Chapter 7

The effect of drinking ad-libitum on performance during a 40-km cycling time trial in the heat

Meriam Berkulo • Susan Bol • Koen Levels • Robert Lamberts
Hein Daanen • Timothy Noakes

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ABSTRACT

Purpose

The main purpose of this study was to investigate if drinking ad-libitum can counteract potential negative effects of a hypohydrated start during a 40-km time trial in the heat.

Methods

Twelve well-trained males performed one 40-km cycling time trial while starting euhydrated (EU: no water during the time trial) and two 40-km cycling time trials while starting hypohydrated. During one hypohydrated trial no fluid was ingested (HYPO), during the other trial ad-libitum water ingestion was allowed (FLUID). Ambient temperature was 35.2 ± 0.2°C, relative humidity was 51 ± 3% and airflow 7 m·s⁻¹. Body mass was determined at the start of the test, and before and after the time trial. During the time trial, power output, heart rate, gastrointestinal temperature, mean skin temperature, RPE, thermal comfort, thermal sensation and thirst sensation were measured.

Results

Prior to the start of the time trial, body mass was 1.2% lower in HYPO and FLUID compared to EU. During the time trial, body mass loss in FLUID was lower compared to EU and HYPO (1.0 ± 0.8%, 2.7 ± 0.2% and 2.6 ± 0.3%, respectively). Hydration status had no effect on power output, heart rate, RPE, gastrointestinal and mean skin temperature, thermal sensation and thermal comfort. Thirst sensation was higher in HYPO than in the other two conditions.

Conclusion

Hypohydration did not adversely affect exercise performance during a 40-km cycling time trial in the heat. Therefore, whether or not participants consumed fluid during exercise could not influence their time trial performance.
INTRODUCTION

It is well established that heat stress has a negative effect on exercise performance. Performance during both fixed-intensity exercise (Galloway and Maughan 1997), and self-paced exercise (Peiffer and Abbiss 2011; Tatterson et al. 2000) is considerably degraded in hot and humid conditions compared to cooler conditions. For exercise at a fixed intensity this may be due to the attainment of a critically high core temperature (Galloway and Maughan 1997; Nielsen et al. 1993). However, core temperature, metabolism and skeletal muscles blood flow do not reach limiting values in self-paced exercise (Tatterson et al. 2000; Tucker et al. 2004). It is suggested that self-paced exercise is regulated in an anticipatory feedback and manner through a centrally mediated mechanism (Tucker 2009; Tucker and Noakes 2009). Due to heat stress, exercise is more difficult to sustain and fatigue occurs earlier, perhaps as a result of greater heat storage. To prevent homeostatic and thermoregulatory derangements, neural drive decreases and, as a consequence, skeletal muscle recruitment and work rate are reduced during exercise in the heat (Tucker et al. 2004). It is suggested that this type of anticipatory control in response to temperature may be complementary to, and not the exclusive regulator of a critical temperature (Cheung 2007).

Heat loss mechanisms are essential to sustain exercise in the heat. Although dissipating body heat can be facilitated by an increased blood flow to the skin and evaporation of sweat, this may result in considerable body water deficits (hypohydration) (Cheuvront et al. 2010). Hypohydration augments hyperthermia and reduces plasma volume, increases cardiovascular and heat strain (Cheuvront et al. 2010; Gonzalez-Alonso et al. 2000), and may compromise endurance exercise performance. Performance decrements are seen as early as BM losses are between 1 and 2% (Armstrong et al. 1985; Bardis et al. 2013; Cheuvront et al. 2010). Also, when starting a time trial hypohydrated, pacing strategy may be altered (Stearns et al. 2009).
Since hypohydration can impair exercise performance (Sawka et al. 2007), fluid intake during prolonged exercise is important to counteract excessive sweat losses. Goulet (2011) demonstrated that when participants were allowed to drink according to their sensation of thirst (ad-libitum), exercise-induced dehydration up to 4% BM loss did not impair cycling performance in temperate-to-warm conditions (20-33°C). However, recommendations regarding fluid replacement remain controversial and have changed substantially over the past 20 years (Convertino et al. 1996; Noakes 1993). Besides, they are difficult to formulate due to the large variation in sweating rates among different conditions and individuals (Murray 2007). The most recent guidelines of the American College of Sports Medicine (ACSM) on Exercise and Fluid Replacement (Sawka et al. 2007) state that to prevent excessive hypohydration and exercise impairment, athletes should drink sufficient to ensure that BM losses are less than 2% during exercise. A contrasting opinion is that athletes should drink to the dictates of their thirst (Noakes 2007, 2010; Sawka and Noakes 2007). Within these papers it is suggested that it is the sensation of thirst, rather than the level of hypohydration, that modulates exercise intensity as part of an anticipatory control. However, one of the key regulators that drives thirst is the level of hypohydration. Hypohydration is, via several chemoreceptors and mechanoreceptors in the body, detected by the brain as a change in plasma osmolality. As a result, neural activity increases and the conscious sensation of thirst develops. Thirst acts in an anticipatory manner by inducing an increase in fluid ingestion and reducing the exercise intensity in order to prevent deficits in either intracellular or extracellular fluid volume and to ensure that the osmolality of the brain remains within the homeostatic range (Johnson 2007; McKinley and Johnson 2004; Sawka and Noakes 2007). In support of this theory, Goulet (2011) showed that drinking to thirst improves time trial performance significantly compared to drinking less than thirst dictates.

Even though drinking ad-libitum results in an incomplete replacement of body water loss, this seems to be more favorable than drinking as much as tolerable (Noakes 2007). This is supported by the observation that the fastest athletes competing in marathons and triathlons are among the athletes who are the most hypohydrated at the finish (Noakes 2010; Zouhal et al. 2011; Sharwood et al. 2004). It is conceivable that athletes drink less to
develop voluntary dehydration in order to carry less water and hence body mass during exercise. Because of inter-individual differences in metabolic and heat dissipation rates, it is very likely that there is a range rather than a fixed point for hypohydration from which self-paced performance is negatively affected.

Although the relationship between hydration status and exercise performance has been studied extensively, results regarding the effect of hypohydration are inconclusive. This is partly due to the period when hypohydration is induced (before or during exercise). Moreover, the effect of drinking ad-libitum on exercise performance is still unclear when exercise begins in the hypohydrated state. Therefore, the main goal of this study was to investigate if drinking according to thirst during a 40-km cycling time trial in the heat can counteract possible negative performance effects of starting hypohydrated. We hypothesize that hypohydration will negatively affect performance during a 40-km cycling time trial in the heat and that by reversing that hypohydration, drinking ad-libitum during the time trial will counteract the negative effects of starting exercise in a hypohydrated state.

METHODS

Participants

Twelve well-trained male cyclists participated in this study (Table 7.1). All participants provided written informed consent and completed a health screening questionnaire and the Physical Activity Readiness Questionnaire (PAR-Q). During the study, participants were instructed to refrain from strenuous exercise two days prior to the test, not to consume alcohol and caffeine during the final 24 hours before each test, and to have their last meal three hours preceding the testing sessions. The experimental protocol for the study was approved by the Human Research Ethics Committee of the University of Cape Town, South Africa.
Table 7.1 Characteristics of the participants (n = 12), including their responses during the incremental exercise testing (mean ± SD).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
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<tbody>
<tr>
<td>Age (years)</td>
<td>34 ± 7</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>80.4 ± 6.4</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>183 ± 7</td>
</tr>
<tr>
<td>Body fat (%)</td>
<td>14.3 ± 3.6</td>
</tr>
<tr>
<td>Sum of skin folds (mm)</td>
<td>54 ± 12</td>
</tr>
<tr>
<td>Peak power output (W)</td>
<td>407 ± 35</td>
</tr>
<tr>
<td>Peak power output (W·kg⁻¹)</td>
<td>5.1 ± 0.5</td>
</tr>
<tr>
<td>$\dot{V}O_2$max (mL·kg⁻¹·min⁻¹)</td>
<td>53.5 ± 4.4</td>
</tr>
<tr>
<td>HR$_{max}$ (beats·min⁻¹)</td>
<td>185 ± 7</td>
</tr>
</tbody>
</table>

Overview of the trials

Participants completed an incremental exercise test until volitional exhaustion, a familiarization 40-km cycling time trial (TT) and three experimental 40-km TTs. The TTs were differentiated by fluid ingestion regime (EU: sufficient fluid ingestion during the pre-exercise protocol to prevent any changes in body mass + no fluid ingestion during the TT; HYPO: no fluid ingestion at all; FLUID: no fluid ingestion during the pre-exercise protocol + ad-libitum fluid ingestion during the TT). The order of experimental trials was counterbalanced among the participants with at least 48 hours between two tests. All tests were performed on the participants’ own bike with the rear wheel attached to a CompuTrainer cycle ergometer (CompuTrainer Pro 3D; RacerMate, Seattle, Washington, USA).

Preliminary testing

During the first laboratory visit anthropometrical measurements were taken: BM, height and seven skinfolds (triceps, biceps, abdomen, calf, thigh, supra-iliac region and subscapular region) (Ross and Marfell-Jones 1991). Body fat was determined as the sum of these seven skinfolds and as percentage of BM (Durnin and Womersley 1974).
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Subsequently, the cyclists own bicycle was placed on a CompuTrainer ergometer and the system was calibrated as recommended. After warming-up the tire for six min, the load against the rear wheel was set to 0.88–0.93 kg to simulate rolling resistance during out-of-door cycling (Davison et al. 2009). Prior to the incremental test, participants completed a warm-up protocol consisting of 6-min cycling at a target heart rate (HR) of 60% of their maximum HR (HR$_{\text{max}}$), followed by a resting period of 30 s to recalibrate the bike-ergometer system, six min of cycling at 80% HR$_{\text{max}}$ and three min of cycling at 90% HR$_{\text{max}}$ (Lamberts and Lambert Submaximal Cycle Test; LSCT: Lamberts et al. (2011)). Five min after completion of the LSCT, participants performed a maximal incremental cycling test (initial work load of 100W + 20W·min$^{-1}$ continuously until exhaustion). When participants were not able to maintain a pedaling frequency of 70 revolutions per minute the test was terminated. Room temperature was 21.8 ± 0.8°C and relative humidity (RH) was 48 ± 4%. Respiratory gas exchange was measured breath-by-breath using open circuit spirometry (Jaeger Oxycon Pro, Viasys Healthcare, Hoechberg, Germany), maximal oxygen consumption ($\dot{V}O_2$$_{\text{max}}$), peak power output (PPO) and HR$_{\text{max}}$ were measured. $\dot{V}O_2$$_{\text{max}}$ was defined as the highest averaged oxygen consumption over a period of 30 s. PPO was determined as the mean PO during the last minute of the test (CompuTrainer Coaching Software 1.6, RacerMate, Seattle, WA, USA). HR$_{\text{max}}$ was determined as the average HR during the last 30 s of the test. Furthermore, a familiarization trial was performed with at least two days after the incremental exercise test. The purpose of this trial was to familiarize participants with the TT distance and the testing protocol. During the familiarization trial, only HR and RPE were measured and participants received continuous feedback about the completed distance of the TT.

**40-km cycling time trial**

The first experimental trial was performed at least three days after the familiarization session. Upon arrival at the lab, BM was determined to the nearest 100 g using an electronic scale (Model 770, Seca, Bonn, Germany). Euhydration was confirmed by a difference in BM of less than 200 g with the preceding trials. The first part of the experimental trial was the LSCT standardized warm-up protocol (Lamberts et al. 2011).
Three minutes after finishing the LSCT, participants cycled for 30 min at a fixed workload corresponding to 50% of their PPO in an environmental chamber with a temperature of 30.3 ± 0.3°C and 55 ± 2% RH. A laminar airflow of 7 m·s⁻¹ was created by four fans with a diameter of 1 m that are part of the environmental chamber. In the EU trial, participants consumed tap water during this pre-exercise protocol to remain euhydrated. The amount of water was determined from the loss in BM during the pre-exercise protocol in a previous trial. If there was no previous trial, the amount was estimated to be 12 mL·kg⁻¹ BM, based on pilot experiments. The total volume was divided in six equal portions to provide the participants water every ten min (Figure 7.1). After this period of cycling, a 20-min recovery period followed in which participants left the environmental chamber. During this period participants were weighted again after ten min and at the end of the recovery period. Following the recovery period, participants re-entered the environmental chamber and completed a warm-up protocol of six min at a target HR of 80% HRmax and three min at 90% HRmax. Participants started the 40-km TT three min after the warm-up protocol with the instruction to finish the trial as fast as possible. During the TT, participants received continuous feedback about distance completed and were free to shift gears and alter their cadence. Ambient temperature was 35.2 ± 0.2°C and 51 ± 3% RH. Airflow was set at 7 m·s⁻¹ in order to simulate airflow during outdoor cycling. Throughout the TT, participants received only feedback about the distance of the TT completed. Directly after the TT, participants were weighted for the last time.

**Figure 7.1** Schematic overview of the experiment. Arrows indicate water ingestion in EU.
Measurements

PO was measured at a sampling rate of 34 Hz (CompuTrainer Coaching Software 1.6, RacerMate, Seattle, WA, USA). Furthermore, the slope of PO during the first 28 km was calculated. HR was recorded at 0.2 Hz (Polar s810i, Polar Electro Oy, Kempele, Finland). A moving average was applied (window size 12) using Matlab software (R2010b) to remove any outliers and the ratio between HR and PO was determined. GI temperature was measured by a disposable core temperature capsule (Jonah, Hidalgo, Cambridge, UK). Participants ingested the capsule at least three hours before each lab visit. \( T_{\text{GI}} \) was recorded throughout the test every 15 s using the Hidalgo Equivital™ Physiological Monitor system (Hidalgo, Cambridge, UK). Due to invalid or incomplete data, only eight participants were included for GI temperature. To determine \( T_{\text{sk}} \), four iButtons (DS1922L, Maxim Integrated Products Inc, Sunnyvale, CA, USA) were attached to the skin (neck, right scapula, right shin and left hand) with hypoallergenic tape (Fixomull stretch, 5 cm x 10m, BSN medical, Hamburg, Germany). Local skin temperature was recorded at 10-s intervals throughout the test. \( T_{\text{sk}} \) was determined using equation 7.1 (ISO9886, 2004). All physiological and performance data were averaged over segments of 4 km.

\[
T_{\text{sk}} (°C) = 0.28 \cdot (T_{\text{neck}} + T_{\text{right scapula}} + T_{\text{right shin}}) + 0.16 \cdot (T_{\text{left hand}}) \quad \text{(Equation 7.1)}
\]

RPE, TC, TS were ranked on a 20-point (Borg, 1970), 5-point and 9-point scale, respectively (ISO10551 1993) and were collected every 4 km. Best fit linear regression lines for RPE scores per condition were determined and absolute individual differences with these lines were calculated in order to obtain a measure of linearity in the development of RPE. Furthermore, every 4 km, participants were asked to give a score for thirst sensation, on a numerical scale ranging from 1 to 9 with associated word anchors (1 = not thirsty, 3 = a little thirsty, 5 = moderately thirsty, 7 = very thirsty, 9 = very, very thirsty) (Engell et al. 1987).
**Statistical analysis**

SPSS statistical software (SPSS 20.0, SPSS Inc., Chicago, IL, USA) was used for statistical analysis. All data were checked for normality by visual inspection of the q-q plot and box plots and by means of a Shapiro-Wilk test. To test the effect of hydration status (EU, HYPO, FLUID) on finish time, change in BM and mean PO, a one-way repeated measures ANOVA and post-hoc analyses with Bonferroni correction were performed. To check if BM changes in EU were different from zero, a one-sample t-test was carried out. Furthermore, hydration status before the start of the TT in HYPO and FLUID was compared using a paired-samples t-test. To test the effect of hydration status (EU, HYPO, FLUID) and distance completed (10 segments of 4-km) on PO, HR, HR/PO, T_{Gl}, T_{sk}, RPE, TS, TC, thirst sensation and RPE, a two-way repeated measures ANOVA was performed. Post-hoc analyses using the Bonferroni correction were carried out to adjust for multiple comparisons. For each analysis, data were considered to be significant if p < 0.05. Data are reported as mean ± SD unless stated otherwise. To determine the practical (rather than the statistical) significance of the effect of hydration status on cycling time trial performance, the effect was also expressed as 95% confidence limits (magnitude based inferences). By comparing the overlap of these limits with the smallest substantial and practically meaningful change in TT performance, the chance that the observed effect is beneficial/trivial/harmful could be determined (Batterham and Hopkins 2006). For this analysis, we assume that the smallest practically meaningful change in 40-km TT performance is 0.7% (Lamberts et al. 2009).

**RESULTS**

**Effect of manipulations**

After the pre-exercise protocol, BM was reduced by 0.0 ± 0.2%, 1.1 ± 0.2% and 1.3 ± 0.3% in EU, HYPO and FLUID respectively. BM change in EU was not different from zero (P=0.96). Therefore, the manipulation to induce mild hypohydration in HYPO and FLUID and maintain euhydration in EU was successful. No differences in BM change after the
pre-exercise protocol were seen between HYPO and FLUID (P=0.20). After the TT, BM was further reduced to losses of 2.7 ± 0.3%, 3.8 ± 0.4% and 2.3 ± 0.8% for EU, HYPO and FLUID respectively. Since 3.8% loss was higher than losses of 2.7% and 2.3% (P<0.001), a main effect for hydration status was found (F=25, P<0.001). Mean fluid losses during the trials are shown in Figure 7.2. An effect for hydration status on the changes in BM during the TT was found (F= 43, P<0.001). Mean BM loss in FLUID (1.0 ± 0.2%) was lower than in EU (2.7 ± 0.1%) and HYPO (2.6 ± 0.1%; P<0.001). During the FLUID trial participants drank on average 1.4 ± 0.6 L.

**Figure 7.2** Mean BM losses during the test in % of initial BM. * Lower BM loss during the TT in FLUID than in EU and HYPO (p<0.001).

**Time trial performance**

Mean finish times and mean PO for every condition are shown in Table 7.2. No effect of hydration status on finish time (F=0.73, P= 0.48), or mean PO (F=0.56, P=0.58) was observed. The chances that the effects are beneficial/trivial/harmful on the finish time of a 40-km TT in real-life competition are 68/21/11% for starting hypohydrated and 19/47/34% for starting hypohydrated combined with ad-libitum drinking during exercise.
Table 7.2 Finish times and mean PO in all conditions (mean ± SD).

<table>
<thead>
<tr>
<th>Condition</th>
<th>Finish time (min:s)</th>
<th>Mean power output (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU</td>
<td>70:06 ± 4:07</td>
<td>223 ± 32</td>
</tr>
<tr>
<td>HYPO</td>
<td>71:12 ± 5:37</td>
<td>217 ± 39</td>
</tr>
<tr>
<td>FLUID</td>
<td>69:55 ± 4:02</td>
<td>224 ± 35</td>
</tr>
</tbody>
</table>

PO, HR, HR/PO

No effect of hydration status was found on PO (F=0.56, P=0.58) and HR (F=0.55, P=0.53). Although a slightly higher increase in HR/PO was seen in HYPO, this effect was not statistically significant (F= 1.3, P=0.31). The slopes of the development of PO over the first 28 km for EU, HYPO and FLUID were -1.75, -1.84 and -1.24 W/km, respectively (F=2.2, P=0.14). The development of PO, HR and HR/PO over time is shown in Figure 7.3a, 7.3b and 7.3c.

Figure 7.3 Development of PO (a), HR (b), and HR/PO (c) over TT distance. For clarity of the figure, no error bars are displayed.
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**Temperature**

No effect of hydration status was observed on \( T_{GI} \) (\( F=1.6, P=0.24 \)) and \( \bar{T}_{sk} \) (\( F=2.1, P=0.14 \)). The development of \( T_{GI} \) over time and \( \bar{T}_{sk} \) are shown in Figure 7.4a and 7.4b.

![Figure 7.4](image)

**Figure 7.4** Development of \( T_{GI} \) (a) and \( \bar{T}_{sk} \) (b) over TT distance. Note that \( T_{GI} \) during FLUID might have been affected by the temperature of the ingested fluid during the time trials. For clarity of the figure, no error bars are displayed.

**Psychophysiological parameters**

RPE increased progressively during all TTs (Figure 7.5a). No effect of hydration status on RPE (\( F=1.5, P=0.25 \)), TC (\( F=0.46, P=0.64 \)) and TS (\( F=0.25, P=0.75 \)) was found. However, an
effect of hydration status was found on thirst sensation (F=26, P<0.001), which was higher in HYPO (7.2 ± 1.5) than in EU (5.7 ± 1.6) and FLUID (4.6 ± 1.7). Also, thirst sensation in FLUID was lower than in EU (P=0.02). At the end of the TT, thirst sensation was 8.1 ± 1.2 for EU, 8.8 ± 0.6 in HYPO and 5.9 ± 2.1 in FLUID (F=22, P<0.01). The development of thirst sensation over time is shown in Figure 7.5b. Mean absolute differences of RPE scores with the linear regression line, as a measure for linearity in the development of RPE over TT distance for EU, HYPO and FLUID were 1.9, 1.7 and 1.2, respectively. An effect of hydration status was found for these differences (F=6.8, P=0.007).

**Figure 7.5** Development of RPE (a) and thirst sensation (b) over TT distance. * Main effect of hydration status (p<0.001). For clarity of the figure, no error bars are displayed.
DISCUSSION

The aim of this study was to determine if potential negative effects on exercise performance due to hypohydration could be offset by drinking to the dictate of thirst during a 40-km cycling time trial in the heat. No effect of hydration status was found on performance, HR, temperature responses and perceptions of temperature and effort. The only effect of hydration status was on thirst sensation. Predictably, drinking ad-libitum when beginning exercise hypohydrated did not have an effect on performance in hot conditions since the hypohydrated state itself did not impair TT performance. Therefore, we have to reject our hypothesis that hypohydration has a negative effect on exercise performance. Consequently we could not determine if drinking ad-libitum during a 40-km time trial in the heat could have counteracted possible negative effects. The absence of an effect of hydration status on performance is in contrast with previous studies that evaluated the effects of exercise-induced dehydration (Armstrong et al. 1985; Cheuvront et al. 2010; Murray 2007). Moreover, Bardis et al. (2013) showed that even mild hypohydration of 1% BM at the start of exercise impaired simulated all-out cycling performance. Also, Stearns et al. (2009) found a decreased ability to maintain an even pace during competition in hypohydrated runners.

It is conceivable that we did not find differences between the conditions due to the laminar airflow of 7 m·s⁻¹ that was applied in our study. Participants cycled for 40-km in hot, humid conditions but with facing wind speed that closely simulated outdoor cycling. The high air velocity, in contrast to those of some other studies (Galloway and Maughan 1997; Montain and Coyle 1992), increases the capacity of the environment for evaporative heat loss (Saunders et al. 2005). As a result, excess heat in the body can be dissipated and body heat storage is smaller (Adams et al. 1992; Cheuvront et al. 2004; Saunders et al. 2005). Under these conditions, hypohydration does not appear to limit the dissipation of heat. As a result an apparent relationship between hypohydration and impaired exercise performance may be better explained by a relationship between hypohydration, inadequate convective cooling, heat retention and impaired exercise performance. It
should be noted that the environmental conditions created in this experiment faithfully reproduce real conditions present in out-of-doors competition in which high rates of evaporative cooling are a predictable consequence of the rapid speed of travel.

Participants started every condition at the same PO and approached the time trial similarly (Figure 7.3a). In addition, they had similar RPE scores among the conditions at the start of the time trial. Apparently, hydration status and thirst sensation at the start did not influence the manner in which participants started their time trials. According to the anticipatory model of Tucker (2009), the optimal rise in RPE is reflected in a linear pre-exercise template (RPE template). This template is a theoretical construct of an anticipated or "acceptable" RPE at any moment during exercise and is designed in such a manner that the RPE which is maximal tolerable will not be reached before the end of the race. Our findings indicate that the RPE template does not differ between EU, HYPO and FLUID with similar RPE scores at the beginning and end of the time trial. The development over time was the most linear in FLUID (Figure 7.5a), indicating a continuous all-out effort without uncertainty and an attempt to conserve a physiological reserve until the end spurt. Swart et al. (2009) showed that RPE does not always increase at a constant rate but depends on the certainty about the endpoint, duration of an exercise bout and the metabolic requirements. When an athlete has sufficient certainty regarding the exercise bout, homeostasis will be preserved. The availability of water and a lower thirst sensation from the start onwards in the FLUID condition may explain the linear RPE-profile (Figure 7.5a and 7.5b). To avoid catastrophic disturbances and reaching the maximal tolerable RPE before finishing, PO will be lowered over time in all conditions (Figure 7.3a). The decline in PO during the time trial is in line with other studies (Peiffer and Abbiss 2011; Tatterson et al. 2000).

An increase over time was seen in HR in all the conditions and the ratio HR/PO, which gives an indication of the HR needed for a certain amount of power, increased over time until the final 4 km (Figure 7.3c). Although no differences were found between the three conditions in PO, HR and HR/PO, it must be noted that from 16 km onwards, a slightly higher increase in HR/PO was seen in HYPO, suggesting that, compared to EU and FLUID, a
higher HR is required to generate the same PO. This increase might be due to hypovolemia, as a consequence of the hypohydration (Cheuvront et al. 2010; Gonzalez-Alonso et al. 2008), assuming that mechanical efficiency was approximately equal during all time trials.

Interestingly, ad-libitum fluid intake did not seem to affect the ability of participants to increase PO in anticipation of the end of the time trial (end spurt phenomenon) (Figure 7.3a). This suggests that, despite the different conditions, participants retained a similar reserve capacity until the end spurt. Moreover, final $T_{gi}$ in EU, HYPO and FLUID was 38.3 ± 0.5°C, 39.0 ± 0.5°C and 38.3 ± 1.0°C respectively, all values that are well below a critical core temperature of approximately 40°C (Galloway and Maughan 1997; Gonzalez-Alonso et al. 1999; Nielsen et al. 1993). This supports the theory that exercise and PO is regulated in an anticipated feed-forward manner to prevent a catastrophic failure. Hence, when participants are free to pace themselves, they down-regulate their PO and metabolic rate in anticipation to ensure that body heat storage does not reach critically high levels before the completion of the time trial (Dugas et al. 2009; Marino 2004; Tucker et al. 2006; Tucker et al. 2004). Not only thermal physiological signals, but also thermal perceptions may play a role in the selection of the initial exercise intensity and the pacing strategy during a time trial (Schlader et al. 2011a).

When individuals are (severely) hypohydrated, the body’s ability to dissipate heat will be reduced and the body heat content (reflected in $T_{gi}$) will increase faster (Maughan et al. 2007). In addition, $T_{sk}$ increases as a consequence of an increased skin blood flow to promote heat loss (Rowell 1974). However, in our study, temperature responses between the different experimental conditions were not different. Nevertheless, we need to be cautious with the interpretation of the data because fluid ingestion may itself have influenced the $T_{gi}$ measured by the capsule in the FLUID condition. It is well established that cool fluid intake can negatively influence the validity of the temperature capsules measurements (Byrne and Lim 2007; Wilkinson et al. 2008).
Although no effect of hydration status was found on PO, HR, HR/PO, $T_{\text{Glu}}$, $T_{\text{sk}}$, RPE, TS and TC, an effect of hydration status on thirst sensation was found. It seems evident that the ingestion of fluid contributes to this effect, because hydration status has a clear effect on thirst sensations (Fitzsimons 1976; Noakes 2010; Sawka and Noakes 2007). Since thirst sensation is a conscious perception of homeostatic disturbances in plasma osmolality (Noakes 2010; Sawka and Noakes 2007), it might be a relevant feedback signal for the anticipatory regulation of exercise intensity during self-paced exercise. In order to preserve homeostasis, fluid intake may be increased or exercise intensity will need to be lowered. In this way, the sensation of thirst, rather than the reduction in BM may cause the (down-)regulation of exercise intensity (Noakes 2010; Sawka and Noakes 2007).

Despite the absence of differences in PO, it can be observed that a higher thirst sensation is accompanied by a greater decrease in exercise intensity in all conditions (Figure 7.3a and 7.5b). However, in the present study, a lower thirst sensation did not result in performance improvements.

In addition to BM and fluid losses, also the rate at which intracellular and extracellular fluid are replaced may play an important role in the regulation of work rate and thirst sensation. The gastric emptying rate (GER) is influenced by many factors such as hydration status and the amount of fluid in the stomach (Ryan et al. 1998). During exercise GER is approximately 1 L·h$^{-1}$. Since the mean fluid intake in the FLUID condition was 1.4 ± 0.6 L, it is not likely that the stomach was fully emptied and all the ingested fluid had entered the intracellular and/or extracellular milieu. As a consequence, beneficial changes due to the complete restoration of intracellular and extracellular fluids spaces may not have occurred and may explain why no differences were found in performance outcomes. However, we did find differences in thirst sensation between EU, HYPO and FLUID. Since GER is too slow for full restoration of fluids, GER cannot fully account for these differences. Also, it is not likely that sensor receptors in the mouth account for performance differences because Dugas et al. (2009) found that exercise performance did not improve when the mouth was rinsed with water. Therefore, we assume that the differences are caused by psychological rather than physiological effects. Maybe, the opportunity to drinking itself already decreases thirst sensations.
CONCLUSION

We did not find a detrimental effect of hypohydration on exercise performance during a 40-km cycling time trial. Also, when participants began the time trial hypohydrated, drinking ad-libitum during the time trial did not enhance exercise performance or counteract any performance effects. The high air velocity and the associated greater capacity for evaporative cooling could have reduced the relevance of hydration status and thirst sensation in this study.