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Progression of human subjective perceptions during euhydration, mild dehydration, and drinking

Lawrence E. Armstrong[a,b,*], Gabrielle E.W. Giersch[a], Abigail T. Colburn[a], Virgilio Lopez[a], Yasuki Sekiguchi[a], Colleen X. Muñoz[c], Elaine C. Lee[a]

[a] *Human Performance Laboratory, Department of Kinesiology, University of Connecticut, Storrs, CT 06269, United States*
[b] *Department of Nutritional Sciences, University of Connecticut, Storrs, CT 06269, United States*
[c] *Department of Health Sciences, University of Hartford, West Hartford, CT, 06117 United States*

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ABSTRACT

Thirst motivates consumption of water necessary for optimal health and cognitive-physiological functions. Other than thirst, little is known about coexisting perceptions and moods that provide information to the brain and participate in body water homeostasis. The purpose of this investigation was to observe perceptions, somatic sensations, and moods during controlled changes of hydration status. During routine daily activities interspersed with laboratory visits, 18 healthy young men (age, 23±3 y; body mass, 80.13±10.61 kg) self-reported hourly ratings (visual analog scales, VAS) of 17 subjective perceptions, across two 24-h periods (ad libitum food and water intake while euhydrated; water restriction with dry food intake [WR]) and during a 30-min rehydration session (R_{30}, 1.46±0.47 L water intake). At the end of WR, body mass loss reached 1.67 kg (2.12%). Distinct perceptions were identified during euhydration, WR and immediately after R_{30}. Starting approximately 4 h after WR began (body mass loss of ~0.5%), perceptual changes included progressively intensifying ratings of thirst, mouth dryness, desire for water, and pleasantness of drinking. In comparison, immediately after R_{30}, participants reported a reversal of the perceptions observed during WR (above) plus cooler thermal sensation, increased satisfaction, and stomach fullness. These VAS ratings suggested that aversive moods contributed to drinking behavior and supported previously published animal studies. In conclusion, this investigation delineates previously unreported perceptions and their evolution (e.g., appearance, extinction, time course) that motivated drinking during WR and discouraged overdrinking after R_{30}.

Introduction

Dehydration degrades cognitive performance [25] and may induce apathy, impatience, weariness, or delirium when the deficit of water is severe (e.g., 4–12% body mass loss) [2,19]. As a result, several research studies have assessed the effects of moderate-to-severe dehydration on cognitive performance, utilizing a variety of methods to induce dehydration (diuretics, exercise, environmental heat stress), and testing diverse cognitive domains (executive function, learning, memory, complex attention) [1,48]. In contrast, few studies have evaluated the moods, subjective perceptions, and somatic sensations during mild dehydration (<2% body mass loss) that occur during routine daily activities involving no exercise, strenuous labor, or environmental heat stress [10,24]. Such research is relevant to a large portion of the world's population because moods and subjective perceptions are sources of information [40] that become part of executive function [39], judgements and decisions [17,18,29], including choices that involve seeking and consuming water [34]. Such research also is relevant because adults, when stratified on the basis of 24-h total water intake (e.g., low versus high volume), experience different moods and perceptions [22,28,33].

The human brain precisely regulates body water volume and concentration via a dynamic network of sensory nerves, brain integration, subconscious autonomic neuroendocrine responses, and multiple organ systems [7,8]. Thirst is an essential, conscious perceptual component of this network and is an adequate stimulus for fluid replacement during

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Brief Title: Subjective Perceptions: Euhydration, Dehydration, and Drinking

[*] Corresponding author at: University of Connecticut, Human Performance Laboratory, Unit 1110, 2095 Hillside Road, Storrs CT 06269-1110, USA

E-mail addresses: lawrence.armstrong@uconn.edu (L.E. Armstrong), gabrielle.giersch@uconn.edu (G.E.W. Giersch), atcolbur@asu.edu (A.T. Colburn), virgilio_lopez@brown.edu (V. Lopez), yasuki.sekiguchi@uconn.edu (Y. Sekiguchi), cmunoz@hartford.edu (C.X. Muñoz), elaine.c.lee@uconn.edu (E.C. Lee).

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sedentary daily activities [20]. Despite its vital role in optimal human health and performance, the interactions of thirst with coexisting perceptions, somatic sensations (e.g., mouth dryness, stomach emptiness) and moods are not fully understood, and the relevant scientific literature is insufficient [25,42,44]. Specifically, although many previous studies have assessed human thirst, few if any have considered the number and nature of other subjective perceptions which appear and change concurrently with thirst. It is informative, however, that McKinley and colleagues [27] reported that thirst in rodents consists of the following components: (1) the host becomes aware of thirst, (2) water becomes desirable, (3) thirst becomes unpleasant and the disagreeable sensation becomes more distressing as its intensity increases, until the aversive state is extinguished by drinking, and (4) memories of source locations direct the search for water.

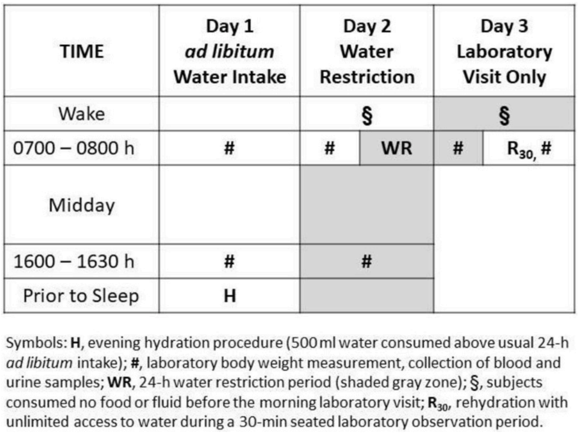
Therefore, to determine if a similar series of events occurs in humans, the present investigation was designed to observe interactions of perceptions, somatic sensations, and moods during changing hydration states in free-living adult men who were conducting routine daily activities. Participants self-rated 17 dehydration-relevant perceptions using visual analog scales (VAS), during each waking hour, across two consecutive 24-h periods: ad libitum fluid and food intake, and water restriction (mild dehydration, no fluid intake and consumption of dry solid food items). At the end of 24-h water restriction, participants were observed during 30 min of unlimited water intake, to evaluate which perceptions were affected by rehydration. Considering previous animal [3,4,9] and human research [7], the present investigation attempted to (a) identify the perceptions, somatic sensations, and moods that change significantly and in concert with the conscious awareness of thirst; (b) determine the onset time and duration of thirst and accompanying perceptual changes, especially relative to 1% and 2% body mass losses; and (c) observe perceptual changes during a 30-min ad libitum rehydration session. We hypothesized that perceptions would evolve dynamically as hydration status changed from euhydration to mild dehydration and rehydration. This hypothesis recognized that identifying contextual patterns of perceptions related to thirst would improve our understanding of the complex integration of neural signals that influence drinking behavior.

Methods

The methods, instrumentation, body fluid sampling, and records of this investigation were reviewed and approved by the university Institutional Review Board for Human Studies. Each subject provided written informed consent to participate, after investigators explained laboratory visits, time commitment, dietary restrictions, and record keeping. Each subject completed a medical history questionnaire that was reviewed by a physician to verify that the following criteria were met: age 21–35y, no acute illness, no chronic illness or medication that altered fluid-electrolyte balance or kidney function.

Before testing began, all participants met with investigators to receive instructions regarding perceptual ratings, food diaries, body fluid sample collections, and to resolve questions. Test participants were free-living and were instructed to conduct daily activities (e.g., university classes, work) as they ordinarily would. Throughout testing, participants were instructed to retire for sleep each night as they did during week nights, and to abstain from exercise and alcohol consumption.

The study timeline and experimental intervention are presented in Fig. 1. Measurements, sample collections and observations were recorded during 5 laboratory visits spanning 48 h. During each laboratory visit, participants rated subjective perceptions as described below, had a small blood sample drawn from an antecubital vein, and provided single urine samples (~ 200 ml). Morning visits (0700 – 0800 h, see Fig. 1) occurred after the first morning bladder void and before eating breakfast or drinking fluid (i.e., in a 9 – 13 h fasted state); afternoon laboratory visits occurred between 1600 – 1630 h. This investigation was part of a large project that will result in multiple publications, each focusing on different research questions. To avoid duplication of published findings, all tables and figures in the present investigation are original.



TIME	Day 1 *ad libitum* Water Intake	Day 2 Water Restriction		Day 3 Laboratory Visit Only	
Wake		§		§	
0700 – 0800 h	#	#	WR	#	R_{30}, #
Midday					
1600 – 1630 h	#	#			
Prior to Sleep	H				

Symbols: **H**, evening hydration procedure (500 ml water consumed above usual 24-h *ad libitum* intake); **#**, laboratory body weight measurement, collection of blood and urine samples; **WR**, 24-h water restriction period (shaded gray zone); **§**, subjects consumed no food or fluid before the morning laboratory visit; $\mathbf{R_{30}}$, rehydration with unlimited access to water during a 30-min seated laboratory observation period.

Fig. 1. Experimental design. Day 1 involved ad libitum water and food intake. Water restriction on Day 2 (experimental intervention) appears as a shaded gray zone; participants consumed no fluids and ate only dry food items. Visual analog scale ratings of perceptions and moods were recorded on all days, at the beginning of each waking hour. On all days, participants conducted usual daily activities interspersed with laboratory visits between 0700 and 0800 h and 1600–1630 h.

During each laboratory visit, urine specific gravity was assessed in a single sample (100–200 ml) with a hand-held refractometer (Atago Co, Tokyo, Japan, model 300CL). Body mass was measured with a calibrated digital floor scale (Ohaus Inc, Florham Park, NJ, model DS44L; ±100 g). One whole blood sample was drawn from an antecubital vein and was centrifuged at 3000 rpm for 15 min; the resulting plasma samples were frozen at −80 °C. Plasma sample osmolalities were measured in duplicate using the freezing-point depression method (200 µl volume; Advanced Instruments, Inc., Norwood, MA, model OsmoPRO).

Test participants consumed ad libitum foods and fluids throughout Day 1. On the evening of Day 1, they consumed 500 ml of water in addition to their habitual fluid intake, to increase the likelihood that they would arrive at the laboratory in a euhydrated state the next day. Beginning on the morning of Day 2, all participants consumed no fluid and ate dry foods containing low water content for 2 h. This experimental intervention (water restriction) occurred between the morning laboratory visits on Day 2 and Day 3, and is illustrated in Fig. 1 as a shaded gray zone. This eating plan was guided by a dietitian-approved list of dry foods such as crackers, pretzels, bread, and nuts. On all days, participants recorded dietary water, beverages and solid foods in a food diary, including the brand, manufacturer, size/volume, and method of preparation. Nutrition labels and food packages were submitted when available. Macronutrient analyses were computed with commercial software (Nutritionist Pro™, Axxya Systems, Woodinville, WA 98,072).

The dehydration phase of testing ended during the 60-min morning laboratory visit on Day 3. Following morning measurements (i.e., body weight, blood sample, urine sample), each subject sat at a table with an investigator and consumed fluids (e.g., with a choice of either bottled water or a fluid-electrolyte replacement beverage at ~23 °C) in unrestricted volume for 30 min (R_{30}). This choice was purposefully given to encourage drinking to satiation. The ingested volume was determined gravimetrically (benchtop pan balance, ±1 g) then morning measurements were repeated.

Seventeen perceptions, moods, and sensations were self-recorded by participants during each laboratory visit and at the beginning of each waking hour shown in Fig. 1. Visual analog scales (VAS) consisted of a question or statement and a 100 mm straight line flanked by bipolar word anchors (adjectives or descriptive phrases). One end of the line represented the low rating/intensity and the other end the high rating/

intensity [36]. The 17 statements and questions (i.e., presented one per 5 cm x 20 cm sheet, in stapled paper packets) are described in the Results section below. To reduce the likelihood of an order effect, the order of VAS questions and the positions of bipolar word anchors (e.g., left versus right) were randomized among the paper packets. These data were reorganized for coherent data presentation in tabular formats (below), with the score of 0 as the left anchor and a score of 100 as the right anchor.

Data are reported as mean ± standard deviation. For each variable, analysis of variance (ANOVA) tested mean differences across time and within day. Significance was determined at an alpha level of $P<.05$. If a significant main effect was identified, *post hoc* Student's t-tests with Bonferroni corrections were performed. The number of data points varied across variables and time points ($n = 13$–18) because test participants did not record some hourly VAS ratings, did not attend some laboratory visits or produce a urine sample at the prescribed time, or because of insufficient blood volume during phlebotomy.

To conduct the pre-investigation sample size calculation, we selected an effect size of 0.2 and a maximum chance of a Type 1 error of 5% (very unlikely). For the present experimental design, the minimal sample size to detect a significant difference ($p < .05$) was computed as $n = 12$. The present participant sample exceeded this minimum size.

Results

The 18 male test participants, all members of the university community, exhibited the following personal characteristics: age, 23±3y; body mass, 80.13±10.61 kg; height, 176 ± 6 cm. Their dietary intakes on Day 1 and Day 2, respectively, were statistically similar ($P>.05$): food energy content, 2392 ± 827 vs 2219 ± 897 kcal; carbohydrate, 40 ± 10 vs 42 ± 12% of total kcal; fat, 37 ± 10 vs 39 ± 10%; protein, 23 ± 8 vs 20 ± 5%.

Table 1 presents test subject hydration indices that were measured during 6 laboratory visits. Although the experimental intervention (24-h water restriction) resulted in a 1.67 ± 0.35 kg (2.12 ± 0.50%) mean body mass loss, due to a 24-h water total intake of only 0.31 ± 0.24 L, no statistical differences in body mass or plasma osmolality were observed across these 6 measurements. This likely occurred because of the large statistical variance (standard deviations) of body mass, and because plasma osmolality is a tightly regulated homeostatic variable. In comparison, multiple significant differences among measurements were determined for urine specific gravity (Table 1). This was anticipated before testing began, because urine concentration and volume are known to be more sensitive biomarkers of daily total water intake (L) than either body mass or plasma osmolality [30].

On Day 1, all participants were instructed to consume 500 ml of water above their typical ad libitum 24-h fluid intake. As a result, body mass, plasma osmolality and single sample urine specific gravity were statistically similar ($P>.05$) on the afternoon of Day 1 and the morning of Day 2 (Table 1). Thus, participants were deemed to be euhydrated on the morning of Day 2, at the beginning of water restriction.

Table 2

Results of ANOVA that determined which VAS ratings changed significantly (all ratings on Days 1 and 2). Significant differences between Day 1 (ad libitum water and food intake) and Day 2 (water restriction) are depicted in Fig. 2.

Statements/Questions on VAS rating sheets	Left Word Anchor (VAS = 0)	Right Word Anchor (VAS = 100)	P level
1. I feel ___	very weak	very strong	$P<.0000001$
2. I feel ___	very anxious	very calm	NS
3. I feel ___	very happy	very sad	NS
4. I feel ___	very cold	very hot	NS
5. I feel ___	very fatigued	very energetic	$P<.0000001$ [a]
6. I feel ___	very tired	very awake	$P<.0000001$ [a]
7. My mouth feels ___	very moist	very dry	$P<.0000001$
8. My stomach feels ___	very full	very empty	NS
9. I desire salt ___	very much	very little	NS
10. I desire water ___	very little	very much	$P<.0000001$
11. How pleasant would it be to drink some water?	not at all	very	$P<.0000001$
12. How thirsty are you?	not at all	Very	$P<.0000001$
13. How hungry are you?	very	not at all	NS
14. Do you have a headache?	not at all	Severe	NS
15. How satisfied do you feel?	not at all	Very	$P<.0000001$
16. How challenging is it for you to concentrate?	very	not at all	NS
17. How angry are you?	not at all	very	NS

Abbreviations: ANOVA, analysis of variance with *post hoc* comparisons via t-tests with Bonferroni corrections; VAS, visual analog scale; NS, no significant change of VAS rating. [a], *post hoc* analysis indicated no significant effect of dehydration, but a significant within-day effect (2000–2200 h) was detected on Day 1 and Day 2 (see Fig. 2D).

Table 2 describes the VAS ratings which test participants completed at the beginning of each waking hour on Days 1 and 2. The statements/questions appear in column 1, the left word anchors appear in column 2 (score=0 at the extreme), and the right word anchors appear in column 3 (score=100 at the extreme). Table 2 also presents the results of ANOVAs (column 4). Eight VAS ratings changed significantly during 48 h of observations, but *post hoc* analyses indicated that not all variables exhibited a significant effect of dehydration. These 8 variables appear in Fig. 2, which depicts statistically significant within-day changes (ˆ symbols) as well as significant between-day treatment effects due to dehydration (* symbols). Fig. 2A presents mouth dryness (rating of 0, very moist; rating of 100, very dry) and thirst (0, not at all; 100, very thirsty) data. Fig. 2B illustrates desire for water (0, very little; 100, very much) and how pleasant it would be to drink water (0, not at all; 100, very). Fig. 2C shows that the subjective states of being satisfied (0, not at all; 100, very) and feeling of strength (0, very weak; 100, very strong) exhibited few within-day statistically significant changes. Fig. 2D presents VAS ratings of feeling energetic (0, very fatigued; 100, very energetic) and feeling awake (0, very tired; 100, very awake); when mean values were compared, neither variable was significantly affected

Table 1

Hydration-relevant physiological variables (mean ± SD) measured during laboratory visits.

Variable	Day 1 Morning (0730 h)[a]	Day 1 Afternoon (1600 h)[a]	Day 2 Beginning of water restriction (0730 h)	Day 2 Afternoon of water restriction (1600 h)	Day 3 End of 24-h water restriction (0730 h)	Day 3 Immediately after R_{30} (0800 h)
Body Mass (kg)	80.13 ± 10.61	80.29 ± 10.60	80.11 ± 10.58	79.26 ± 10.63	78.43 ± 10.52	79.63 ± 10.79
Plasma Osmolality (mOsm/kg) [b]	294 ± 5	296 ± 6	296 ± 4	299 ± 7	299 ± 5	293 ± 5
Urine specific gravity [b]	1.025 ± 0.004[c,d,e,f]	1.017 ± 0.009[c,g,h,i]	1.020 ± 0.007[d]	1.028 ± 0.003 [g]	1.030 ± 0.008[e,h]	1.029 ± 0.003[f,i]

Abbreviation: R_{30}, 30 min ad libitum drinking session with unlimited access to water.

[a] *ad libitum* food and fluid intake.

[b] single laboratory sample;[c,d,e,f,g,h,i]analysis of variance determined that values with identical letters are significantly different.

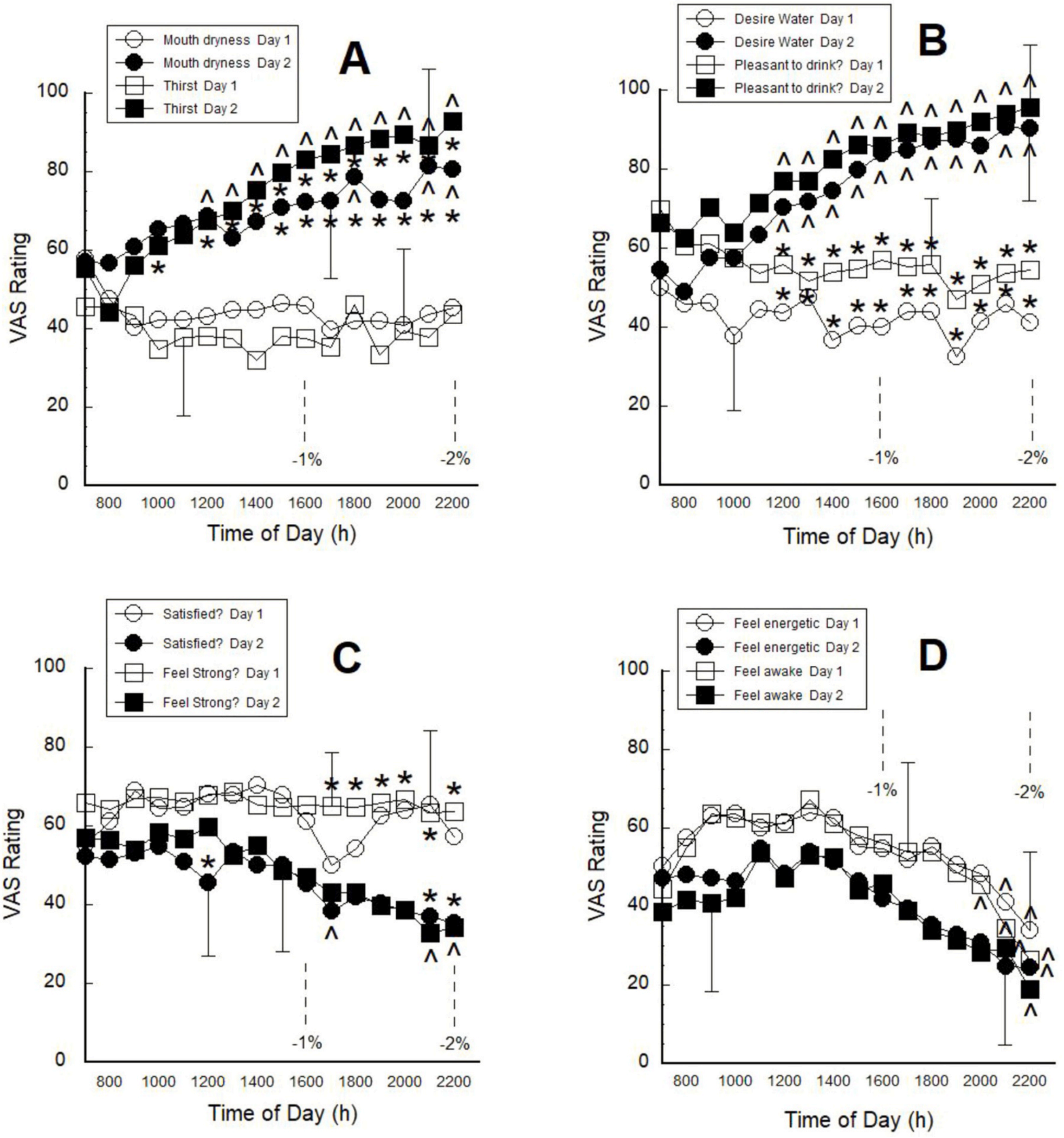


Fig. 2. Visual analog scale (VAS) ratings during 24-h ad libitum water and food intake (Day 1, open symbols) and during 24-h water restriction (Day 2, filled symbols). Perceptual factors include mouth dryness and thirst (panel A), desire for water and pleasant to drink (panel B), satisfaction and feeling strong (panel C), and energetic and awake (panel D). Statistically significant within-day changes (^ symbols) and significant between-day treatment effects due to water restriction (**x** symbols) were determined by ANOVA. Vertical dashed lines represent the times of day at which body mass decreased by 1% and 2%.

by dehydration.

Two specific phases of the experimental intervention (Fig. 1) were evaluated to identify possible changes in VAS ratings, and to clarify matters that otherwise would not appear in these data. The first compared the final night ratings on Days 1 and 2 (2200 h) versus the initial ratings upon waking (Days 2 and 3, <0700 h), an elapsed time of approximately 8.5 h. Based on the nearest body mass measurements (1600 h and 0700 h) and a 0.06 kg/h average rate of weight loss, the calculated mean body mass loss overnight was 0.52 kg (0.7%) per 8.5 h on both nights. Table 3 compares the overnight changes of VAS ratings and indicates that dehydration (column 3) resulted in changes that were significantly different from euhydration (column 2).

The second specific comparison evaluated the 30 min unrestricted water intake session on Day 3 (R_{30}), conducted at the end of water restriction when mean body mass loss reached 2.12%. During R_{30}, a mean volume of 1.46 ± 0.47 L of water was consumed. This 30-min intake significantly modified ($P<.002$ to 0.0000001) 7 of the 17 mean VAS ratings (Table 4). Regression analyses indicated that none of the 17 VAS ratings was significantly correlated ($P>.05$) with the volume of fluid consumed during R_{30} (expressed as L and ml/kg body mass); the coefficients of determination (r^2) ranged from 0.001 to 0.29.

Distinct perceptual changes occurred during the 24-h dehydration period on Day 2 and immediately after the 30-min rehydration period on Day 3.These unique perceptions were identified on the basis of statistically significant changes ($P<.05$) that occurred concurrently with changes of VAS ratings of thirst (Tables 2 and 4, Fig. 2). Table 5 describes the variables that changed significantly and provides a summary of VAS ratings to enhance clarity of interpretation.

To investigate the inter-relationships among VAS ratings, four correlation matrices were computed and are presented in Table 6. These 11

Table 3
Comparison of overnight VAS rating changes from Day 1 to 2 (euhydrated) versus Day 2 to 3 (dehydrated).

VAS Statements/Questions	Overnight Change from Day 1 to Day 2[a,b]	Overnight Change from Day 2 to Day 3[a,c]	P level
1. I feel ___ (very weak/very strong)	+ 22 ± 10	- 14 ± 4	$P<.00005$
2. I feel ___ (very anxious/very calm)	+ 5 ± 20	- 6 ± 17	NS
3. I feel ___ (very happy/very sad)	- 9 ± 16	+ 6 ± 9	$P<.025$
4. I feel ___ (very cold/very hot)	+ 6 ± 18	+ 1 ± 14	NS
5. I feel ___ (very fatigued/very energetic)	+ 8 ± 26	- 13 ± 28	NS
6. I feel ___ (very tired/very awake)	+ 11 ± 23	- 14 ± 23	$P<.05$
7. My mouth feels ___ (very moist/very dry)	+ 29 ± 26	+ 2 ± 23	$P<.025$
8. My stomach feels ___ (very full/very empty)	- 18 ± 28	- 8 ± 20	NS
9. I desire salt ___ (very much/very little)	- 3 ± 7	- 6 ± 7	NS
10. I desire water ___ (very little/very much)	- 17 ± 30	- 1 ± 5	NS
11. How pleasant would it be to drink some water? (not at all/very)	+ 17 ± 16	0 ± 7	$P<.005$
12. How thirsty are you? (not at all/very)	- 23 ± 31	+ 3 ± 14	$P<.05$
13. How hungry are you? (very/not at all)	+ 10 ± 54	+ 4 ± 43	NS
14. Do you have a headache? (not at all/severe)	- 9 ± 19	+ 9 ± 20	NS
15. How satisfied do you feel? (not at all/very)	+ 23 ± 22	- 2 ± 21	$P<.025$
16. How challenging is it for you to concentrate? (very/not at all)	+ 12 ± 16	- 8 ± 28	NS
17. How angry are you? (not at all/very)	- 2 ± 33	+ 6 ± 15	NS

Abbreviation: NS, not significantly different.
[a] measured at 2200 h and <0700 h;.
[b] while in a euhydrated state;.
[c] while in a dehydrated state. Note: although the order of these 17 items and the left-right orientation of word anchors were randomized in the paper packets presented to participants, the left word anchors above (in parentheses) represent the lowest score of 0 and the right word anchors represent the highest score of 100.

Table 4
Change of VAS ratings that resulted from a 30-min unrestricted, ad libitum drinking session (R_{30}) on Day 3. R_{30} marked the end of the 24-h water restriction period.

VAS Statements/Questions	Mean VAS rating immediately before R_{30}	Mean VAS rating immediately after R_{30}	P level
1. I feel ___ (very weak/very strong)	52 ± 17	64 ± 15	NS
2. I feel ___ (very anxious/very calm)	82 ± 16	80 ± 20	NS
3. I feel ___ (very happy/very sad)	30 ± 15	26 ± 18	NS
4. I feel ___ (very cold/very hot)	55 ± 12	43 ± 7	$P<.002$
5. I feel ___ (very fatigued/very energetic)	45 ± 20	61 ± 18	NS
6. I feel ___ (very tired/very awake)	41 ± 21	60 ± 21	NS
7. My mouth feels ___ (very moist/very dry)	77 ± 31	25 ± 19	$P<.00001$
8. My stomach feels ___ (very full/very empty)	69 ± 15	30 ± 18	$P<.00001$
9. I desire salt ___ (very much/very little)	94 ± 7	77 ± 20	NS
10. I desire water ___ (very little/very much)	87 ± 22	16 ± 18	$P<.0000001$
11. How pleasant would it be to drink some water? (not at all/very)	92 ± 12	28 ± 14	$P<.0000001$
12. How thirsty are you? (not at all/very)	84 ± 26	15 ± 10	$P<.0000001$
13. How hungry are you? (very/not at all)	46 ± 23	51 ± 25	NS
14. Do you have a headache? (not at all/severe)	8 ± 9	8 ± 11	NS
15. How satisfied do you feel? (not at all/very)	45 ± 21	72 ± 16	$P<.001$
16. How challenging is it for you to concentrate? (very/not at all)	67 ± 29	74 ± 25	NS
17. How angry are you? (not at all/very)	6 ± 9	4 ± 5	NS

Abbreviation: NS, not statistically significant. The Table 3 footnote applies to the orientation of word anchors above.

Table 5
Summary interpretations of perceptual changes, observed during the 24-h dehydration phase and after a 30-min rehydration session.

VAS ratings[a]	Interpretation of Perceptual Changes	
	24-h Water Restriction[b]	30-min Rehydration[c]
4. Cold-hot sensation	[d]	Slightly cooler
7. Mouth feeling	Dry	Moist
8. Stomach sensation	[d]	Full
10. Desire for water	Great desire	Little desire
11. Pleasant to drink?	Very pleasant	Unpleasant
12. Thirst?	Great thirst	Low thirst
15. Satisfied?	[d]	Satisfied

[a] VAS rating details appear in Table 2;.
[b] VAS ratings during the 24-h dehydration exhibited statistically significant changes that occurred concurrently with significant changes of thirst (Fig. 2);.
[c] these VAS ratings exhibited statistically significant changes after a 30-min rehydration session (Day 3 at 0800 h);.
[d] not included on the basis of criteria described in footnote [b] above.

VAS ratings were identified as significantly different ($P<.05$ to $P<.0000001$) in Tables 2-4. Values were self-reported by participants at four morning time points (Fig. 1): (A) the initial VAS rating (Day 1 at 0800 h); (B) the final measurement of ad libitum water and food intake, immediately before water restriction began (Day 2 at 0700 h); (C) the end of the 24-h water restriction period (Day 3 at 0700 h); and (D) immediately after the 30-min rehydration session (R30; Day 3 at 0800 h).

Discussion

In the present investigation, the 1.67 kg mean weight loss that resulted from 24 h of water restriction represented 2.12% of mean body mass (Table 1). To provide context, a 2% dehydration level has been recognized as a threshold for decreased cognitive performance in tests of short-term memory, attention, visual-motor tracking [25], motor coordination, and executive function [48]. Surprisingly few studies have evaluated the effects of mild dehydration (<2% of body mass) on thirst, moods and subjective perceptions. Because the relevant scientific literature is inconclusive, we identified which somatic sensations, perceptions, and moods appeared and changed in concert with thirst; this supports the concept that drinking behavior is motivated by more than perceived thirst. Table 2 (column 4) acknowledges 8 VAS ratings which significantly changed during the 24-h dehydration phase (Day 2). Three VAS ratings (i.e., mouth dryness, desire for water, and pleasantness of drinking) occurred concurrently with changes of the VAS ratings of

Table 6

Intercorrelations of VAS ratings at morning time points representing euhydration (A and B), dehydration (C), and rehydration (D).

A

Initial VAS Rating Day 1 at 0800h	1. weak / strong	3. happy / sad	4. cold / hot	5. fatigued / energetic	6. tired / awake	7. moist / dry mouth	8. full / empty stomach	10. desire water?	11. pleasant to drink?	12. thirsty?	15. satisfied?
1. weak / strong	1.00										
3. happy / sad	-0.89	1.00									
4. cold / hot	0.32	-0.47	1.00								
5. fatigued / energetic	0.82	-0.65	0.20	1.00							
6. tired / awake	0.69	-0.64	0.06	0.75	1.00						
7. moist / dry mouth	-0.40	0.43	-0.15	-0.36	-0.48	1.00					
8. full / empty stomach	-0.14	0.07	-0.03	-0.30	-0.40	0.20	1.00				
10. desire water?	-0.44	0.54	-0.33	-0.33	-0.31	0.46	0.40	1.00			
11. pleasant to drink?	-0.47	0.47	-0.27	-0.49	-0.16	0.32	-0.09	0.20	1.00		
12. thirsty?	-0.52	0.45	-0.29	-0.58	-0.60	0.58	0.62	0.45	0.45	1.00	
15. satisfied?	0.72	-0.65	0.37	0.66	0.41	-0.40	-0.37	-0.40	-0.34	-0.47	1.00

B

Final Euhydration Rating Day 2 at 0700h	1. weak / strong	3. happy / sad	4. cold / hot	5. fatigued / energetic	6. tired / awake	7. moist / dry mouth	8. full / empty stomach	10. desire water?	11. pleasant to drink?	12. thirsty?	15. satisfied?
1. weak / strong	1.00										
3. happy / sad	-0.64	1.00									
4. cold / hot	0.68	-0.31	1.00								
5. fatigued / energetic	0.77	-0.50	0.58	1.00							
6. tired / awake	0.52	-0.49	0.14	0.74	1.00						
7. moist / dry mouth	-0.49	0.06	-0.70	-0.50	-0.20	1.00					
8. full / empty stomach	-0.07	-0.17	-0.29	-0.13	-0.14	0.39	1.00				
10. desire water?	-0.14	-0.35	-0.19	-0.25	0.13	0.23	-0.07	1.00			
11. pleasant to drink?	-0.33	-0.23	-0.42	-0.31	0.03	0.25	-0.01	0.76	1.00		
12. thirsty?	-0.08	-0.35	0.06	-0.02	0.18	0.10	0.02	0.82	0.61	1.00	
15. satisfied?	0.15	-0.25	0.29	0.51	0.63	-0.06	-0.42	0.16	-0.10	0.36	1.00

C

Final Dehydration Rating Day 3 at 0700h	1. weak / strong	3. happy / sad	4. cold / hot	5. fatigued / energetic	6. tired / awake	7. moist / dry mouth	8. full / empty stomach	10. desire water?	11. pleasant to drink?	12. thirsty?	15. satisfied?
1. weak / strong	1.00										
3. happy / sad	-0.34	1.00									
4. cold / hot	0.15	0.18	1.00								
5. fatigued / energetic	0.81	-0.37	0.04	1.00							
6. tired / awake	0.37	-0.24	0.09	0.60	1.00						
7. moist / dry mouth	-0.60	0.53	-0.01	-0.58	-0.70	1.00					
8. full / empty stomach	-0.22	-0.48	-0.09	-0.07	0.06	-0.12	1.00				
10. desire water?	-0.43	0.43	0.06	-0.62	-0.79	0.88	-0.12	1.00			
11. pleasant to drink?	-0.39	0.34	-0.08	-0.59	-0.78	0.88	-0.15	0.94	1.00		
12. thirsty?	-0.46	0.42	0.02	-0.62	-0.81	0.90	-0.12	0.99	0.93	1.00	
15. satisfied?	0.30	-0.16	0.16	0.45	0.78	-0.64	-0.16	-0.78	-0.70	-0.76	1.00

D

After 30-min Rehydration Day 3 at 0800h	1. weak / strong	3. happy / sad	4. cold / hot	5. fatigued / energetic	6. tired / awake	7. moist / dry mouth	8. full / empty stomach	10. desire water?	11. pleasant to drink?	12. thirsty?	15. satisfied?
1. weak / strong	1.00										
3. happy / sad	-0.41	1.00									
4. cold / hot	-0.10	0.09	1.00								
5. fatigued / energetic	0.86	-0.29	-0.08	1.00							
6. tired / awake	0.77	-0.35	-0.37	0.68	1.00						
7. moist / dry mouth	-0.48	0.60	-0.06	-0.47	-0.61	1.00					
8. full / empty stomach	-0.21	0.38	0.15	-0.09	-0.43	0.61	1.00				
10. desire water?	0.07	-0.28	-0.32	-0.12	-0.08	0.44	0.43	1.00			
11. pleasant to drink?	-0.09	0.27	-0.08	-0.07	-0.14	0.53	0.39	0.39	1.00		
12. thirsty?	-0.32	0.23	-0.11	-0.30	-0.41	0.77	0.52	0.66	0.75	1.00	
15. satisfied?	0.05	-0.22	0.23	0.10	0.22	-0.18	-0.35	-0.15	-0.08	-0.17	1.00

Note: Shaded cells indicate strong correlations ($r \geq 0.70$; $P < .01$).

thirst (Tables 2 and 4, Fig. 2). These 4 ratings are compared to those observed after rehydration (R$_{30}$) in the section below titled, Perceptual changes following rehydration. Significant changes in VAS ratings of satisfaction and strength (Fig. 2C) did not appear concurrently with changes of thirst.

In 6 previous studies that assessed the effects of mild dehydration via $\geq$24 h water restriction on subjective perceptions, the most commonly identified effects of dehydration were increased thirst [5,16,25,28,42,44] and decreased alertness (3/6 studies). No other subjective perception was reported (i.e., as significantly affected by dehydration) in more than 2 of these 6 studies. We propose three explanations for these heterogeneous findings. First, these studies focused on different moods and subjective perceptions; with few exceptions, the VAS ratings in Table 2 are unique to the present investigation. Second, 2 of these studies involved only women [32,44] and 2 included only men [31,36]. The effects of mild dehydration on perceptions may be sex-specific [5,16,46]. Third, the research environment may have influenced moods and subjective perceptions. Three of these 6 studies were conducted in a laboratory, hospital, or nutrition research center [31,32,33,46], and 3 allowed test participants to conduct daily activities with scheduled visits to the laboratory for measurements, as was done in the present investigation [36,42,44].

Perceptual effects of mild dehydration appeared at ∼0.5% body mass loss. The variables that significantly changed on Day 2 (Table 2, column 4) are depicted in Figs. 2-5, to illustrate within-day (time of day; ˆ symbol) and between-day (dehydration; * symbol) effects. In Figs. 2A and 2B, all variables exhibited statistically significant, intense responses to dehydration on Day 2 whereas significant time of day effects occurred on Day 2 (beginning at approximately 1200 h) but not on Day 1. These values are relevant to our second investigational goal (i.e., to determine the onset time and duration of dehydration-induced changes). Figs. 2A and 2B also show that a statistically significant increase of these four variables occurred at a body mass loss of ∼0.5% (i.e., at approximately 1200 h) during daily activities, less than the classic estimates of 1–2% body mass loss during exercise-heat stress [2,20]. In comparison, Fig. 2C illustrates a significant dehydration effect that reduced the perception of feeling strong later in the day (1700–2200 h), whereas Figs. 2C and 2D show that few or no significant effects of dehydration were observed for satisfaction, fatigue-energy, and tired-awake ratings.

Recently developed optogenetic technologies have revealed competition among innate motivations and sensory drives regulated by neurons. Feeding and drinking behavior studies using advanced in vivo methods demonstrate that Sherrington's "singleness of action" principle presented in 1906 [41] can be observed on a neuronal cell level in animal models; for example, hunger sensations in mice activated by specific neurons suppress competing motivational systems such as thirst, anxiety, fear, and social interaction [13]. Optogenetic experiments isolating the relative hierarchy of thirst among other behaviors (i.e., as they influence drinking behavior) have not been conducted to this date, but our data support the functional outcome of human perception by demonstrating a contextual hierarchy of perception and likely of behaviors. In other words, perceptions that were not affected by mild dehydration may represent suppressed sensations even in a mildly dehydrated state.

Within-day effects of mild dehydration. Although some moods and subjective perceptions follow circadian patterns [26], the 4 VAS that changed significantly during water restriction did not show significant effects of time when participants were euhydrated on Day 1 (see open symbols in Figs. 2A and 2B). However, the VAS ratings of fatigued-energetic and tired-awake perceptions exhibited significant within-day changes between 2000 and 2200 h on both days (see ˆ symbols in Fig. 2D on Days 1 and 2), with no between-day effect of dehydration. Considering a simple interpretation, these tendencies toward fatigue and tiredness (Fig. 2D) could be attributed to accumulated fatigue and need for sleep, late at night. Research indicates, however, that VAS ratings of human moods are influenced by a multifaceted and nonadditive interaction of circadian phase and duration of prior wakefulness that is beyond the scope of the present investigation [11].

During the overnight periods of this investigation (Fig. 1), body mass losses were mild (0.52 kg, 0.7% both nights). However, the state of mild dehydration (Day 2) resulted in significantly different overnight changes of moods and subjective perceptions when compared to euhydration (Day 1). The significant differences due to dehydration (Table 3; range, $P<.05$ to $P<.00005$) are summarized as follows (VAS item numbers in parentheses): weaker (item 1), sadder (3), more tired (6), drier mouth feeling (7), and less satisfied (15); with regard to pleasantness of drinking water (11) and thirst (12), the mean VAS ratings indicated virtually no change from the night of Day 2 to the morning of Day 3, suggesting that these ratings were intense (i.e., nearly maximal) before sleep and changed little overnight. These summary interpretations include the assumption that sleep was similarly refreshing/restorative on both nights (not measured).

Perceptual changes following rehydration. The third goal of this investigation focused on subjective perceptions that were affected by the 30-min rehydration session (R_{30}). As presented in Table 4, the strong perceptions of thirst, mouth dryness, desire for water, and pleasantness of drinking were significantly reversed during R_{30}. Not surprisingly, the perception of stomach fullness increased significantly following the mean water intake of 1.46 ± 0.47 L, as did the VAS rating of satisfaction. Thermal sensation also changed significantly toward a slightly cooler state, and is considered in the following paragraph. These statistically significant findings indicate that thirst changes concurrently with other perceptions, somatic sensations and moods to influence whole body fluid-electrolyte homeostasis by reducing the motivation to seek and consume water. In contrast, 10 other VAS ratings were unchanged ($P>.05$) by drinking during R_{30} (Table 4).

Unexpectedly, the cold-hot perception changed significantly ($P<.002$) after R_{30}, representing an increased perception of cooling. Although unaffected by 24-h dehydration (−2.12%, Table 2), this perceived cooling after ingesting 1.46 L of fluid (Table 4) may have occurred because cold sensory nerves primarily exist in the anatomical periphery (i.e., tongue, oral cavity, skin [14]) and because cold afferent signals converge on the same brain regions that create the sensation of thirst. Specifically, both osmosensitive and thermosensitive neurons coexist in the subfornical organ, organum vasculosum of the lamina terminalis (i.e., which borders the hypothalamus), and paraventricular nucleus of the hypothalamus. Their efferent nerve signals modulate osmotic, fluid, and thermal homeostasis as well as the sensation of thirst [7,43]. The influence of the temperature of the fluid consumed during R_{30} (i.e., presented at room temperature, approximately 23 °C) is unknown. However, if oral temperature was 37 °C, drinking water at 23 °C would have been perceived by participants as cooling and moistening the oral cavity. Both cooling and moistening the tongue or oropharynx quenches thirst in humans and rats [7,50], theoretically increasing satisfaction and reducing the likelihood of excessive water intake [15]. These effects are consistent with all other perceptions that were measured after rehydration (Table 5, column 3).

Statistical regression analyses indicated that none of the 17 VAS ratings (i.e., including body mass loss) was significantly correlated ($P>.05$) with the volume of fluid consumed during R_{30} (analyzed using L and ml/kg body mass). It is reasonable that no single factor predicted the volume of fluid consumed because many subjective perceptions, oropharyngeal/gastric sensations, and osmoregulatory neural signals are integrated by the brain during such a 30-min rehydration session [7]. Also, inter-subject variability is large for a multifaceted process such as water intake (e.g., the volume consumed during R_{30} ranged from 0.94–2.17 L). This large variance has been attributed to differences in the ways that humans prioritize and integrate visceral, cognitive, motivational, and affective information [45].

Evidence of aversive moods after rehydration (R_{30}). A fully satiated, post-drinking state in humans involves discomfort, swallowing inhibition, and aversion to drinking [38]–all factors that reduce the likelihood of overdrinking. Human imaging experiments also have identified specific brain regions that are activated during overdrinking; these neural activations occur concurrently with, and are significantly correlated with, ratings of unpleasantness [37]. These observations are relevant to the VAS ratings in Tables 4 and 5, which indicate that perceptions were altered by recent fluid intake. In fact, two VAS ratings suggest that aversive moods (i.e., negative affect) were involved. First, the group mean response to the question, "How pleasant would it be to drink some water?" (Table 4, row 11) on the morning of Day 3 was extreme (92 ± 12 at 0700 h). After rehydration (1.46 L consumed), this VAS rating (28 ± 14 at 0700 h) indicated that drinking water would be unpleasant. A similar pattern of change was observed for the statement, "I desire water ___" (Table 4, row 10), before and after R_{30}. These mood changes suggest aversion to additional drinking, when the VAS rating of satisfaction increased. Analogous responses have been observed in rodents and humans during overdrinking [7].

Perceptual interrelationships. Table 6 presents four correlation matrices of VAS ratings that were self-reported by participants during the morning hours of Days 1–3. Shaded cells indicate strong statistical correlations ($r \geq 0.70$). The following text describes four insights, each of which can be stated as a testable hypothesis for future studies regarding dynamic perceptual relationships during changing hydration status. First, although decades of human [2,7,20,36] and animal studies [3,4,9] have focused on thirst as the primary impetus for seeking and consuming water, and have regarded thirst as an adequate stimulus for fluid replacement during sedentary daily activities [20], correlation matrix 6C and Tables 2-4 show that the perception of mouth dryness increased concurrently with thirst, desire for water, and pleasantness of drinking. Similarly, previous human research has reported an association between mouth/pharyngeal sensations and drinking behavior [7,36,50]. Thus, we recommend that future studies assess the relationships between mouth sensations and perceived thirst as they influence drinking behavior. Second, a previous human study involving 24-h water deprivation [36] associated stomach fullness with attenuation of drinking. During the present investigation, stomach fullness increased markedly after rehydration (R_{30}) on Day 3 (Table 4) but was not strongly correlated with the desire for water or pleasantness of drinking (range, $r = -0.15$ to $+0.43$) at any time point in Table 6. Third, the single VAS rating which alluded to tiredness (VAS item 6, I feel tired/awake) was strongly and negatively correlated (range, −0.70 to −0.81) with the following 4 variables at the point of peak dehydration (Day 3 at 0700 h; matrix 6C): thirst, moist/dry mouth, desire for water, and pleasantness of drinking. Thus, dehydration-related perceptions were associated with a feeling of tiredness (i.e., versus feeling awake; VAS item 6 in matrix 6C), but not a feeling of being fatigued (i.e., versus feeling energetic; VAS item 5 in matrix 6C). Similarly, other investigators have reported decreased ratings of alertness during water restriction [32,42,47] when employing a variety of cognitive instruments. Because the brain regions and mechanisms of these phenomena are unknown, we recommend that future studies assess an extended range of perceptions, sensations, and moods and observe regional activations during brain imaging.

Fourth, as noted in the Introduction section above, McKinley and colleagues [27] described thirst in water-deprived rodents as unpleasant and disagreeable. This sensation became more distressing as its intensity increased during prolonged dehydration, until the aversive state was extinguished by drinking. Table 6 presents similar phenomena in humans. The VAS ratings of thirst, mouth dryness, desire for water, and pleasantness of drinking were strongly and positively correlated during dehydration ($r = +0.88$ to $+0.99$; matrix 6C). During euhydration (matrix 6B) and rehydration (matrix 6D), fewer strong correlations were observed among these variables. Supporting Table 6, Figs. 2A and 2B show a concurrent within-day increase of these 4 VAS ratings during water restriction (ˆ symbols on Day 2) but not during euhydration. Table 4 further describes the nature of these perceptions; before rehydration (R_{30}), VAS ratings indicated great desire for water and great pleasantness of drinking (i.e., an aversive state), whereas immediately after R_{30} VAS ratings indicated little desire for water, and low pleasantness of drinking.

Evidence regarding central regulation. Although our understanding of the central nervous system creation and regulation of perceptions is incomplete, three lines of evidence inform the findings of the present investigation. The first arises from consistent and substantial animal research evidence [4,21] which describes an aversive state arising from specific brain regions (i.e., lamina terminalis; anterior cingulate cortex, ACC; insular cortex, IN) that initiates thirst and motivates the search for water. In addition, a recent human brain imaging study reported that mild dehydration influenced 8 brain regions [49], adding to previous imaging studies which observed activations in 10 other brain loci, when body water losses were induced by water restriction and exercise [6]. After rehydration, a different aversive state decreases motivation to drink and protects animals from overdrinking [9,21], in agreement with the summary interpretations of Table 5 (i.e., satisfied, little desire for water, unpleasant to drink). Indeed, both the human ACC and IN are deactivated (i.e., fMRI signal strength decreases) when drinking results in satiety [7,9]. Thus, it is likely that the aversive state of intense thirst and the aversive state of overdrinking arise from multiple brain regions, and generate specific motivational drives by activating-deactivating those brain regions. The second line of evidence clarifies the first and proposes that perceptions and motivations evolve during changing hydration status (Table 5) because unique neural networks are activated during dehydration and drinking [7]. In the rodent brain, for example, at least two neural pathways connect sensory centers (e.g., the lamina terminalis integrates extracellular osmolality, hormonal, and fluid consumption information) to the ACC and the IN, where the conscious perception, where the conscious perception of thirst reportedly arises [27]. In addition, Leib and colleagues [23] reported that, following fluid imbalance, multiple rodent brain signals are unified within the lamina terminalis and are differentially distributed, as they exit along at least three parallel nerve pathways that dissociate thirst, drinking, and cardiovascular responses. The third line of evidence arises from functional magnetic resonance imaging during controlled human experiments. These experiments indicated that autonomic nervous system activity influenced cognitive performance and mood negatively during mild dehydration (0.6% body mass loss) [49]. Subsequently, water consumption ameliorated the decline of fMRI brain activity and increased heart rate variability (i.e., an index of autonomic activity). The authors interpreted these findings to mean that mild dehydration and rehydration activated distinct counter-regulatory autonomic responses with affective consequences. These paradigms suggest research questions and experimental approaches to the future study of the complex, dynamic central nervous system regulation of perceptions.

Although the present investigation focuses on the evolution of subjective perceptions during changing hydration status, this emphasis is not meant to diminish the importance of physiological inputs to the brain; several regulated physiological factors are known to induce or inhibit thirst and influence drinking behavior, including blood concentration, volume, pressure, and hormone concentrations [36,43,50]. Recognizing this, our research team recently investigated the interactions of 4 thirst-relevant perceptions with physiological (i.e., subconscious, autonomic, neuroendocrine, homeostatic) variables during 24-h periods of euhydration, water restriction, and reestablished euhydration [6]. The data indicated that thirst and drinking behavior are influenced by both subconscious neuroendocrine responses and conscious perceptions in some situations (i.e., water restriction), and predominantly by conscious perceptions at other times (i.e., reestablished euhydration following 24-h of unrestricted drinking). This evidence supports a complex paradigm of thirst and satiation and reinforces previously published human research [12,35].

Summary. Thirst and mouth dryness are widely regarded as the primary perceptions by which humans detect their need to drink. However, the means by which human brain transforms these perceptions into drinking behavior, or extinguishes drinking after water consumption, are only superficially understood [23]. The present investigation (a) identified the onset time and duration of thirst and concurrent perceptions during water restriction, especially relative to 1% and 2% body mass losses; (b) demonstrated that thirst and mouth dryness appeared concurrently with, and were strongly correlated with, other perceptions and moods (i.e., pleasantness of drinking and desire for water) during water restriction (Day 2), but were weak or absent during euhydration (Day 1) and after a 30-min rehydration session (Day 3); and (c) observed unique differences (euhydration versus dehydration) in overnight changes of perceptions (Table 3). Considering the vast networks in the human brain, and because this investigation evaluated only 17 VAS ratings, it is likely that future studies will discover other relevant perceptions, moods, and emotions that motivate and extinguish drinking, as part of the regulation of body water volume and concentration.

Author contributions

Contributed to the research design, L.E.A., E.C.L., C.X.M.; All authors participated in Human Use Committee applications and approvals; Data and specimen analyses, L.E.A, C.X.M., E.C.L., A.C., G.E.W.G.; Funding acquisition, L.E.A., E.C.L., C.X.M.; Investigation and daily data collection, G.E.W.G., A.C., V.L., Y.S.; Project administration/supervision, L.E.A., E.C.L., G.E.W.G.; Writing the original draft, L.E.A., E.C.L.; All authors reviewed and approved the final version of this manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

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