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**Provision of instructions to drink *ad libitum* or according to thirst sensation:
impact during 120 km of cycling in the heat in men**

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Running Head: *Ad libitum* vs. thirst drinking during prolonged cycling

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Abstract

The terms drinking to thirst and *ad libitum* drinking are used interchangeably, but should they? We investigated the differences in how athletes consume fluids during exercise when instructed to drink according to thirst or *ad libitum*. Using a randomized, crossover and counterbalanced design, 10 males (27 ± 4 y) cycled 120 km ($48 \pm 4\%$ of peak power, 33°C , 40% relative humidity) on two occasions, while drinking water according to thirst or *ad libitum*. Participants covered the cycling trials in 222 ± 11 min ($p = 0.29$). Although the body mass loss at the end of exercise and total volume of water consumed were similar between trials, thirst perception before each sip and the volume consumed per sip were significantly higher with thirst than *ad libitum* drinking, whereas the total number of sips was significantly lower with thirst than *ad libitum* drinking. Perceived exertion, rectal temperature and heart rate were all significantly higher with thirst than *ad libitum* drinking, but the difference was trivial. In conclusion, thirst and *ad libitum* drinking are associated with different drinking patterns, but equally maintain fluid balance during prolonged exercise. The terms drinking to thirst and *ad libitum* drinking can be used interchangeably for guiding fluid intake during prolonged exercise.

Keys-words: *ad libitum*; drinking; fluid intake; hydration; perception; thirst

NOVELTY

- Both strategies are associated with different patterns of fluid ingestion during prolonged exercise, but are equally effective in maintaining fluid balance;
- Perceived exertion, rectal temperature and heart rate are regulated dissimilarly by thirst and *ad libitum* drinking, but the difference is trivial.

Draft

INTRODUCTION

Exercise-induced dehydration may impact physiological functions, perceptual sensations and performance (Cheuvront and Kenefick, 2014). More specifically, it has been shown that in a state of dehydration endurance performance can sometime decrease, and heart rate, core temperature, thirst and perceived exertion increase (Cheuvront and Kenefick, 2014, Periard et al., 2021). Hence, adequate fluid replacement during exercise is important. In that respect, recommendations on fluid intake during endurance exercise have evolved over the past 6 decades, progressing from 1) the consumption of only a small volume of liquids in the 1960s (Coyle, 2004), 2) the frequent ingestion of fluids during competitions in the 1970s (ACSM, 1975), 3) the recommendation for runners to ingest 100-200 mL every 2-3 km in the 1980s (ACSM, 1987), 4) the full replacement of sweat and urine losses in the 1990s (Convertino et al., 1996), 5) encouraging to limit the body mass losses $< 2\%$ (Casa et al., 2000, McDermott et al., 2017, Sawka et al., 2007) in the 2000s and 2010s and, 6) the recommendation to drink based on thirst sensation (Hew-Butler et al., 2015, Hew-Butler et al., 2006) in the 2000s and 2010s. Although the rationale underlying the use of the current recommended drinking strategies (i.e., to limit the loss of body mass $< 2\%$ or drink according to thirst) differ, their impact on endurance performance seems undistinguishable (Goulet and Hoffman, 2019). This is critical, as it allows athletes to decide which strategy may be most suitable depending on the racing or training circumstances.

Although the drinking strategy based on the gauge of body mass loss requires, for adequate fluid replacement, the knowledge of exercise-related intensity, temperature, humidity level, sweat rate and urine production (Sawka et al., 2007), that based on thirst sensation requires only the reliance on perceived thirst to adjust fluid replacement (Dion et al., 2013).

Whereas the goal of the former strategy is to maintain body water within a certain range, the goal of the latter is to maintain plasma osmolality within physiological limits, irrespective of the extent of body water losses (Sawka and Noakes, 2007). Albeit the replacement of a fixed amount of fluid during exercise is a relatively straightforward process, that of drinking according to thirst sensation may not be, as several athletes may struggle to distinguish the act of drinking based on thirst solely and drinking *ad libitum*.

Drinking to thirst may be defined as the process of drinking only when one feels thirsty, with the goal of decreasing thirst to an individually-based and physiologically acceptable level, using only the necessary volume of fluid (McDermott et al., 2017). On the other hand, *ad libitum* drinking represents the act of drinking whenever one wants, at whatever desired volume one wants (Kenefick, 2018, McDermott et al., 2017), irrespective of the presence of thirst. Because the concept of thirst may substantially differ from one individual to the other, and that “thirst” cannot be separated from the concept of *ad libitum* drinking, certainly creates confusion. Hence, drinking to thirst and *ad libitum* drinking are frequently used synonymously and interchangeably in the literature.

Armstrong et al. (2014) compared two groups of cyclists who were asked to drink *ad libitum* or according to thirst during prolonged cycling in the heat. They observed that both strategies resulted in similar fluid consumption and physiologic and perceptual outcomes. However, this study has important limitations that substantially reduce the applicability of its findings. First, participants were recruited based on their self-reported habitual fluid intake during exercise, i.e., whether they were drinking according to thirst or a plan. But, what if we would ask and specifically instruct an athlete who does not follow any particular drinking strategy during exercise to drink either *ad libitum* or based on its thirst during

exercise? Would he/she be able to understand the subtleties between these strategies? Given that both terms are used interchangeably, it appears critical, from an education standpoint, to provide an answer to this question. Second, exercise intensity, which influences heat production and therefore sweat losses and potentially fluid intake was not controlled for. Finally, food intake was not standardized during exercise; this is not irrelevant, as sodium intake differed significantly between conditions. Additionally, due to the nature of their research design, Armstrong et al. (2014) could not identify potential fundamental difference between hydration strategies regarding drinking frequency, volume of fluid per sip, thirst perception prior to drinking or drinking pattern changes over time. (Valentine, 2007)(Valentine, 2007)(Valentine, 2007)Therefore, this study aimed to provide answers to the following questions during 120 km cycling trials: 1) when clearly explained to athletes and distinguished by them, do these strategies lead to different volumes of water intake and, therefore, different levels of dehydration?; 2) do these hydration strategies lead to different drinking frequencies, number of sips or volumes of fluid consumed with each sip?; 3) how do these strategies affect perceived exertion and thirst perception? and; 4) do these hydration strategies impact physiological functions, heart rate and rectal temperature similarly?

METHODS

Participants

Ten endurance-trained, non-heat-acclimatized healthy male cyclists and triathletes were recruited to participate in this study, which was approved by the CIUSSS Estrie-CHUS Ethics Committee (#2020-3459). Their baseline physical characteristics are reported in Table 1. At the time of the study participants had a cycling experience of at least 4 y and were performing 8 h of aerobic training per week. Written informed consent was obtained

from each participant after explaining the procedures and risks of the study. Since they could not be blinded to the interventions, research hypotheses were not explained to participants. All experimentations were performed in North America from the end of October to the beginning of January.

Overview of the experiment

Following a preliminary visit where baseline measurements were taken, participants took part in two cycling experiments performed in an environmental chamber where they were requested to drink either based on their thirst sensation or *ad libitum*. Conditions were administered in a randomized, crossover (i.e., participants acted as their own control) and counterbalanced fashion. Experiments were performed at the same time of the day and separated by 3 to 14 days.

Preliminary visit

Following explanations of the study's procedures, participants filled a health form. They were then thoroughly instructed about the definitions of drinking to thirst and *ad libitum* drinking. The definition of drinking to thirst was provided as follows: you (the athlete) should have an attention on the presence of thirst as the only stimulus for drinking (Armstrong et al., 2014, McDermott et al., 2017). Thirst is caused by dehydration and it is associated with physiological sensations. You should rely exclusively on them, alone or in combination, to consume liquid. These sensations are a dryness in the mouth and throat in association with a desire for liquids (Brunstrom, 2002, Hew-Butler et al., 2006) and thoughts about, and an important desire for, getting water in the mouth (McDermott et al., 2017). The definition of drinking *ad libitum* was provided as follows: you (the athlete) can drink at any time during the exercise, according to your desire, without rules or patterns to

respect, and without limits for the volume to be consumed (Valentine, 2007). In other words, to drink *ad libitum* is to drink whenever, and in whatever quantity you want, without worrying about thirst sensation and without necessarily having a predetermined plan of liquid ingestion, although this may be possible (Kenefick, 2018, Sawka and Noakes, 2007). Once these concepts were well understood, measurements of resting blood pressure and heart rate were taken with a digital sphygmomanometer (Welch Allyn 420 series, Skaneateles Falls, NY, USA). Subsequently, a post-void nude body mass was taken with a digital scale (± 20 g, BX-300 +, Atron Systems, West Caldwell, NJ, USA) and height with a wall stadiometer. Afterwards, body composition was measured using dual-energy X-ray absorptiometry (Lunar Prodigy, GE Healthcare, Chicago, IL, USA). Finally, peak oxygen consumption ($\text{VO}_{2\text{peak}}$) was measured with participants using their own bike mounted on a calibrated Computrainer™ (Racermate, Seattle, WA, USA) (Perreault-Briere et al., 2019). Gas exchanges were measured by a gas analysing system (Cosmed Quark CPET, Cosmed, Chicago, IL, USA) that had been calibrated with gases of known concentration. From the relationship between power output (measured as the mean power output during the last minute completed) and O_2 consumption, a power output corresponding to 50-80% of $\text{VO}_{2\text{peak}}$ was then computed.

Pre-experimental procedures

For 48 h before the first experimental visit participants maintained and completed a dietary log. Participants reproduced this log for the last 48 h prior to the second visit. Dietary supplements, as well as lower body strength training, were forbidden for 48 and 72 h before each experimental visit, respectively. Such to arrive at the laboratory in an euhydrated state, participants had to drink 250 mL of tap water 60 min before going to bed the night before

the experimentations and 60 min before arriving at the laboratory. Following drinking 60 min before arrival at the laboratory participants were requested to refrain from food and fluid intake. Physical training was controlled for the last 24 h prior to each experimentation. In that respect, participants could choose between 3 options: rest, 45 min of light training or a pre-competition typical training. They had to replicate their choice prior to the second experimental visit.

Experimental protocol

Arrival at laboratory

Upon arrival, participants' cycling clothes and shoes were weighed. Afterwards, participants voided their bladder and collected a midstream urine sample for urine specific gravity and osmolality assessment. Then, participants inserted a calibrated telemetric probe passed the anal sphincter for rectal temperature measurement. Subsequently, they dressed and were instrumented with a chest electrode to measure heart rate. Finally, body mass was measured. Prior to entering the environmental chamber participants were told about their drinking condition and their comprehension about the definitions were verified and confirmed.

Experiments

Immediately after entering the environmental chamber, participants sat down on their bike with their left hand immersed in 30°C water for 5 min. Then, a capillary blood puncture was performed, as explained in Perreault-Briere et al. (2019). After this procedure, participants underwent a 120 km cycling ride on a virtual flat course simulated by a calibrated Computrainer™. During their first experiment, participants could maintain a self-selected exercise intensity that was within 50-80% of their $\text{VO}_{2\text{peak}}$. They were asked

to replicate this ride during the second experiment, aiming to maintain a power output within $\pm 5\%$ of their first ride. Hence, participants were given feedback on their average power output every 15 min during the second experiment. During exercise participants had continuous access to their riding time, speed and power output. Experiments were performed at 33°C with 40% of relative humidity, and 3 fans placed in front of them provided wind at ~25 km/h.

Water was served at room temperature in an opaque and insulated bike water bottle placed on a desk in front of the participants. Every 30 min participants consumed energy gels (GU Energy gel, Lemon Sublime). Carbohydrate intake was individualized and maintained constant between conditions (mean: 0.8 ± 0.2 g/kg/h, range: 0.5 to 1.2 g/kg/h). Heart rate, rectal temperature, perceived thirst, perceived exertion and total volume of fluid consumed were measured every 6 km. Moreover, perceived thirst was measured prior to each sip. Capillary blood punctures were performed at 60 km and immediately following the ride. After exiting the environmental chamber, participant towed themselves, were weighed and urinated.

Measurements

Heart rate was measured with a Garmin™ electrode (Garmin, Olathe, KS, USA), rectal temperature with a CorTemp (HQ Inc, USA) telemetric pill (Gosselin et al., 2019), perceived thirst with an 1-11 arbitrary scale (Goulet et al., 2008), perceived exertion with a 6-20 RPE Borg scale (Borg, 1982), hemoglobin by spectrophotometry (Alere H2 Hemopoint, Alere, Lowell, MA, USA), hematocrit by micro centrifugation, whole blood sodium concentration using the ion selective electrode technique (Easy Electrolytes, Medica, USA) and whole blood osmolality by freezing point depression (Micro

Osmometer, Osmette, Precision Systems Inc.). Changes in plasma volume were computed using the Dill and Costill equation (Dill and Costill, 1974). Fluid volume was measured with a digital scale (Symmetry, Cole-Parmer). Percent dehydration was taken as the difference between post-void pre- and post-exercise body mass relative to pre-exercise body mass, with corrections for carbohydrate intakes. Sweat loss was calculated from the difference in body mass measured at the end of exercise, corrected for fluid and energy gels intakes as well as urine losses. Sweat loss was divided by exercise duration to obtain sweat rate. A sip of water was taken as the total amount of fluid consumed by the athletes between the moment they removed the bottle from the desk to the one where they placed it back on the desk. Drinking bottles were weighed once full, prior to be placed for the first time on the desk, and then following each sip, which allowed to precisely determine the amount consumed during each sip. Only one water bottle was present at any moment on the desk during the trials. That water bottle was replaced randomly across time by a full one to ensure that participants could not keep track of their fluid intake. Loss of mass associated with respiratory water loss and the respiratory exchange of O₂ and CO₂ during exercise were not considered and assumed to be similar among trials. The percentage of sweat loss replaced was calculated by dividing the water consumed by the sweat loss.

Statistical analyses

Data were analyzed using the IBM SPSS Statistics software (Version 26, New York, Armonk, NY, USA) and are presented as means $\pm$ standard deviations (including figures) and, on occasions, 95% confident intervals (CI). Data normality was verified with a Shapiro–Wilk test. Paired t-tests (or Wilcoxon signed ranks test when abnormally

distributed), two way (condition $\times$ time) repeated measures analysis of variance (ANOVA) and linear mixed-effects models (in cases of missing values) were used to evaluate statistical significance of all the variables measured. Greenhouse–Geisser corrections were applied when sphericity was violated. In case of significant interaction effects, multiple pairwise comparisons were performed and corrected with the false discovery rate procedure. Statistical significance was set *a priori* at $p < 0.05$. All presented data are $n = 10$ unless stated otherwise. Because of inter- and intra-participants differences throughout time, data regarding the number of sips, volume of water per sip and thirst perception before each sip were analyzed based on percentage of total exercise duration. In this case, for each participant and condition, exercise time was divided into six equal parts representing 17, 33, 50, 67, 83 and 100% of exercise duration.

Based on the type of research protocol used (counterbalanced), a standard deviation of 220 mL/h associated with the normal variation in thirst-driven fluid consumption during a 1 h cycling exercise (pilot study from our laboratory) and an α coefficient of 0.05, a sample size computation revealed that 10 participants provided an 89% chance to detect a difference in fluid consumption of 250 mL/h between conditions.

RESULTS

Hydration status prior to the trials

Indices of hydration found in Table 2 indicate that participants began both exercise trials well-hydrated and in a similar state of hydration.

Cycling trials duration and intensity

Participants covered the 120 km cycling rides at an average time of 222 ± 11 min without difference between conditions ($p = 0.29$). Participants maintained a mean power output of 188 ± 25 W ($\Delta_{\text{ad libitum-thirst drinking}} = 0$ W, 95% CI: -6-6 W, $p = 0.99$) during exercise, representing a mean exercise intensity of $48 \pm 4\%$ of peak power output or $57 \pm 4\%$ of $\text{VO}_{2\text{peak}}$.

Fluid balance

Fluid loss

Sweat rate was not different between conditions, with a mean value of 1.3 ± 0.2 L/h ($\Delta_{\text{ad libitum-thirst drinking}} = -0.03$ L/h, 95% CI: -0.08-0.02 L/h, $p = 0.25$). Following exercise, participants produced a similar amount of urine (thirst drinking: 172 ± 106 mL, *ad libitum* drinking: 197 ± 143 mL, $p = 0.58$). Body mass loss was similar across conditions at the end of the exercise (thirst drinking: 3.1 ± 1.2 , *ad libitum* drinking: $2.8 \pm 0.8\%$, $p = 0.38$).

Fluid intake

There was no order effect for total fluid consumption during exercise. During their first experiment, participants consumed an average of 2894 ± 948 mL, compared to 2634 ± 674 mL for their second experiment ($p = 0.22$). The first sip of water following the onset of exercise was taken on average at 8 ± 7 min with *ad libitum* drinking, compared to 19 ± 20 min with thirst drinking ($p = 0.09$). On average, each sip of water was interspersed by 7 ± 3 min and 10 ± 6 min ($p = 0.08$) with *ad libitum* and thirst drinking, respectively. Figure 1 depicts fluid intake accumulation during exercise with *ad libitum* and thirst-driven fluid

intake. Overall, no significant difference was found between conditions (thirst drinking: 2714 ± 933 mL, *ad libitum* drinking: 2815 ± 718 mL, $p = 0.65$). Five participants drank more fluid in the thirst condition. Percent of sweat loss replaced was $54 \pm 16\%$ with thirst drinking compared to $58 \pm 11\%$ with *ad libitum* drinking ($p = 0.45$). Figure 2 shows the number of sips (a), volume of water per sip (b) and thirst perception before each sip (c) through time. Mean number of sips increased over time ($p = 0.01$) and was higher with *ad libitum* than thirst drinking ($p < 0.01$) without interaction effect ($p = 0.14$). The total number of sips was higher ($p = 0.02$) with *ad libitum* (34 ± 15) than thirst drinking (29 ± 16). The volume of water per sip increased over time ($p < 0.01$) for both drinking strategies, with a condition (109 vs. 95 mL, $\Delta_{\text{ad libitum-thirst drinking}} = -14$ mL, 95% CI: $-20 - -9$ mL, $p < 0.01$) and an interaction ($p = 0.03$) effect. Post-hoc analyses revealed a difference between conditions at 67 and 83% of total exercise time only (both $p < 0.01$), with a trend at 50% ($p = 0.07$). Thirst perception before each sip was higher with thirst compared to *ad libitum* (6 vs. 5 arbitrary unit, $\Delta_{\text{ad libitum-thirst drinking}} = -1$, 95% CI: $-1.1 - -0.8$, $p < 0.01$) drinking, with a time ($p < 0.01$) but no interaction ($p = 0.37$) effect.

Blood and urine variables

Figure 3 shows that plasma volume (a) decreased and whole blood osmolality (b) increased over time (both $p < 0.01$), without a condition ($p = 0.51$ and 0.29) or an interaction effect ($p = 0.60$ and 0.74). Accordingly, time ($p < 0.01$) but neither condition ($p = 0.93$) nor interaction ($p = 0.97$) effects were observed for whole blood natremia (c). Both, urine osmolality ($+200 \pm 245$ vs. -27 ± 223 mOsm/kg; $p = 0.03$, $n = 9$) and specific gravity ($+0.007 \pm 0.008$ vs. $+0.001 \pm 0.005$ g/mL; $p = 0.04$, $n = 9$) increased more in *ad libitum* compared to thirst drinking.

Rectal temperature, heart and perceived exertion

Figure 4 shows rectal temperature (a), heart rate (b) and perceived exertion (c) responses throughout exercise. Rectal temperature increased over time ($p < 0.01$), with condition ($p < 0.01$) but no interaction effects ($p = 0.94$). The same pattern was observed for heart rate and perceived exertion, with time and condition (both $p < 0.01$) but no interaction effects ($p = 1.0$ and 0.06 , respectively). Average rectal temperature, heart rate and perceived exertion during exercise were $38.8 \pm 0.6^{\circ}\text{C}$, 151 ± 19 beats/min and 12 ± 2 arbitrary units with *ad libitum* drinking compared to $39.0 \pm 0.7^{\circ}\text{C}$, 156 ± 21 beats/min and 13 ± 3 arbitrary units for thirst drinking (all $p < 0.01$).

DISCUSSION

This is the first study to investigate the drinking patterns of athletes specifically educated and required to drink either to their thirst sensation or *ad libitum* during a prolonged cycling exercise conducted in a warm controlled environment. Our main goal was to determine whether the subtleties between drinking strategies could be consciously detected by athletes and lead to different discernable changes in fluid intake patterns during exercise. Although our results show that athletes drank less often and were thirstier before each sip while drinking according to thirst sensation compared with *ad libitum* drinking, they compensated by drinking more important volumes during each sip, which ultimately resulted in a similar total volume of fluid consumed between conditions at the end of exercise. These results indicate that unless athletes decide to drink such to maintain their loss of body mass during exercise under a particular target, they do not need to receive specific instructions on how to drink during exercise.

We observed no significant difference in total fluid consumption nor in final body mass loss between drinking strategies. These finding agree with and confirm those made by

Armstrong et al. (2014) during a field study consisting in a 164 km cycling ride conducted at 35.5°C. The reproduction of Armstrong et al.'s, (2014) observations is important, given that the nature of their study where potential confounders could not be controlled as easily as during a controlled laboratory study might have led to misleading conclusions. In the present study, we educated athletes and provided specific cues enabling them, we hoped, to differentiate both drinking strategies. It appears that participants had well understood the subtleties and differences between the drinking conditions since thirst perception before each sip was always higher in the thirst vs. the *ad libitum* drinking condition throughout exercise. Therefore, evidence from our controlled study suggests that although athletes may consciously differentiate between *ad libitum* vs. thirst drinking, when thereupon properly educated, ultimately both drinking strategies will maintain fluid intake and body mass loss to similar levels, at least during prolonged cycling exercise.

Neither drinking strategies could maintain the loss of body mass $< 2\%$. This threshold is potentially critical given that, according to Cheuvront et al. (2003), a loss of body mass $> 2\%$ should consistently be associated with a decrement in endurance performance, although this assertion has been challenged (Goulet, 2011). Moreover, sweat and urine losses should not be totally replaced during exercise such to prevent the development of hyponatremia (McDermott et al., 2017). Armstrong et al. (2014) have also demonstrated that neither drinking according to thirst sensation nor *ad libitum* drinking could prevent a loss of body mass $> 2\%$. In a controlled laboratory study, Dugas et al. (2009) showed that *ad libitum* drinking could also not maintain the loss of body mass $< 2\%$ during an 80 km cycling time-trial conducted at 33°C. Taken together, these results suggest that, unless athletes force their intake of fluid beyond what they would naturally do while drinking

based on their thirst sensation or drinking *ad libitum*, the prevention of a 2% body mass loss or full replacement of sweat and urine losses during prolonged cycling in the heat is unlikely.

Although both drinking conditions led to a similar total fluid consumption during exercise, the roads taken by each strategy to get to this common destination were different. Indeed, thirst drinking was associated with longer delays between sips and, as a result, less sips in total, the combination of which likely explains why perceived thirst sensation before each sip was systematically higher with thirst than *ad libitum* drinking. Mathematically, then, the only way total fluid consumption could match up between conditions was that during each sip fluid intake needed to be greater with thirst than *ad libitum* drinking, which is what we observed. These results highlight fundamental differences between these hydration strategies regarding the regulation of fluid intake during prolonged cycling. Their implications are not clear, but may potentially imply that independently of whether fluid intake is consciously (through thirst) or unconsciously (*ad libitum*) driven, thirst and *ad libitum* drinking will be equally effective at maintaining body fluid homeostasis. To this effect, blood and urine markers of fluid balance were similar between conditions following exercise and within the normal physiological range. Although speculative, the behavior associated with *ad libitum* drinking may have been driven by the integration of signals from the oral cavity and the composition of the blood at the brain level, which would predict how ongoing water consumption alters fluid balance in the future so as to be able to adjust drinking behavior accordingly (Zimmerman et al., 2016).

Interestingly, significant statistical differences were found in rectal temperature and heart rate between hydration conditions. These differences are not easy to explain from a

physiological standpoint. Indeed, total fluid consumption and changes in body mass loss, plasma volume, whole blood osmolality and whole blood sodium levels were similar between drinking conditions at the end of exercise. Notwithstanding, the greater heart rate and rectal temperature observed with thirst drinking should not be taken lightly as, in combination with a greater perception of thirst, could possibly explain the difference in perceived exertion observed between hydration conditions. And perceived exertion could predict exercise capacity and explain changes in pace and pacing strategy (Eston, 2012). Murray et al. (1995) demonstrated that the rate of fluid consumption during exercise impacts heart rate and perceived exertion. They had subjects complete a 1 h cycling bout at 32°C while providing them with 400 mL of water immediately prior to exercise and then, in one condition, 100 mL every 5 min and, in the other, 200 mL every 10 min, thereby ensuring to maintain fluid balance between conditions. They observed, as in the current study, that the greater rate of fluid intake decreased heart rate and perceived exertion, although not significantly. They reported no difference in oral temperature between conditions, which is not surprising given the poor validity of this measurement site. It is, therefore, highly possible that our observations could be explained by this phenomenon, as not only the rate of fluid intake was lower with thirst vs. *ad libitum* drinking, but the accumulated fluid volume at each time point was also lower, although this did not reach significance. Albeit the differences in rectal temperature (0.2°C), heart rate (5 beats/min) and perceived exertion (1 unit) were relatively trivial between conditions and unlikely to be significant from a performance and health standpoint, these findings may nevertheless have potential practical implications. Indeed, they imply that athletes should not be

encouraged to focus on their thirst perception to guide fluid intake during prolonged exercise, if protecting physiological functions and perceptual sensation is the ultimate goal. There are some limitations that need to be considered when interpreting the current results. Participants were not familiarized with any of the drinking conditions. Whether this might have changed the findings is unclear. However, we acknowledge that it might take some time for an athlete to master the art of drinking according to thirst sensation. During the drinking to thirst trial, participants' attention was heavily focused on recognizing the thirst-associated signs. This might have potentially influenced the rating of perceived exertion and of perceived thirst. Warm water was served to participants. Had participants been provided cool water or a cool sports drink might have impacted findings. Indeed, their palatability is enhanced compared with warm water (Burdon et al., 2012, Passe et al., 2004). Also, we cannot exclude the possibility that different instructions regarding thirst or *ad libitum* drinking might have led to different observations. Finally, our results only apply to men.

In conclusion, the current results indicate that although thirst and *ad libitum* drinking are associated with different drinking patterns during prolonged exercise, ultimately both are equally effective at maintaining fluid balance. Thirst drinking is associated with a lower frequency of drinking during prolonged exercise, which may result in an increased heart rate, rectal temperature and perception of effort compared with *ad libitum* drinking. However, these physiological and perceptual alterations are likely to be inconsequential from a performance and health perspective. This needs to be confirmed in future studies.

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CONFLICT OF INTEREST

The authors report no conflict of interest.

AUTHORS CONTRIBUTION

P.C. and E.D.B.G conceived and designed the research. P.C., T.A.D., D.J. and T.P performed the experiments. P.C., T.A.D. and E.D.B.G performed the statistical analyses, designed the figures, interpreted the results and drafted the first draft of the manuscript. All the authors revised and approved the final draft.

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DATA AVAILABILITY STATEMENT

The data will be made available from the corresponding author upon reasonable request.

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Tables

Table 1. Baseline characteristics of the participants.

Characteristics	Mean ± SD
Age (y)	27 ± 4
Height (cm)	178 ± 7
Body mass (kg)	74 ± 5
Fat mass (%)	11 ± 2

Lean body mass (%)	86 ± 2
Resting systolic blood pressure (mmHg)	126 ± 10
Resting diastolic blood pressure (mmHg)	72 ± 5
Resting heart rate (beats/min)	66 ± 12
Peak oxygen consumption (mL/kg/min)	60 ± 3
Peak power output (W)	395 ± 44
Relative peak power output (W/kg)	5.3 ± 0.5

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Table 2. Hydration state before experimentations.

Parameters	<i>Ad libitum</i>	Thirst	<i>p</i> -value
Body mass (kg)	73.5 ± 5.1	73.4 ± 5.0	0.96
Urine specific gravity (g/mL)	1.008 ± 0.007	1.013 ± 0.008	0.03
Urine osmolality (mOsm/kg)	362 ± 254	581 ± 283	0.02
Whole blood osmolality (mOsm/kg)	297.7 ± 3.6	297.6 ± 3.3	0.96
Whole blood natremia (mmol/L)	139.2 ± 0.9	139.0 ± 1.3	0.76

Heart rate (beats/min)	86 ± 12	89 ± 13	0.26
Thirst perception (AU)	4 ± 2	4 ± 1	0.56

Results are mean ± SD. AU: arbitrary units. *n* = 9 for urine osmolality and heart rate.

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Figure legends

Figure 1.

Fluid intake accumulation through time in both conditions. Δ: difference of fluid intake between *ad libitum* and thirst drinking (a positive value corresponds to higher intake in *ad libitum*). Overall represents the total fluid intake.

Figure 2.

Number of sips (a), volume of water per sip (b) and thirst perception before each sip (c) through time in both conditions. AU: arbitrary unit. *: $p < 0.05$ between conditions when an interaction effect was observed.

Figure 3.

Changes in plasma volume (a) whole blood osmolality (b) and whole blood natremia (c) over time in both conditions.

Figure 4.

Rectal temperature (a), heart rate (b) and perceived exertion (c) responses throughout exercise in both conditions. AU: arbitrary unit.

Figures

Figure 1.

Figure 2.

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Figure 3.

Figure 4.