ml of water and 250 kcal). The precise fluid deficit incurred was calculated from the acute change in body mass from pre- to post-heat exposure, corrected for snack, and expressed as a percentage of preexercise body mass.

In the afternoon, subjects sat in a cold (2°C, 50% relative humidity, 2.2 m/s air speed) or temperate (20°C, 50% relative humidity, 1 m/s air speed) environment with minimal clothing (t-shirt, shorts, socks, shoes, cotton gloves, and head band) for 1 h before performing 30 min of cycle ergometry at 50% $\dot{V}O_{2\text{ peak}}$ followed immediately by a 30-min performance time trial. No motivation was provided during the time

trial, and subjects performed without distraction from any data-collection measurements. Time trial performance was assessed by the total amount of work (kJ) completed in 30 min. Rectal (T_{re}) and mean skin temperatures (26) and heart rate (HR) were collected remotely at regular intervals throughout testing. Rating of perceived exertion was assessed at 30 min and again immediately after the completion of exercise. Gas-exchange measurements were made once in the initial 10 min of exercise using an automated system, and workloads were adjusted to reflect a 50% $\dot{V}O_{2\text{ peak}}$ intensity.

Statistical Analysis

Following tests for normality of distribution and equality of variances, treatment effects were analyzed using a paired *t*-test and one- or two-way ANOVA for repeated measurements. A one-sample *t*-test was also used to compare performance effects against a hypothetical value of importance (20). When appropriate, Tukey's honestly significant difference procedure was used to identify pairwise differences among means following significant main and/or interaction effects. The primary outcome variable of interest in this experiment was time trial performance. An analysis selecting conventional α (0.05) and β (0.20) parameters showed that eight subjects would provide sufficient power to detect a 5% change in time trial performance (~ 15 kJ) using the mean total work (295 kJ) and coefficient of variation (CV; 2.5%) calculated from trials of negligible difference (i.e., practice trials 2 and 3; $P > 0.05$) during 2 wk of time trial practice. The desire to detect a twofold change from the %CV was chosen based on the likelihood of experimental perturbations producing unique performance infidelity (12, 13, 15), thus increasing variability. A sample size of eight allows detection of said differences with a CV up to 4.5%. The practical importance of hydration effects on performance within environments was also interpreted using 95% confidence limits of the true effect for % change in performance to include comparison against an a priori zone of indifference (2.5% CV) using a one-sample *t*-test, which affords evaluation against an evidentiary standard other than zero (5, 14, 20). The spirit of this approach, most closely related to equivalence testing in the clinical sciences (5), has recently been championed as a performance interpretation tool for the exercise sciences (14). Graphical data are presented with unidirectional error bars and may be slightly juxtaposed for presentation clarity. All data are presented as means \pm SD except where indicated.

RESULTS

Hydration

EUH was estimated on the morning of each trial by a body mass within 1% of the average 10-day baseline (3). Two subjects $>1\%$ lower than 10-day baseline were given additional water with breakfast. Serum osmolality (289 ± 1 mosmol/kgH₂O) confirmed EUH (16). The fluid deficit achieved before the start of each HYP trial was -2.9 ± 0.7 and $-3.0 \pm 0.8\%$ of body mass for cold and temperate, respectively. Values for EUH trials were -0.3 ± 0.6 (cold) and $-0.4 \pm 0.7\%$ (temperate) of starting baseline. Differences were significant ($P < 0.05$) between hydration levels (HYP vs. EUH) but not between environments (cold vs. temperate). Thus subjects were adequately matched for preexercise hydration status in EUH and HYP trials.

Exercise Performance

Table 1 presents individual and mean time trial performance data. Total work in temperate HYP was lower than temperate EUH ($P = 0.012$). There was no effect of hydration in the cold (cold EUH vs. cold HYP) and no independent effect of environment on performance (cold EUH vs. temperate EUH).

Table 1. Time trial work performance

Subject No.	Cold		Temperate	
	EUH	HYP	EUH	HYP
1	156.3	157.3	165.1	161.0
2	207.3	191.0	214.0	184.9
3	289.5	291.7	300.6	289.4
4	298.4	274.0	300.5	243.1
5	308.0	324.9	308.8	296.5
6	361.8	342.3	311.5	297.4
7	296.0	293.2	276.8	251.0
8	300.8	282.0	304.3	291.4
Mean	277.3	269.6	272.7	251.8*
SD	64.5	63.6	53.9	53.3

EUH, euhydration; HYP, hypohydration. *Significantly lower ($P < 0.05$) than cold EUH and temperate EUH.

Associated mean power outputs from Table 1 were 140 ± 30 (temp HYP), 152 ± 30 (temp EUH), 154 ± 36 (cold EUH), and 150 ± 35 W (cold HYP). Viewed individually, all eight subjects performed worse when hypohydrated in temperate air, whereas only five of eight experienced the same from HYP in the cold. Figure 1 presents the % change in performance from EUH to HYP in temperate and cold environments. The change was significantly larger for temperate ($-7.6 \pm 5.9\%$) than cold ($-2.7 \pm 4.9\%$) ($P = 0.021$). The means and 95% confidence limits for performance (-12.6 to -2.7% temperate; -6.8 to 1.4% cold) provide the likely range of the true change effects and illustrate why there is a difference between HYP and EUH within temperate but not within cold (i.e., confidence interval crosses zero for cold). In addition, only the range of the confidence interval for temperate falls entirely outside the a priori zone of indifference ($P = 0.04$, 1-sample t -test), which provides evidence that the negative effect of HYP on performance in temperate air is also of practical importance.

Physiological Responses

Metabolic rate. Metabolic rates during the initial 30 min of cycling were calculated from a 2-min gas sample made 5 min

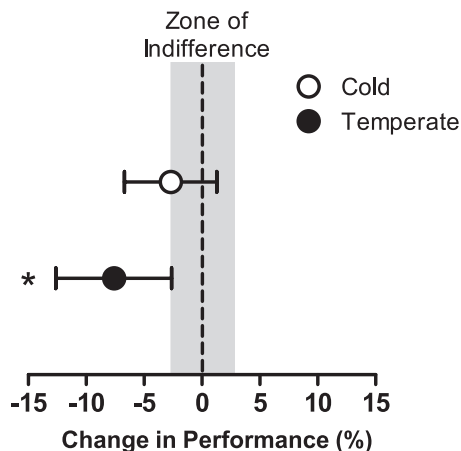


Fig. 1. Percent change in performance from euhydration (EUH) to hypohydration (HYP) in temperate and cold trials. Data are means; bars are 95% confidence intervals. Shaded area represents zone of indifference ($\pm 2.5\%$) based on the typical performance variability measured during practice sessions (see text for detailed explanation). *Significant difference between trials (paired t -test, $P = 0.021$) and significant difference from zone of indifference (1-sample t -test, $P = 0.044$).

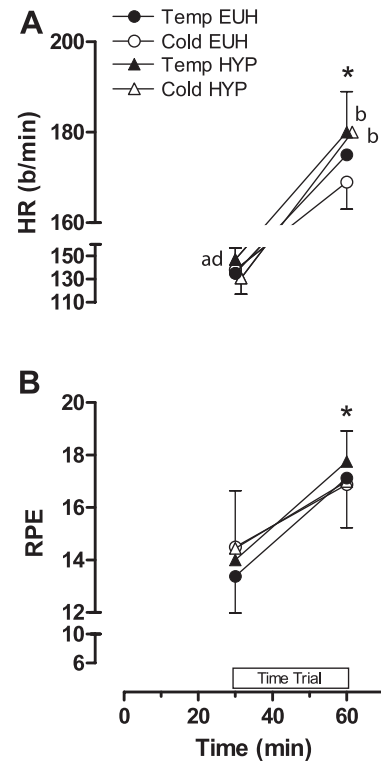


Fig. 2. Effect of hydration and environment on heart rate (HR; A) and ratings of perceived exertion (RPE; B). Values are means \pm SD. ^{a,b,c,d}Significant differences ($P < 0.05$) from corresponding values from temperate EUH, cold EUH, temperate HYP, and cold HYP, respectively. *Significant effect of time (60 > 30 min; $P < 0.05$).

into exercise and adjusted to reflect $\sim 50\%$ of $\dot{V}O_{2\text{ peak}}$. All measurements were similar ($P > 0.05$) at 49 ± 6 (cold EUH), 51 ± 5 (cold HYP), 47 ± 2 (temperate EUH) and $48 \pm 3\%$ (temperate HYP) $\dot{V}O_{2\text{ peak}}$. Subjects were therefore matched among trials for exercise intensity preceding the cycling time trial.

Cardiovascular strain and thermoregulatory strain. Figure 2, A and B, represents HR and perceived exertion responses to exercise at 30 and 60 min of exercise. Data collected at rest were unreliable due to extreme shivering in the cold trials and were therefore excluded from the analysis. All 60-min HR exceeded 30-min values ($P < 0.05$). HR for temperate HYP at 30 min was higher than for temperate EUH and cold HYP. Both temperate HYP and cold HYP were higher than temperate EUH (~ 5 beats/min; $P > 0.05$) and cold EUH (~ 11 beats/min; $P < 0.05$) at 60 min. Rating of perceived exertion increased over time with no differences among trials (60 min > 30 min; $P < 0.05$). T_{re} increased significantly over time in all trials (Fig. 3A). At rest, T_{re} was higher in both cold compared with temperate trials due to rigorous shivering. No differences among trials were seen at 30 min, but temperate HYP was higher than cold EUH (0.4°C ; $P < 0.05$) and temperate EUH (0.3°C ; $P < 0.05$) at exercise cessation. Skin temperature was significantly lower in the cold (Fig. 3B) and was independent of hydration status.

DISCUSSION

This study determined the effects of HYP on endurance exercise performance in temperate and cold air. In accordance

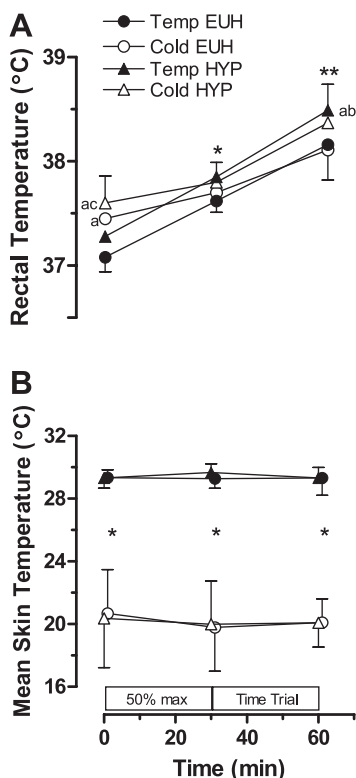


Fig. 3. Effect of hydration and environment on rectal (A) and mean skin temperatures (B). Values are means \pm SD. Significance by letter designation as indicated in Fig. 2. Significant effects of time ($P < 0.05$): * 30 > 0 min; **60 > 30 and 0 min.

with our hypothesis, the principal finding of this study is that HYP by -3% body mass impaired cycling time trial performance in a temperate, but not a cold, environment. In addition, we found that cold stress per se did not reduce performance.

The % change in performance (EUH - HYP) within cold ($-2.7 \pm 4.9\%$) and temperate ($-7.6 \pm 5.9\%$) environments was statistically different (Fig. 1). The 95% confidence limits were plotted about the mean to provide insight into the likely range of the true change value (Fig. 1). These limits were also applied in the traditional sense to examine the importance of the change relative to an evidentiary standard other than zero (5, 14, 20). This standard is the zone of indifference selected a priori as any value within the typical noise of the performance measurement (i.e., 2.5% CV) (5, 14). Although the choice of 95% confidence limits for this integrated analytic approach is admittedly conservative (14, 15), the fact that the entire temperate confidence interval lies outside this zone (Fig. 1) strongly supports the conclusion that the performance impairment due to HYP in temperate environments is both statistically significant and of practical importance (5, 14, 20). No statistical difference in performance was observed between EUH and HYP in cold air, but since one-half of the cold interval lies outside the zone of indifference, the meaning of this effect is ambiguous at best (5, 14, 20).

The preservation of endurance performance in cold air when hypohydrated may be explained by differences in cardiovascular and oxygen uptake dynamics. Although the present experiment was not designed to assess the mechanisms behind performance changes, reasonable explanations can be gleaned

from our observations when combined with the work of others. For example, Gonzalez-Alonso et al. (9-11) demonstrated that tachycardia (via hyperthermia) and hypovolemia explain most of the reduction in cardiac output between EUH and HYP in hot environments, with similar effects of lesser magnitude in the cold (9). In addition, hypovolemia reduces maximal O_2 uptake and endurance capacity even in the presence of normothermia and cool skin (22). It is conceivable that hypovolemia and a higher T_{re} ($\sim 0.30^\circ\text{C}$) and HR (~ 5 beats/min) in temperate HYP (Fig. 2A) reduced stroke volume, cardiac output, and oxygen uptake enough to reduce performance (253 kJ) relative to temperate EUH (273 kJ) despite similar efforts (Fig. 2B). However, the preservation of performance in cold HYP (270 kJ) vs. cold EUH (277 kJ) occurred with similar T_{re} differences and a larger HR disparity (11 beats/min) between HYP and EUH (Fig. 2A). It therefore remains possible that cold skin in cold HYP (Fig. 3B) maintained a larger central blood volume and better preserved stroke volume and cardiac output (9, 17, 19, 22, 29). Similar T_{re} and HR at exhaustion between cold HYP and temperate HYP also seem to support this conclusion since performance in temperate HYP, but not cold HYP, was less than cold and temperate EUH (Table 1).

The finding that cold stress per se did not reduce performance (temperate EUH vs. cold EUH) (Table 1) is in opposition to others (1, 7, 25), but comparisons are made difficult by several methodological factors. For example, Galloway and Maughan (7) found that time to fatigue at 4°C was reduced compared with 11°C , but no different from 20°C , or improved relative to 31°C . Patton and Vogel (25) compared -20 and 20°C , but wearing heavily insulated clothing at -20°C limits the interpretation of reduced performance at the latter temperature. Both of these studies and that of Adolph and Molnar (1) also used open-ended endurance exercise tasks. Adolph and Molnar (1) suggested that the most important predictor of performance in the cold using this kind of task was exposure time and cold tolerance. Indeed, Cabanac and Leblanc (2) demonstrated that simultaneous exposure to cold and exercise fatigue produces a sensory conflict resolved by compromise toward the least displeasing input signal, but others (7, 25) implicate local muscle effects for accelerated fatigue under similar circumstances. Exposure time in this experiment was fixed, which may have alleviated motivation issues related to cold tolerance. Postexperiment interviews even suggest that total work in cold EUH and cold HYP may have actually been augmented by cold avoidance (2). It is inconclusive whether using time to exhaustion, rather than a time trial, would (1, 25) or would not (7) have altered the performance outcomes observed herein between 2 and 20°C .

We conclude that moderate HYP impairs endurance performance in temperate, but not cold, air. Cold stress per se had no effect. Application of these findings to competitive endurance exercise contested in environments similar to those described herein is logical (13, 14) but tentative given the subject population tested. These findings are nonetheless of phenomenological importance.

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