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Thirst sensitivity to post-exercise fluid replacement needs and controlled drinking

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ABSTRACT

Purpose: Thirst was evaluated as a dependent variable, to see if perceived thirst (TP) can clearly distinguish among several levels of acute dehydration, and if so, how it responds over time to the ingestion of a predetermined volume of water post exercise. TP reliability was also evaluated.

Methods: in a repeated-measures design, eight physically active students (24.5±3.6 years, mean±standard deviation), reported to the laboratory after an overnight fast (10 hours or longer), on four non-consecutive days. They exercised intermittently in a controlled climate chamber at 32±3°C db and 65±6% r.h. to a randomly assigned dehydration equivalent to 0, 1, 2 and 3% of body mass (BM). Following exercise, subjects ingested a fixed volume of water equivalent to 1.20% BM in 30 minutes; urine output, TP and plasma volume changes were measured every 30 minutes over 3 hours.

Results: Baseline characteristics were not different among conditions ($p>0.05$). TP was not different before taking a shower from 30 minutes later after showering ($p = 0.86$), but it was clearly different among conditions after exercise (TP = 2.50 ± 0.45, 4.44 ± 0.72, 6.38 ± 0.82, and 8.63 ± 0.18 for 0, 1, 2, and 3% BM, $p = 0.001$). TP was already the same for all conditions 30 min after drinking, (1.1±0.3, 1.1±0.3, 2.6±1.4, and 3.3±2.3 for 0, 1, 2 and 3% BM, respectively, $p>0.05$); it remained so for 3h. There was a clear association between TP and net fluid balance ($r_{part} = -0.62$, $p < 0.0001$).

Conclusion: this subjective scale of thirst perception is able to detect dehydration equivalent to 2% BM or greater. The measure is reliable, and it shows a clear, significant association with net fluid balance. It is, however, disproportionately reduced in dehydrated subjects after acute

ingestion of water. Under these conditions, we deem thirst to be insufficient as it responds inappropriately to water intake.

KEYWORDS: Dehydration: *prevention and control. Voluntary Fluid Intake. Drinking behavior: *physiology. Thirst: *physiology. Humans. Water-electrolyte balance: *physiology.

INTRODUCTION

When humans exercise in the heat, they may incur dehydration to an extent that impairs performance; on the other hand, it is possible for triathletes, marathon, and ultramarathon runners, to drink too much, resulting in asymptomatic and even symptomatic hyponatremia (Sawka et al. 2007). Different fluid replacement guidelines have been developed over time, trying to find a well-documented balance between the extremes of drinking too much and drinking too little. These guidelines, however, have been strongly criticized, to the extreme of suggesting they are more influenced by commercial interests than science (Cohen 2012).

Drinking according to thirst has been advocated as the perfect solution to supplying needed fluids to exercising humans, but the advice has been handed out with scant experimental support. At the same time, there is evidence that thirst may not be enough (Maughan et al. 2005, Passe et al. 2007, Shirreffs et al. 2004, Solera & Aragón 2006), if *enough* means achieving zero net fluid balance at the end of observation, not only on average but for each individual. When the issue at hand is performance, there are very few studies supporting the claim that drinking to thirst during exercise works well for athletes (e.g. Goulet, 2011). To date, drinking to thirst remains an appealing yet not well supported strategy for adequate hydration during and after exercise.

The physiological mechanisms associated with the detection and correction of cellular and extracellular fluid losses have been widely studied in animals and humans, but mostly in sedentary conditions (Adolph & Dill 1938, Corbit 1968, Fitzsimons 1931, Johnson 1990, Johnson & Thunhorst 1997, Obika et al. 2009, Sagawa et al. 1992). While some of these mechanisms defend homeostasis by limiting additional fluid or sodium losses, it is only through the integration of input from several sources that the brain produces the neural state associated with thirst which will, in turn, cause the behaviors to replace water and sodium loss. Thirst is a perception, “the subjective experience evoked by fluid deficits” (Engell et al. 1987, p. 229) or, as explained by Johnson (2007), a motivational mechanism for the acquisition and consumption of water, created in the brain as the synthesis of multiple sources of information, both physiological and psychological.

A crucial question is whether thirst *per se*, understood as the drive to drink, is accurate and strong enough to result in the replacement of sweat losses from exercise and maintain euhydration. Most studies related to this question have relied on monitoring voluntary fluid intake during exercise, a surrogate measure of thirst (Passe et al. 2007, Peacock et al. 2012, Peacock et al. 2013, Rivera-Brown et al. 1999, Rivera-Brown et al. 2008, Scaglioni 2009, Shirreffs et al. 2005, Wilk et al. 2007). Voluntary fluid intake is, however, influenced by external factors such as the so-called Hawthorne effect (a change in behavior induced by the awareness of being observed) (McCarney et al., 2007), ambient conditions and, of course, beverage temperature and composition (Hubbard et al. 1984, Hubbard et al. 1990, Rivera-Brown et al. 1999, Rivera-Brown et al. 2008, Szlyk et al. 1989).

Several researchers have combined subjective reports of thirst with measures of voluntary fluid intake during or after exercise (Brown et al., 2011, Maresh et al., 2004). This latter approach makes sense, but it has an important limitation, the possible confounding between cause and effect: higher thirst may drive a larger fluid intake, but fluid intake may in turn shut off thirst, independent of hydration status.

The complexity of this topic warrants addressing one question at a time. This is more feasible with a post-exercise rehydration protocol than looking at hydration during exercise. The purpose of the present study was to evaluate thirst solely as a dependent variable: to see if perceived thirst can clearly distinguish among several levels of acute dehydration, and if so, how it responds over time to the ingestion of a predetermined volume of water post exercise. In addition, we evaluated reliability for the thirst scale we used (Engell et al., 1987). We expected this information to shed some light on the plausibility of thirst functioning as a good measure of rehydration needs after exercise and sweat loss.

MATERIALS AND METHODS

Eight apparently healthy, physically active students (4 males, 4 females) age = 24.5 ± 3.6 y.o., weight = 73.09 ± 12.67 kg, and height = 169.2 ± 6.1 cm (mean ± S.D.) signed an informed consent prior to participation in this study, approved by the institution's Ethics and Science Committee. The experiment was part of a larger study designed to understand the diuretic response to a constant load of water. Each participant visited the laboratory on four different non-consecutive days, one for each dehydration condition, in a repeated-measures design; the order of tests was randomized.

Procedures

Pre-dehydration and dehydration procedures for this type of study are commonly used (see Capitán-Jiménez & Aragón-Vargas, 2012). Briefly, each participant reported to the laboratory at 7 a.m. after an overnight fast (at least 10 hours without solids or liquids). To estimate initial hydration status upon arrival, he/she provided a urine sample which was analyzed for urine specific gravity (USG) with a manual refractometer (ATAGO®, model URC – Ne, d 1.000-1.050), and discarded. After completely emptying their bladders, participants were weighed nude to the nearest 10 grams on a calibrated scale (e-Accura®, model DSB291). This fasting body mass (BM_{fast}) was used to calculate the water volume to be ingested by each individual. After sitting quietly for 15 minutes in a comfortable chair, a 5 mL blood sample was obtained by venipuncture, and a subjective perception of thirst (TP) was obtained from the response to the question *How thirsty are you?* on a 9-point scale (1 = not thirsty at all; 9 = very, very thirsty), developed by Engell et al. (1987). They ingested a standardized breakfast (750 kilocalories: 24.6% fat, 20.7% protein, and 54.7% carbohydrate; 250 mL of fluid, 1500 mg sodium), and proceeded to rest for 30 minutes.

A second nude body weight was obtained at the end of the rest period (pre-exercise body mass, BM_{pre}), together with another thirst perception score. When the individual protocol did not require dehydration (0%BM), the participant rested for an additional 45 minutes outside the chamber; if the protocol for the day called for dehydration, he/she started intermittent exercise (20 minutes exercise, 5 minutes rest) alternating between pedaling on a cycle ergometer (Monark® 818c) and jogging on a treadmill (SportsArt® model 3250), as long as necessary to achieve a dehydration equivalent to 1, 2, or 3% BM_{pre}; body mass was measured at the end of every 20 minutes of exercise with participants nude and dry. This dehydration protocol was performed in a controlled environment chamber (32 ± 3°C dry bulb and 65 ± 6% relative humidity); exercise intensity was 70% to 85% of maximum heart rate (estimated from 220 – age) and controlled with a Polar® heart rate monitor, model A1.

Once the exercise or prolonged resting period was over, a thirst score was obtained, and each participant was instructed to take a cold shower and to completely empty his/her bladder in a 750 mL plastic container. This urine was weighed on a food scale (OHAUS® Compact Scales, model CS2000) to the nearest 1 g; no fluid intake was allowed at this time. All participants were weighed again nude and dry at this point to obtain post-exercise body mass (BM_{post}). They sat down and a 20G intravenous catheter (Vacutainer®, Franklin Lakes, NJ) was placed in the antecubital vein for repeated blood sampling, using a heparin seal. After sitting quietly for 10 minutes, a new thirst score and 5 mL blood sample were obtained, and each participant started his/her rehydration process.

Participants ingested a volume of water (temperature = 4.98 ± 0.32°C) equivalent to 1.20% BM_{fast}, regardless of the condition, divided into three equal volumes, one every 10 minutes, and started a three-hour monitoring period at rest. Blood samples were obtained upon completing fluid intake and 60, 120 and 180 minutes later. They emptied their bladders into labeled plastic containers upon completion of water ingestion (time 0), and every 30 minutes over three hours. The containers were weighed to the nearest 1 g, and the volume was recorded assuming 1 g is equivalent to 1 mL. Thirst perception was recorded every 30 minutes over three hours; all thirst perception ratings were obtained at ambient temperature (26.0 ± 0.9°C, 72.0 ± 5.5% r.h.), outside the environmental chamber.

Blood hemoglobin was analyzed with a Sysmex® XE-2100 and XS-1000 using protocol IN-064; hematocrit with protocol IN-063, and total red blood cell count with protocol IN-066, all of them at an internationally certified laboratory. Resulting values were used to calculate plasma volume (PV) change according to Dill and Costill (1974).

Net fluid balance (NFB) was calculated for each 30-minute interval of the monitoring period relative to BM_{pre}, using body mass measurements, fluid intake and urine output. Plasma osmolality could not be measured with the available equipment.

Statistical analysis. Descriptive statistics (mean and standard deviation) were calculated for age, body mass, and height in order to characterize the participants. All variables were checked for normality.

To verify that all participants showed the same characteristics under each condition, but achieved the desired differences, several repeated-measures one-way analyses of variance were performed for baseline USG, pre-exercise body mass, pre-exercise thirst, exercise time, actual dehydration incurred, and prescribed water intake.

To assess the reliability of the thirst scale used we performed a repeated-measures two-way analysis of variance (4 conditions by 2 measurements) using only the post-exercise thirst scores obtained 30 minutes apart, before and after a cold shower. A test-retest reliability coefficient was also calculated from a simple correlation between these two thirst scores.

A two-way analysis of variance with repeated measures on both condition and time was performed for each dependent variable: thirst perception, plasma volume change, and net fluid balance. Post-hoc analyses were performed using a Bonferroni adjustment for multiple comparisons. Partial correlation coefficients and their statistical significance were calculated to assess the association among the same three dependent variables: TP, PV, and NFB. After confirmation, a multiple regression model was tested using thirst perception as the dependent variable, and plasma volume, net fluid balance, condition, measurement time, and subject as the potential predictors.

RESULTS

Table 1 shows the reference values for each condition. There were no significant differences for baseline body mass, baseline urine specific gravity, pre-exercise thirst perception, or prescribed water intake ($p > 0.05$). Exercise time and actual dehydration were, however, significantly different ($p < 0.0005$), in line with the study design.

Table 1. Reference values for each condition, prior to rehydration. Mean ± S.D.

Variable	**0% BM**	**1% BM**	**2% BM**	**3% BM**	**p-value**
Baseline USG	1.015 ± 0.005	1.019 ± 0.005	1.018 ± 0.007	1.016 ± 0.007	0.392
BMpre (kg)	73.66 ± 12.66	74.03 ± 12.97	73.59 ± 12.84	74.31 ± 12.58	0.132
Pre-exercise thirst (a.u.)	2.12 ± 1.55	1.62 ± 0.51	2.12 ± 0.83	2.37 ± 1.60	0.199
Exercise time (min)	0	32.5 ± 10.0	73.6 ± 12.8	87.5 ± 13.3	$6.4x10^{-14}$
Actual dehydration (%BM)	0.26 ± 0.10	1.07 ± 0.10	1.85 ± 0.16	2.93 ± 0.23	$2.9x10^{-20}$
Prescribed water intake (mL)	877.2 ± 152.4	880.0 ± 154.4	876.8 ± 154.1	885.5 ± 150.9	0.136

Figure 1 shows post-exercise thirst perception. There was no significant interaction between condition and measurement time ($p = 0.62$). In addition, thirst perception was not different before taking a shower from 30 minutes later after showering ($p = 0.86$). The condition main effect was significant (thirst perception = 2.50 ± 0.45, 4.44 ± 0.72, 6.38 ± 0.82, and 8.63 ± 0.18 for 0, 1, 2, and 3% dehydration, $p = 0.001$). Finally, the Pearson correlation coefficient between both post-exercise thirst scores (a test-retest correlation) was $r = 0.946$.

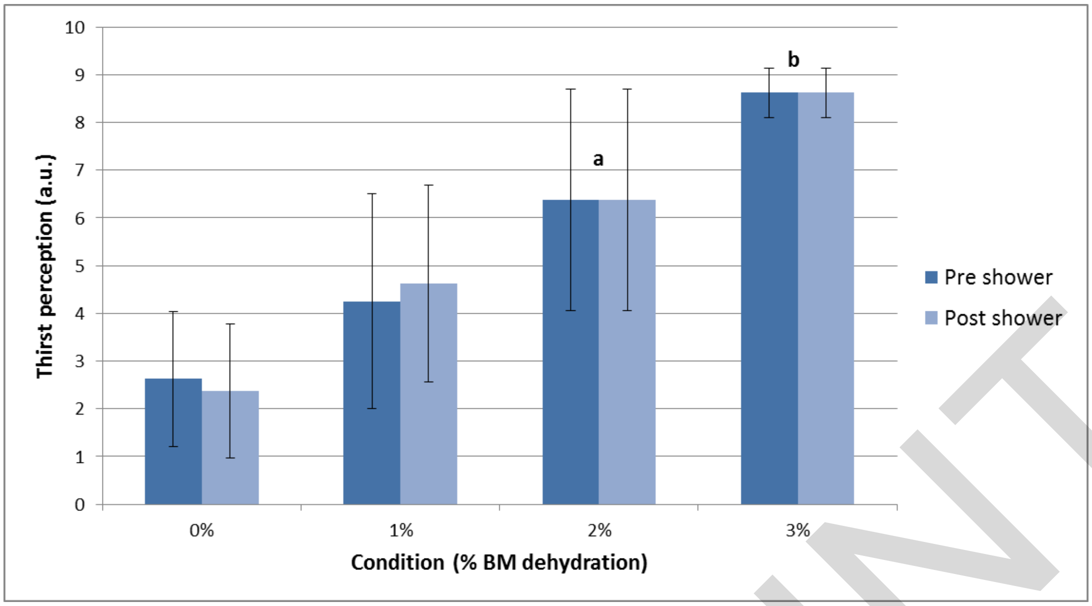

Figure 1. Post-exercise thirst perception. Bars represent means ± SD. Interaction F = 0.60, p = 0.623. Dehydration level main effect F = 26.4, $p = 2.5 \times 10^{-7}$. Measurement time (pre or post-shower) main effect F = 0.03, p = 0.862. (a) different from 0% and 1%, $p < 0.05$. (b) different from 0% and 1%, $p < 0.005$.

When the complete time of monitoring was analyzed, thirst perception showed a significant interaction between time and condition ($p = 2.98 \times 10^{-10}$) (Figure 2). The time main effect was significant ($p = 2.34 \times 10^{-18}$), as well as the condition main effect (p = 0.00012). At the end of exercise, both the 3% (8.63 [8.19, 9.06]) (mean [95%CI]) and the 2% (6.38 [4.43, 8.35]) conditions were different from 0% (2.62 [1.45, 3.80]), but 1% was not (4.25 [2.37, 6.13]). Post-hoc analysis for each condition over time showed a significant increase in thirst after exercise relative to pre-exercise ($p < 0.05$), and a return to pre-exercise thirst scores immediately after rehydration, for all except the 0% dehydration condition.

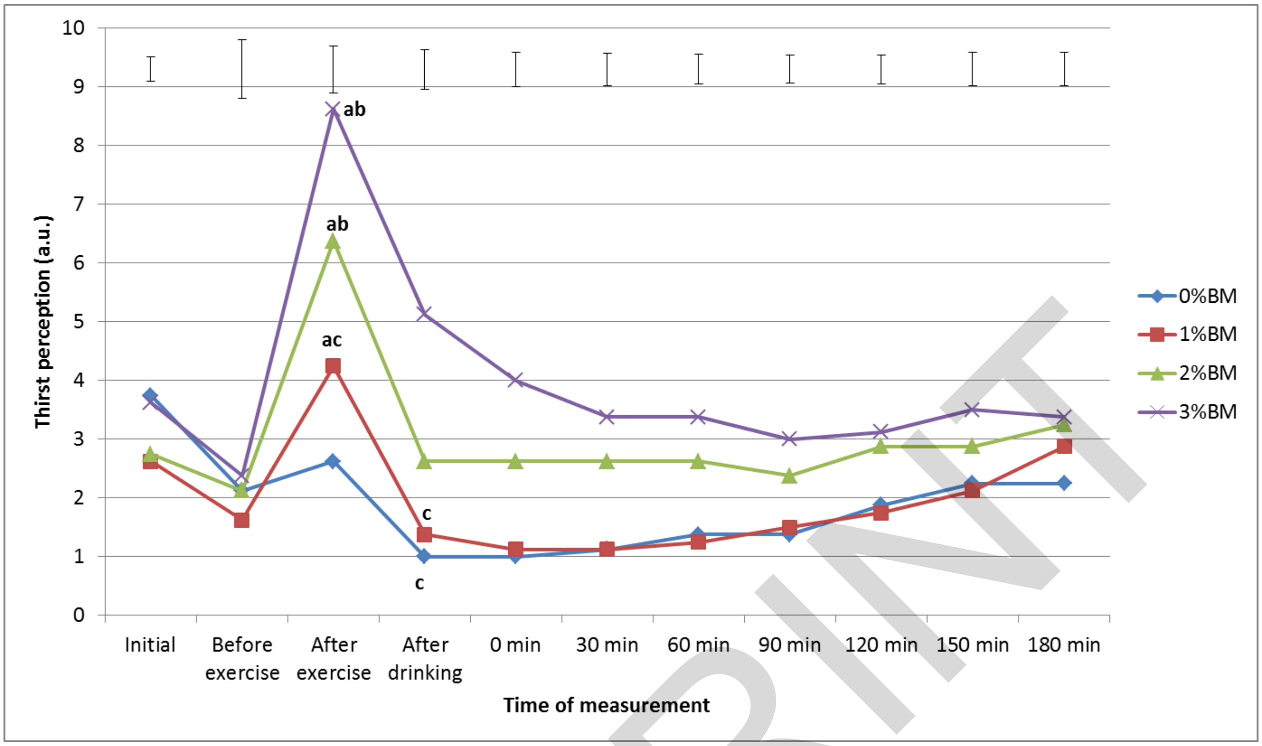

Figure 2. Thirst perception over time, by condition. Points are mean values; upper bars represent group standard errors of measurement. Interaction F = 4.20, $p = 2.98 \times 10^{-10}$. Condition main effect F = 11.34, p = 0.00012. Time main effect F = 22.95, $p = 2.34 \times 10^{-18}$.
(a) Different from pre-exercise ($p < 0.05$). **(b)** Different from 0% and 1% ($p < 0.05$) **(c)** Different from 3% ($p < 0.05$).

Plasma volume changes are shown in figure 3. There was no significant interaction between condition and time of measurement (p = 0.883). There was no condition main effect (p = 0.064), but the main effect of measurement time was significant: ($p = 1.7 \times 10^{-6}$). Plasma volume was higher at all times after rehydration, compared to baseline ($p < 0.05$). It was also higher at 60, 120 and 180 minutes compared to post-exercise.

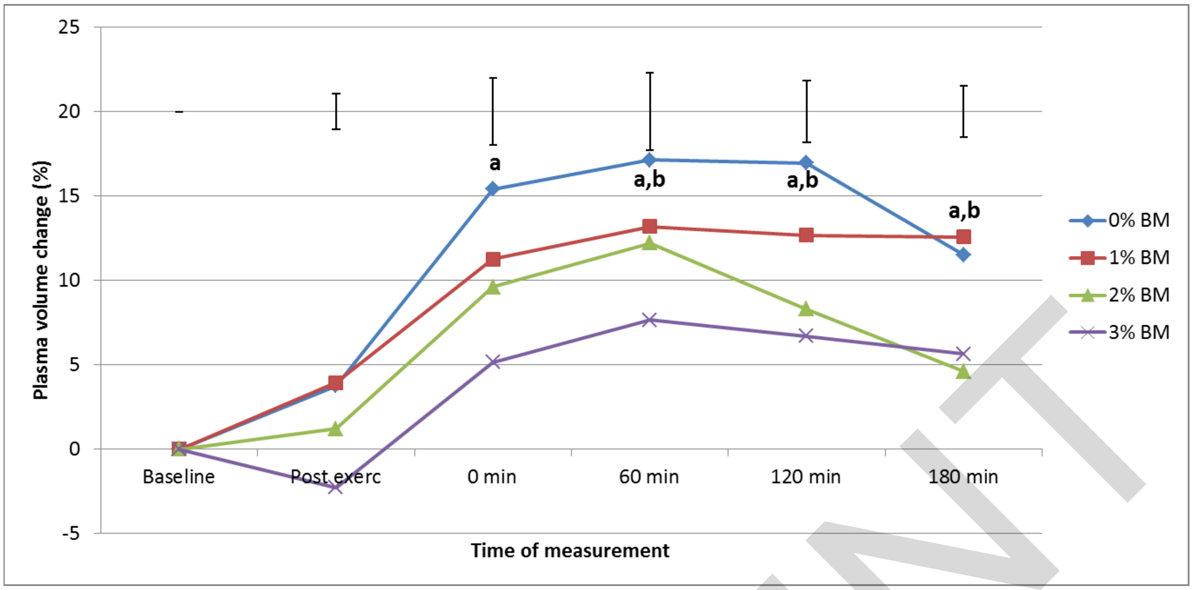

Figure 3. Plasma volume changes. Points are mean values; upper bars represent group standard errors of measurement. Interaction F = 0.58, p = 0.883. Condition main effect F = 2.82, p = 0.064. Time main effect F = 11.22, $p = 1.7 \times 10^{-6}$.
(a) Different from baseline, $p < 0.05$. **(b)** Different from post-exercise, $p < 0.05$.

Net fluid balance is shown in Figure 4. There was a significant interaction between time and condition ($p = 9.6 \times 10^{-69}$), as well as significant main effects for both time ($p = 4.8 \times 10^{-30}$) and condition ($p = 2.9 \times 10^{-12}$). Net fluid balance was negative for all conditions after the exercise time, but it remained lower than zero after fluid intake only for the 1%, 2% and 3% dehydration conditions, with the exception of the first hour in the 1% dehydration condition. The 0% condition maintained a positive or neutral fluid balance until the end of monitoring. At this point, mean NFB was -290 g, with a 95% Confidence Interval from -627 to 47g. Net fluid balance was different among conditions at all time points except that the difference between 0% and 1% disappeared from the measures at 60 minutes and beyond.

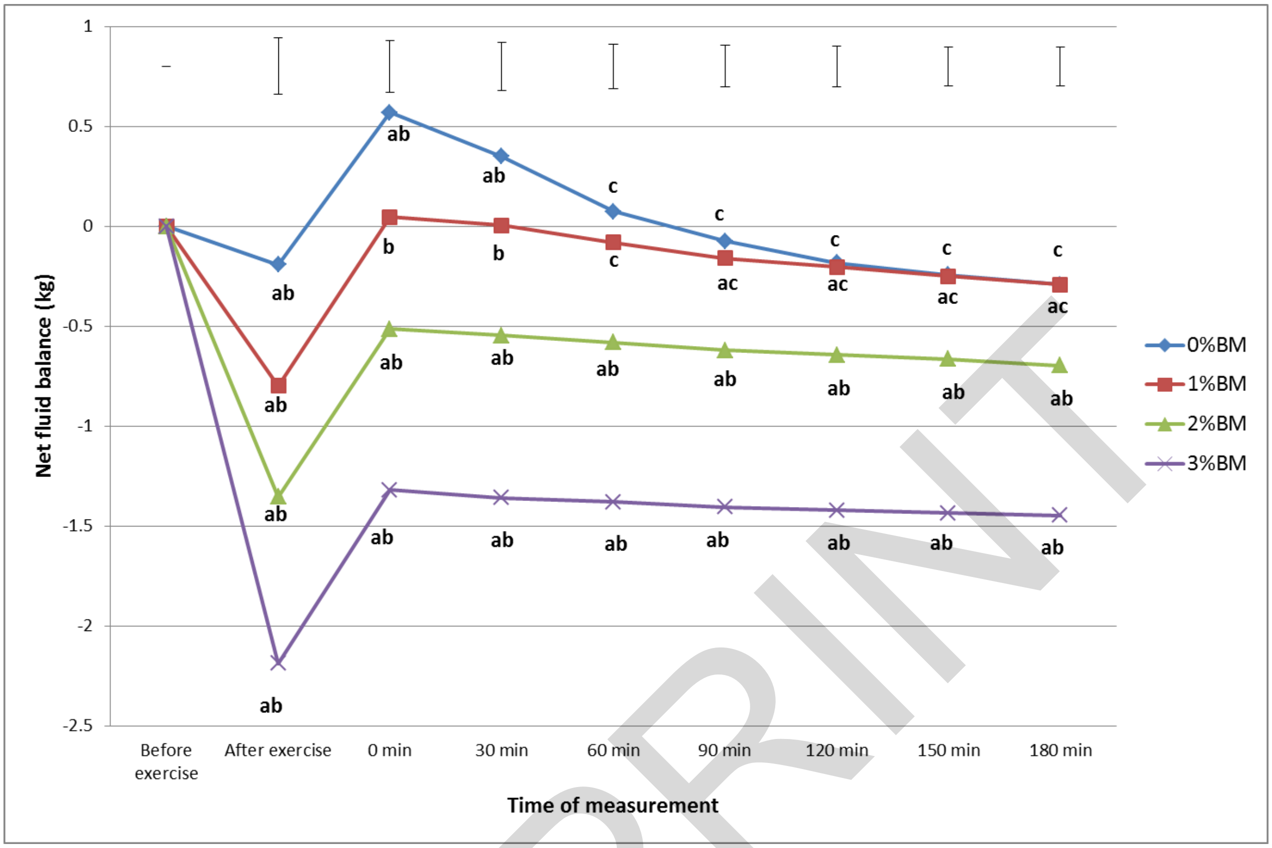

Figure 4. Net fluid balance over time, by condition. Points are mean values; upper bars represent group standard errors of measurement. Interaction F = 58.13, p = $9.6x10^{-69}$. Condition main effect F = 92.41, p = $2.9x10^{-12}$. Time main effect F = 97.57, p = $4.8x10^{-30}$. After exercise NFB < 0 for all conditions, p < 0.05. **(a)** different from the reference value (BM_{pre}) ($p < 0.05$). **(b)** different from all other conditions ($p < 0.05$). **(c)** different from 2% and 3% ($p < 0.05$).

Partial correlation coefficients were significant between TP and NFB (-0.62, p = 2.88×10^{-18}) and between PV and NFB (0.31, p = 0.001), but not between PV and TP (-0.04, p = 0.572). Adjusted R^2 for the multiple regression model was 0.64 ($p < 0.0001$); NFB was a significant predictor (F = 28.125, $p < 0.0001$), but PV was not (F = 0.284, p = 0.595). The model also included subjects, condition, and time of measurement (Figure 5).

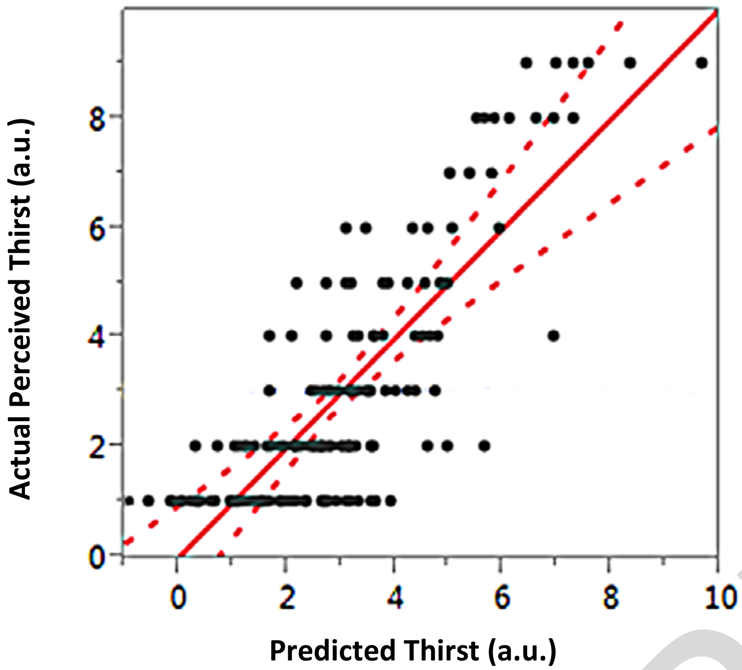

Figure 5. Multiple regression model. Thirst perception at the end of exercise in the heat as the dependent variable. Predictors were NFB, PV, subject, condition, and measurement time. $R^2_{adj} = 0.64$, $p < 0.0001$. Solid line is the line of adjustment; red dotted lines represent 95% CI.

DISCUSSION

This study looked at the thirst response to ingesting a pre-determined, constant volume of water after exercising in the heat to different levels of dehydration. First, we confirmed that the subjective perception of thirst after exercise was able to detect levels of hypohydration equivalent to 2% BM or greater: the scores for both 3% and 2% dehydration were different from 0%, while 3% was also different from 1%. Thirst perception immediately after exercise was robust: as long as no water was ingested, TP was reliable, giving consistent results before and after a cold shower, 30 minutes apart (r = 0.946); the difference between the two scores was not significant (p = 0.862). Engell et al. (1987) obtained two measures for each sensation, one when subjects first reached their target dehydration, and a second one the following morning, 12 to 15 h later. They stated that most sensations were significantly correlated using the test-retest method, but unfortunately no correlation was reported for "feel thirsty", our measure of interest. We are not aware of other studies reporting the reliability of Engell's thirst scale.

Our main finding was that thirst perception decreased quickly with drinking regardless of dehydration, reaching pre-dehydration levels (TP = 2.53 ± 0.85) immediately after ingestion of about 880 mL and remaining there for the entire three hours of monitoring. In the 3% BM dehydration condition, water intake represented only 40.4% of fluid loss and achieved a NFB of ≈ -1.3 kg, which is far from euhydration. Therefore, while we found that thirst is strongly associated with an objective measure of hypohydration, i.e., net fluid balance, in the absence of water intake, the association weakens when subjects who are significantly dehydrated drink an insufficient amount. Using the same TP scale, Maresh et al. (2004) reported thirst being significantly reduced (from ≈ 5.5 pre exercise to ≈ 3.2 post exercise) in previously hypohydrated subjects who exercised in the heat for 90 min while drinking *ad libitum*; fluid intake was high, but they were still hypohydrated by about 3%BM at the end of exercise. In another study comparing the rehydration properties of coconut water and other drinks (Pérez-Idárraga and Aragón-Vargas 2012), subjects ingested four aliquots equivalent to 30% of sweat loss each after exercising in the heat to 2.0% BM dehydration. Thirst perception was higher immediately after exercise but returned to baseline after drinking the first aliquot. Those two studies with different designs support our finding that thirst is quickly turned off after drinking water, even when the amount is insufficient to return to euhydration.

Net fluid balance (a measure of hydration status), plasma volume change, and thirst perception were interrelated. However, NFB showed a very strong inverse association with thirst, with a partial correlation coefficient of -0.62, while PV and TP showed no association. Our multiple regression model confirmed NFB as a significant predictor, but not PV. Plasma volume change by itself was weakly and insignificantly associated with TP. This has already been hinted by others: Engell et al. (1987) assessed thirst and measured fluid intake and many blood parameters during and after exercise in dry heat at 0, 3, 5, and 7%BM hypohydration (0.9, 4.0, 5.9, and 7.3%BM at the end of testing), concluding that hypovolemia contributes minimally to fluid intake (the contribution of perceived thirst was not reported). In their study, actual hypohydration showed a strong, direct association with thirst, and also with fluid intake.

Maresh et al. (2004) examined the responses of ten subjects walking in the heat for 90 minutes on four different occasions: previously euhydrated without fluid intake, previously hypohydrated (≈ -3.8%BM hypohydration) without fluid intake, previously euhydrated and drinking during exercise, or previously hypohydrated and drinking during exercise. Pre-exercise thirst was significantly higher for the hypohydrated conditions than for euhydration. Post-exercise thirst was even higher in the hypohydrated condition when subjects were not allowed to drink, but when fluid intake was allowed, post-exercise thirst was not different from that at pre-exercise euhydration. Thirst was found to respond predictably to dehydration, but plasma volume changes were not different between pre-exercise hydration conditions. Our results confirm a clear association between actual hypohydration and thirst perception before subjects were allowed to drink, and even an association between these two variables over the course of the entire experiment, while plasma volume was only weakly associated with thirst.

In our study, plasma volume changes were not different among conditions, although the trend was in the right direction. That may be because they were calculated relative to a baseline which occurred prior to a standardized breakfast; this blunted PV changes, as there is no hypovolemia after exercise except for the 3%BM dehydration condition (see Figure 3). Our conclusions regarding plasma volume must be taken with caution in the light of these limitations; plasma osmolality (not measured in the present study due to technical limitations) would be likely to show a much stronger association with thirst and actual dehydration (Maresh et al., 2004).

Thirst is considered by some as too elusive a variable, impossible to measure accurately (Greenleaf, 1992). Others take advantage of this characteristic and use the term imprecisely to suit their arguments, meaning anything from “dry mouth” to “what we actually drink”. It is not surprising then that Greenleaf stated at the beginning of his seminal paper *Problem: thirst, drinking behavior, and involuntary dehydration* that “the debate concerning the meaning of thirst is endless, so the emphasis here will be on actual fluid intake that can be measured.” (1992, p. 645). Thirst perception, however, can be measured reliably, although it is only measurable in humans, as Johnson (2007) points out. The paper by Engell et al. (1987) is a good example; their scale has been widely used by others (Maresh et al. 2004, Maresh et al. 2001, Riebe et al. 1997). As any self-reported measure, TP could be sensitive to extraneous variables. Nevertheless, since the present experiment was part of a larger study designed to understand the diuretic response to a constant load of water, we consider that the participants had many different things to pay attention to which distracted them from the actual thirst reports–the main focus of this paper–and hence they were less likely to be distorted by subjectivity.

Plain water has been advocated as the perfect drink, with little experimental evidence in favor and in the face of experimental evidence against it. We chose to do the present study using plain, bottled water, not because we consider it ideal, but because we wanted to avoid the commercial and palatability issues by using the more neutral and natural drink, which is normally chosen as the standard for comparison. In addition, the present study required a decision regarding how much is enough fluid replacement, clearly a basic element of the current hot debate around hydration and thirst. It may be argued that *enough* means not impairing performance in real life situations, but this is difficult to evaluate as there is no standard for comparison. In a very thorough study, Dugas et al (2009) attempt to address this issue, but in their effort to mimic athlete performance in normal situations, they are unable to control for key variables, precluding the careful reader from making many of the meaningful comparisons that could have been made. Goulet (2011) claims that drinking to thirst during exercise works well for athletes; however, this claim is based on a metaanalysis of only two cycling papers. Thirst was not measured in one of them and, while it was measured in the other, the original performance comparisons were made among actual fluid intake conditions, not among thirst measures (Dugas et al., 2009). Other laboratory studies on this issue have been dismissed by some (see Noakes' position in Sawka & Noakes 2007).

Enough may also be argued to mean preventing hyperthermia, but again the evaluation is not simple as the tests must consider environmental conditions and exercise duration and intensity, while providing core temperature measurements; in self-paced experiments, the resulting different intensities may be precisely the subjects' strategy to maintain core temperature in spite of inadequate hydration. If *enough* means an amount that will prevent hyponatremia, as suggested by some, there is major conflict because humans will most likely avoid exercise-associated hyponatremia if they don't drink any fluid at all. In order to have a clear, objective basis for discussion, we chose *enough* to be euhydration, meaning a return to pre-dehydration body mass.

In conclusion, this study confirms that the subjective perception of thirst after exercise in the heat is able to detect dehydration equivalent to 2% BM or greater. The measure is reliable and robust, and it shows a clear, significant association with net fluid balance (but not with plasma volume).

Thirst is, however, disproportionately reduced in dehydrated subjects after acute ingestion of water. When the goal is to replace all fluid lost through sweating after exercising in the heat, we deem thirst to be insufficient as it responds inappropriately to fluid intake.

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