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Mild Dehydration Affects Mood in Healthy Young Women[1,2]

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Abstract

Limited information is available regarding the effects of mild dehydration on cognitive function. Therefore, mild dehydration was produced by intermittent moderate exercise without hyperthermia and its effects on cognitive function of women were investigated. Twenty-five females (age 23.0 ± 0.6 y) participated in three 8-h, placebo-controlled experiments involving a different hydration state each day: exercise-induced dehydration with no diuretic (DN), exercise-induced dehydration plus diuretic (DD; furosemide, 40 mg), and euhydration (EU). Cognitive performance, mood, and symptoms of dehydration were assessed during each experiment, 3 times at rest and during each of 3 exercise sessions. The DN and DD trials in which a volunteer attained a ≥1% level of dehydration were pooled and compared to that volunteer's equivalent EU trials. Mean dehydration achieved during these DN and DD trials was −1.36 ± 0.16% of body mass. Significant adverse effects of dehydration were present at rest and during exercise for vigor-activity, fatigue-inertia, and total mood disturbance scores of the Profile of Mood States and for task difficulty, concentration, and headache as assessed by questionnaire. Most aspects of cognitive performance were not affected by dehydration. Serum osmolality, a marker of hydration, was greater in the mean of the dehydrated trials in which a ≥1% level of dehydration was achieved (P = 0.006) compared to EU. In conclusion, degraded mood, increased perception of task difficulty, lower concentration, and headache symptoms resulted from 1.36% dehydration in females. Increased emphasis on optimal hydration is warranted, especially during and after moderate exercise. J. Nutr. doi: 10.3945/jn.111.142000.

Introduction

Adequate fluid intake and homeostasis of total body water is essential for human health and survival, including maintaining brain function. Severe dehydration clearly produces decrements in cognitive function (1,2). For example, clinical observations demonstrate severe dehydration results in acute confusion and delirium (3). However, insufficient research has been conducted to determine if mild dehydration, at levels that may occur in healthy individuals during their ordinary daily activities, degrades cognitive performance, alters mood, or produces adverse symptoms.

Many studies use heat and exercise to produce dehydration. One of the most comprehensive (ambient temperature of 45°C with 30% RH[8]) assessed the effects of dehydration ranging from 1 to 4% in 1% increments in 11 healthy, young males aged 20–25 y (4). A serial addition test, word recognition test, and trail-making test were administered; all detected deterioration at 2–4% dehydration. A similar study (5) assessed the effects of dehydration at ~1, 2, and 3% body mass loss in 8 young males. Moderate exercise in the heat induced dehydration and behavioral testing was conducted in three environments: thermoneutral (37°C, 50% RH), hot dry (45°C, 30% RH), and hot humid (39°C, 60% RH). Tests included symbol substitution, concentration, and eye-hand coordination. Effects of dehydration were observed in two of three tests at 2 and 3% dehydration, but, in

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[8] Abbreviations used: DD, dehydration with diuretic treatment condition; DN, dehydration with no diuretic treatment condition; EU, euhydrated treatment condition; POMS, Profile of Mood States; PVT, psychomotor vigilance task; RH, relative humidity; T_{gi}, gastrointestinal temperature; VAS, visual analogue scale.

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the symbol substitution test, effects were observed only at 3% dehydration ($P < 0.05$). Other studies assessed information processing during simulated sporting events with similar outcomes (6–8); dehydration (from −1 to −4% body mass) impaired mood, choice reaction time, and vigilance. Collectively, these studies provide insight into the effects of mild-to-moderate dehydration on cognitive performance but not a clear indication of which aspects of cognitive performance are most affected by dehydration or its effects on mood, perceived effort, or symptoms. Furthermore, the high levels of heat used to induce dehydration may have interacted with dehydration to exacerbate degradation of cognitive performance (1).

The present investigation used a battery of tests of cognitive performance, mood, perceived exertion, and symptoms sensitive to various environmental and nutritional factors, including mild dehydration (9–11). To avoid confounding effects of high heat exposure, mild dehydration was induced by moderate exercise in a moderately warm environment (mean ± SD, 27.6 ± 0.8°C). Physiological variables associated with hydration state were also assessed. Volunteers were healthy, young females.

A problem with previous work in this area is the difficulty designing a double-blind study of dehydration (1). Therefore, this study disguised the treatment conditions from volunteers and investigators responsible for testing by using several procedures. Inclusion of a positive control condition, dehydration induced by combination of a diuretic and exercise, disguised the experimental conditions, because in one of two dehydration experiments, volunteers lost substantial fluid in urine. To further blind the experimental conditions, a pill (either diuretic or placebo) was administered prior to every experiment and some fluid, with the volume disguised, was consumed. We hypothesized mild dehydration would primarily affect mood and symptoms of dehydration and have modest effects on cognitive function.

Methods

Participants. Twenty-five females (age, 23.0 ± 0.6 y; body mass, 63.0 ± 10.3 kg) attended an informational briefing and gave informed voluntary consent to participate in this study, which was approved by the University of Connecticut Institutional Review Board for Human Studies. The women were selected from 30 volunteers. Any woman who consumed an extreme diet, had evidence of disordered eating, was taking medications that altered fluid-electrolyte balance, was restricting caloric intake, or had a chronic disease (e.g., renal dysfunction) was excluded from participation. Use of oral contraceptives for at least three consecutive months prior to this investigation was an inclusion criterion. Test participants were physically fit (i.e., could complete three walking exercise sessions/d) but were neither highly trained nor totally sedentary. Prior to this investigation, most participated in 30–60 min of exercise on 2–4 d/wk. All participants spoke English as their primary language.

Experimental design. In this crossover study, women participated in 3-day-long laboratory experiments: *1*) exercise-induced dehydration plus placebo capsule containing no diuretic (DN); *2*) exercise-induced dehydration plus a diuretic capsule (DD); and *3*) euhydration plus placebo capsule (EU). The order of assignment to each of the experiments was randomized. All experiments involved an identical exercise regimen, described below. A third party, not involved in data collection, randomized and counterbalanced the order of experiments. Test participants as well as investigators in the environmental chamber were unaware of the treatments, but an investigator who monitored water administration was not. The 3 experiments were conducted ~28 d apart during the 7-d placebo phase of each woman's oral contraceptive schedule. Prior to each experiment, participants presented their empty oral contraceptive pill packs to a female investigator to verify they were in the placebo phase of their contraceptive schedule. Because experiments were separated by 28 d to control for the menstrual cycle, males were not tested in this study. However, a separate study of males was conducted using a similar protocol during a different period of time.

Procedures. To become familiar with study procedures, each participant visited the laboratory for 3–5 preliminary sessions to practice cognitive tests and behavioral testing on a desktop computer while sitting at a workstation and a laptop computer while walking on a treadmill. When a woman's cognitive performance reached an asymptote on 2 consecutive days, she could participate in experiments.

Participants were instructed regarding adequate fluid intake and sleep prior to each experiment and refrained from consuming caffeine and alcohol for 12 h prior to each. To ensure all participants began each experiment in a euhydrated state, they consumed 240 mL of supplemental mineral water (i.e., above their usual/habitual water intake) on the night before testing and 240 mL of mineral water upon waking on the morning of testing. This was supplied as Volvic Natural Mineral Water (Danone), which contained the following dissolved substances (mg/L): calcium, 10; chloride, 8; bicarbonate, 65; magnesium, 6; nitrate, 1; potassium, 6; silica, 30; sodium, 9; and sulfates, 7 (109 mg/L of total dissolved solids). The mineral water also was consumed with a standardized breakfast and during the experiments (see below). Further, participants consumed the same meals for 24 h prior to each experiment to reduce the effects of variation in nutritional intake on outcome variables. The foods and beverages consumed prior to the first experiment (i.e., self-selected by each participant) were duplicated for the second and third experiments. Compliance was verified with dietary records of all food and beverages consumed during the 24 h before each experiment.

On the morning of each experiment, participants reported to the laboratory at 0800 or 0900 h and, after a blood sample was collected, consumed one capsule under the supervision of an investigator. Capsules were prepared by a licensed pharmacist (Compounded Solutions in Pharmacy), were identical in appearance, and contained either a diuretic (40 mg furosemide; Lasix) or placebo. Volunteers reported at two different times so testing could be staggered (times provided in the text are for women starting at 0800 h). Participants rested quietly in an anteroom adjacent to the testing rooms and consumed no food until 1000 h when a standardized breakfast was provided; it contained ~700 kcal (2929 kJ[9]) + 174 mL mineral water. They also consumed two small food bars as snacks [210 kcal (879 kJ)/feeding] immediately after the first (1350 h) and second (1550 h) cognitive test batteries. A blood sample was also collected at 1750 h.

At 1200, 1400, and 1600 h, participants entered the environmental chamber and began 40 min of dehydrating exercise (described below) then rested for 20 min. Participants began identical cognitive test batteries at 1300, 1500, and 1700 h. In the DN and DD experiments, the women consumed no water to replace water loss in urine or sweat, except for 50 mL after completing the first and second cognitive test batteries, to wet their palates and disguise the experimental condition. Procedures in the EU experiment were identical to the DN and DD experiments except fluid lost in urine and sweat was replaced by consuming an equal volume of mineral water during and after each exercise bout based on the individual's loss during that session. Ambient laboratory environmental conditions were controlled and monitored. In the anteroom outside the environmental chamber and in the cognitive testing room, air temperature was maintained at 23.0°C. Fluid lost in urine during the experiment was assessed by collecting each woman's total urine output. Sweat loss was calculated as the difference in body mass, corrected for urine production and fluid intake.

Exercise dehydration protocol. Participants performed 40 min of treadmill walking (5.6 km/h, 5% grade) in a moderate-warm environment to produce body mass loss without inducing hyperthermia. Inside the environmental chamber, where dehydrating exercise sessions were conducted, the air temperature was 27.6 ± 0.8°C, the RH was 49.4 ±

[9] 1 kcal = 4.184 kJ.

6.9%, and the wind speed was 3.5 m/s as provided by a floor fan. Body mass was measured (±50 g) every 13 min during exercise when participants briefly stepped off the treadmill onto a floor scale (Healthometer model 349KLX). Heart rate was measured every 10 min with a chest cardiotachometer (model S150, Polar Instruments). The T_{gi} was measured every 10 min of exercise by using an ingestible temperature sensor (CorTemp, HQ). On the morning of each experiment, each participant swallowed the sensor upon arrival to the laboratory. After every exercise session, participants left the environmental chamber, moved to a comfortable room (23.0°C, dimly lit, quiet), dried their skin and hair with a towel, and rested on a chair for 20 min.

The rating of perceived exertion scale [6–20 point scale (12)] was administered at 40 min of exercise; the extreme options on this scale were "very, very light" and "very, very hard." At the same time, a perceived leg muscle pain intensity rating was obtained from each woman (13). This scale ranged from 0 ("no pain at all") to 10 ("extremely intense pain, almost unbearable") and offered one unnumbered rating option beyond 10 ("unbearable pain").

To disguise the experimental condition, participants were unaware of their body mass, urine volume, and ingested fluid volume during experiments. This was accomplished by obscuring the body mass scale dial, collecting urine in individual aliquots and removing these samples from the room before placement in the urine collection container, and by providing mineral water in opaque, covered containers. In spite of these efforts, differences in urine flow between conditions may have been detectable by the women. However, upon completion of all testing, volunteers were not able to distinguish between the hydrated and dehydrated experiments.

Physiological variables at rest. A urine sample was collected shortly after participants arrived at the laboratory (0800 h) for evaluation of urine specific gravity via a hand-held refractometer. Immediately preceding the final cognitive test battery, the T_{gi} was recorded at rest (see previous section). A blood sample was collected when participants arrived at the laboratory (0800 h) and after the third cognitive test battery (1700 h). Osmolality was measured in both samples; lactate, glucose, and cortisol were measured in the 1700-h sample. Osmolality was measured in duplicate using a freezing-point depression osmometer (model 3250, Advanced Instruments). Lactate and glucose were analyzed (YSI 2300 Stat Plus) in duplicate using an automated enzymatic technique. Cortisol was analyzed using a competitive cortisol enzyme immunoassay technique (ELISA, DSL-10–2000; Diagnostic Systems Laboratories).

Cognitive test battery. Behavioral tasks were selected that assessed a broad spectrum of cognitive functions, from simple abilities to complex skills, including vigilance, reaction time, learning, working memory, and logical reasoning. Mood states and symptoms were also assessed. Testing was conducted 20 min after completing each exercise session in a quiet, dimly lit room (23.0°C) and took 45–50 min to complete. Computerized tasks (NTT Systems; Cognitive Test Software, version 1.2.4) were administered in the same order during each experiment.

Cognitive testing at rest. Testing at rest was conducted using desktop computer systems running the Windows operating system. Visual stimuli were presented on 49-cm (diagonal) LCD monitors (Acer model A1716F). Participant responses were input using keyboards (Razer Tarantul, model RZ03–00070100-R2U1) that recorded responses with a 1-ms response latency.

Scanning visual vigilance task. This test is sensitive to a wide variety of environmental conditions, nutritional factors, sleep loss, and very low doses of hypnotic drugs and stimulants (14,15). The participant continuously scans a computer screen to detect the occurrence of stimuli that are infrequent and difficult to detect. The volunteer detects a faint stimulus that appears randomly on a computer screen, approximately once per minute, then presses the space bar on the keyboard as rapidly as possible. The computer records whether or not a stimulus is detected and the response time (in milliseconds). Responses made >2 s after a stimulus was presented were recorded as false alarms. During the preliminary practice sessions, each volunteer's performance was adjusted to a criterion of ~60% correct detections.

PVT. This is a test of simple visual reaction time (16). A series of stimuli are presented at random intervals on a screen and the participant responds as rapidly as possible when a stimulus appears. Reaction time, false alarms, and number of lapses (long duration responses) are recorded. The test requires sustained attention and responses, performed by pressing a button in a timely manner, in response to a randomly appearing stimulus on the computer screen. This is the only portion of the cognitive test battery that was administered during treadmill exercise.

Four-choice visual reaction time test. Choice reaction time tasks are sensitive to the effects of nutritional factors on cognitive performance (10,17–19). Volunteers are presented with a series of visual stimuli at one of four different spatial locations on a computer screen. They indicate the correct spatial location of each stimulus by pressing one of four adjacent keys on the computer keyboard. Correct responses, incorrect responses, response latency, premature errors, and time-out errors (i.e., response latency > 1 s) are recorded for each test administration.

Matching to sample test. This test assesses short-term spatial memory (working memory) and pattern recognition skills (17,20). The volunteer is presented with a matrix of a red and green checkerboard on a color screen. The matrix appears on the screen for 4 s, then is removed during a variable delay involving a blank screen. After the delay, two matrices are presented on the screen: the original sample matrix and a second matrix that differs slightly (i.e., the color sequence of two of the squares is reversed). The volunteer selects the comparison matrix by touching keys that match the original sample matrix. The task lasts ~5 min. If a response is not made within 15 s, a time-out error is recorded. Correct responses and the response time to choose a matrix also are recorded.

Repeated acquisition test. This test assesses learning and short-term memory (17). The volunteer is required to learn a sequence of 12 key presses on the four arrow keys of a computer; this task requires ~10 min. The outline of a rectangle is presented on the screen at the beginning of a test. Each correct response fills in a portion of the rectangle with a solid yellow color, from left to right. Each incorrect response blanks the screen for 0.5 s. When the screen returns, the volunteer is at the same point in the sequence as before the incorrect response. The volunteer has to learn the correct sequence by trial and error. When a sequence is correctly completed, the rectangle fills, the screen blanks, and another empty rectangle reappears for the next test. A test ends when the volunteer completes 15 correct sequences. Each test consists of a new sequence that is randomly selected from a list of 32 different sequences. Incorrect responses and time to complete each test are recorded.

Grammatical reasoning. This 5-min test assesses language-based logical reasoning and has been used to assess the effects of various treatments on cognitive function (21). On each test, a logical statement, such as "A is preceded by B," is followed by the letters AB or BA. The volunteer decides whether each statement correctly describes the order of the two letters. The "T" key on the keyboard is pressed to indicate that a statement is true and the "F" key is pressed to indicate that a statement is false.

POMS questionnaire. The POMS is a widely used, brief, standardized inventory of mood states (22). It is sensitive to a wide variety of nutritional manipulations, environmental factors, sleep loss, and subclinical drug doses (14,17–20,23). The volunteers rate a series of 65 mood-related adjectives on a five-point scale, in response to the question, "How are you feeling right now?" The adjectives factor into six mood subscales (tension-anxiety, depression-dejection, anger-hostility, vigor-activity, fatigue-inertia, and confusion-bewilderment). A computerized version of the POMS was administered during treadmill exercise and during seated rest.

VAS. To complete these scales, the participant placed a mark on a 100-mm line between extreme answers at opposite ends of the line. The

extreme answers were "very strong(ly)" and "not at all strong(ly)." The questions were, "How hard was the effort required to complete these tests?," and "How hard did you have to concentrate to accomplish the tasks successfully?" Headache symptoms also were evaluated at the end of each cognitive test trial by rating the statement, "I have a headache."

Cognitive testing during exercise. In addition to cognitive testing at rest, during each treadmill walking session, three tests, the POMS, VAS, and PVT, were administered on a laptop computer (Sony, Vaio, model PCG-5G3L) placed on a stationary platform suspended in front of the participant while she walked at the required pace. Participants responded using a Razer DeathAdder mouse (model RZ01–00150100-R3M1) with a 1-ms response time.

Statistical methods. Statistical analyses were performed using IBM SPSS Statistics v19.0. Due to variability in rate and extent of dehydration over the course of the DN and DD experiments, statistical comparisons for all dependent variables were conducted only when a volunteer attained a level of dehydration ≥ 1% body mass loss. A criterion of 1% was established, because this is the lowest level of dehydration that has been suggested as capable of altering cognitive function (1,4,5).

Variability was expected, because dehydration was induced by moderate exercise in a temperate environment in the absence of hyperthermia. To determine whether levels of dehydration induced during DD trials compared to DN trials of ≥1% body mass loss were different, a paired *t* test was conducted comparing the change of plasma osmolality, a standard measure of hydration status, of these conditions at the completion of testing. The increase in osmolality from the beginning to end of the test day was nearly identical in the DN (11 ± 9 mOsm/kg) and DD (10 ± 6 mOsm/kg; $P = 0.58$) trials. In addition, a CI-based equivalence test demonstrated that the small difference in percent body mass changes in DN (−1.38 ± 0.20%) compared to DD (−1.37 ± 0.17%) were equivalent (<0.2%; $P = 0.93$). Therefore, data from the DN and DD conditions were pooled for analysis.

Results from cognitive tests in which participants had ≥1.0% body mass loss were combined, regardless of whether the dehydration occurred in the DN or DD trial, and were compared using a paired samples *t* test to the mean of the corresponding EU tests. This procedure resulted in ≤25 data pairs. A *P* value of ≤0.05 (2-tailed) was the criterion for significance. Values in the text are means ± SD.

Results

When participants reported for testing at 0800 h each day, there were no differences between treatment conditions in body mass, urine specific gravity, or self-reported sleep duration (**Table 1**).

For the DN and DD trials that resulted in a ≥1% weight loss, mean body mass decreased (−1.36 ± 0.16%). For the EU experiments, the fluid replacement regimen was deemed successful, because body mass declined very little (−0.12 ± 0.05%); for our test participants, this difference was equivalent to 48 mL of water in a total body water of 39.69 L (24).

Cognitive performance was for the most part not affected by mild dehydration. There were no significant changes in the scanning visual vigilance task with one exception (false alarms), PVT, four-choice reaction time test, matching to sample, repeated acquisition, and grammatical reasoning task (**Table 2**) at rest. The single aspect altered on the scanning visual vigilance task was false alarm errors ($P = 0.02$), which slightly increased in the dehydrated condition (Table 2). During exercise on the treadmill, performance on the PVT was not affected by dehydration (**Table 3**).

When testing was conducted on a desktop computer at rest (i.e., quiet room that was adjacent to the environmental chamber, 23.0°C, dimly lit), 3 of the 6 POMS subscales were adversely affected by dehydration. Participants reported increased anger-hostility ($P = 0.04$) and fatigue-inertia ($P = 0.003$) as well as a decrease in vigor-activity ($P = 0.03$) (Table 2) when dehydrated. The aggregate measure of POMS ratings, the total mood disturbance score also deteriorated when women were dehydrated ($P = 0.01$). The 3 VAS administered also detected adverse effects of dehydration [perceived task difficulty ($P = 0.004$); concentration ($P = 0.01$); headache ($P = 0.05$)]. During exercise, adverse effects of dehydration on the POMS subscales and VAS also were observed ($P \leq 0.05$) (Table 3).

Physiological measurements revealed that post-exercise T_{gi} and heart rate were greater ($P < 0.001$) following mild dehydration (≥1%) (**Table 4**). Resting T_{gi}, immediately before cognitive test administration was greater ($P = 0.004$) when participants were mildly dehydrated. The change of plasma osmolality throughout the experimental day (0800 to 1750 h) also was greater during ≥1% than during EU ($P = 0.006$); however, plasma concentrations of lactate, glucose, and cortisol were similar across these experimental conditions (Table 4).

TABLE 1 Morning body mass, urine specific gravity, and sleep status of female volunteers prior to testing in the dehydration (≥1%) or the EU condition[1,2]

Physiological variables	EU	≥1%	*P* value[2]
Body mass, *kg*	63.0 ± 10.5	63.4 ± 10.5	0.13
Urine specific gravity	1.014 ± 0.009	1.012 ± 0.006	0.31
Previous night's sleep, *h*	7.6 ± 0.9	7.7 ± 0.5	0.66

[1] Values are mean ± SD, $n = 25$ or 24 (sleep, due to a missing value in the EU condition). Data were analyzed using paired *t* tests that compared the dehydrated baseline values of each volunteer to that volunteer's EU values. DD, dehydration with diuretic treatment condition; DN, dehydration with no diuretic treatment condition; EU, euhydrated treatment condition.

[2] For the dehydrated conditions, DN and DD data were averaged if ≥1% dehydration was achieved at any time point during data collection.

Discussion

When female volunteers, at rest or during exercise, were dehydrated (mean loss of 1.36% body mass), vigor, fatigue, and aggregate mood, assessed by total mood disturbance score, were adversely affected. Perception of task difficulty and headache severity increased and ability to concentrate decreased when volunteers were dehydrated compared to their own EU (control) trials, at rest, and during exercise. Performance on most aspects of cognitive function assessed, including psychomotor vigilance, reaction time, working memory, and reasoning, was not affected during mild dehydration with the exception of a small increase in visual vigilance false alarm errors.

Limited data are available on mood, cognitive performance, ability to concentrate, headache, and perception of task difficulty when volunteers are at rest or actively exercising in a mildly dehydrated state. This study demonstrates that, not only at rest but also during moderate exercise, a wide variety of adverse changes occur in slightly dehydrated, young, healthy females. These may, in theory, interfere with motivation to continue exercise or other activities. Our findings are consistent with a study conducted by Szinnai et al. (11) in which dehydration was induced by fluid restriction for 28 h, resulting in a mean dehydration level of 2.6% body mass loss. In that study, aspects of mood similar or identical to those we assessed were degraded, with tiredness increasing and alertness and perceived ability to concentrate declining. As in our study, the perceived effort necessary for task accomplishment increased

TABLE 2 Cognitive performance, mood, and VAS ratings of female volunteers at rest in a quiet, dimly lit room during EU and dehydrated conditions[1]

Cognitive tests and their components	EU	≥1%	*P* value[2]
Scanning visual vigilance			
Correct responses, *n*	16.9 ± 4.4	16.5 ± 3.9	0.66
Reaction time, *s*	0.96 ± 0.20	1.00 ± 0.18	0.31
False alarms, *n*	2.6 ± 1.9	3.5 ± 2.9	0.02
Psychomotor vigilance test			
Correct hits, *n*	71.1 ± 2.0	70.8 ± 1.5	0.51
Premature errors, *n*	1.5 ± 1.1	1.3 ± 0.8	0.49
Reaction time, *s*	0.33 ± 0.05	0.33 ± 0.03	0.74
Four-choice reaction time			
Reaction time, *s*	0.36 ± 0.05	0.36 ± 0.04	0.94
Incorrect responses, *n*	3.6 ± 3.7	3.2 ± 4.1	0.42
Time-out errors, *n*	0.10 ± 0.20	0.24 ± 0.56	0.24
Matching to sample			
Correct responses, *n*	8.2 ± 1.7	8.0 ± 1.3	0.57
Time-out errors, *n*	0.39 ± 0.61	0.61 ± 0.59	0.16
Reaction time, *s*	3.9 ± 1.0	3.7 ± 0.9	0.40
Repeated acquisition			
Incorrect responses, *n*	19.1 ± 4.6	19.0 ± 3.8	0.90
Time to complete, *s*	12.7 ± 3.8	12.0 ± 3.9	0.23
Grammatical reasoning			
Correct responses, *n*	29.8 ± 2.2	29.5 ± 1.5	0.44
Incorrect responses, *n*	2.2 ± 2.2	2.5 ± 1.5	0.45
No response, *n*	0.04 ± 0.20	0.05 ± 0.20	0.33
Reaction time, *s*	2.5 ± 0.8	2.6 ± 0.9	0.45
POMS			
Tension-anxiety	9.3 ± 3.5	10.4 ± 2.8	0.14
Depression-dejection	17.7 ± 3.7	18.7 ± 4.5	0.33
Anger-hostility	14.5 ± 3.3	15.6 ± 3.1	0.04
Vigor-activity	−16.1 ± 4.7	−14.2 ± 2.4	0.03
Fatigue-inertia	14.6 ± 3.1	17.1 ± 2.5	0.003
Confusion-bewilderment	6.7 ± 2.6	7.7 ± 1.7	0.06
Total mood disturbance	46.6 ± 15.4	55.4 ± 15.1	0.01
VAS			
Task difficulty	1.9 ± 1.4	3.0 ± 1.5	0.004
Concentration	2.9 ± 2.1	4.2 ± 1.6	0.01
Headache	1.1 ± 1.8	2.3 ± 2.2	0.05

[1] Values are means ± SD, *n* = 25 comparisons. The number of women dehydrated ≥1% in DN after exercise bout 1 was *n* = 2, after exercise bout 2 was *n* = 14, and after exercise bout 3 was *n* = 24. In DD, no women were ≥1% dehydrated after exercise bout 1; 8 women were dehydrated ≥1% after exercise bout 2, and 23 women were dehydrated ≥1% after exercise bout 3. DD, dehydration with diuretic treatment condition; DN, dehydration with no diuretic treatment condition; EU, euhydrated treatment condition; POMS, Profile of Mood States; VAS, visual analogue scale.
[2] *P* values result from paired *t* tests comparing EU trials to the corresponding mean of DN (exercise-induced dehydration with no diuretic) and DD (exercise-induced dehydration plus diuretic) trials achieving dehydration of ≥1%.

with dehydration. Cognitive performance was not affected in that study, although some sex differences in performance were noted (11). In addition to Szinnai et al. (11), other studies have not found substantial changes in cognitive performance at dehydration levels <2% body mass loss including one we conducted in men (25,26). Our study demonstrates that a wide variety of mood states and symptoms are adversely affected at dehydration of 1.36% body mass loss, which is substantially less than the 2.6% induced by Szinnai et al. (11). In addition, we detected adverse effects in <8 h and these effects were present when individuals were both exercising and resting.

TABLE 3 Vigilance, mood, perceptions of performance and symptoms reported during treadmill walking in female volunteers during EU and dehydrated conditions[1,2]

Cognitive tests and their components	EU	≥1%	*P* value[3]
Psychomotor vigilance test			
Correct hits, *n*	72.1 ± 1.4	72.0 ± 1.8	0.73
Premature errors, *n*	2.3 ± 1.9	2.8 ± 2.3	0.40
Reaction time, *s*	0.29 ± 0.03	0.29 ± 0.03	0.88
POMS			
Tension-anxiety	9.8 ± 3.3	11.2 ± 3.8	0.075
Depression-dejection	18.5 ± 4.4	19.9 ± 5.7	0.21
Anger-hostility	15.0 ± 4.4	16.4 ± 5.0	0.23
Vigor-activity	−19.3 ± 5.5	−17.4 ± 3.7	0.04
Fatigue-inertia	13.3 ± 3.3	16.0 ± 4.9	0.003
Confusion-bewilderment	6.4 ± 2.2	7.5 ± 2.0	0.05
Total mood disturbance	43.7 ± 19.0	53.5 ± 20.8	0.04
VAS			
Task difficulty	1.9 ± 1.8	2.8 ± 1.7	0.03
Concentration	2.4 ± 2.1	3.6 ± 1.8	0.02
Headache	1.1 ± 1.7	2.2 ± 2.1	0.03
RPE	11.0 ± 2.0	11.3 ± 2.0	0.24
Pain rating	1.3 ± 1.1	1.4 ± 1.0	0.25

[1] Values are means ± SD, *n* = 25 comparisons. The number of women dehydrated ≥1% in DN after exercise bout 1 was *n* = 2, after exercise bout 2 was *n* = 14, and after exercise bout 3 was *n* = 24. In DD, no women were ≥1% dehydrated after exercise bout 1; 8 women were dehydrated ≥1% after exercise bout 2, and 23 women were dehydrated ≥1% after exercise bout 3. DD, dehydration with diuretic treatment condition; DN, dehydration with no diuretic treatment condition; EU, euhydrated treatment condition; POMS, Profile of Mood States; PVT, psychomotor vigilance task; RPE, rating of perceived exertion; VAS, visual analogue scale.
[2] PVT and POMS data were recorded on a notebook computer mounted on a stationary platform that was suspended in front of the participant during treadmill walking.
[3] *P* values resulted from paired *t* tests comparing EU trials to the corresponding mean of DN and DD trials achieving dehydration of ≥1%.

Information-processing when dehydrated during simulated sporting events has also been investigated with similar findings (6–8). During such events, dehydration (−1 to −4% body mass) impairs mood, choice reaction time, and vigilance. Although these studies assessed effects of mild-to-moderate dehydration on cognitive performance during simulated sporting events, they did not determine which aspects of cognitive performance are most affected, nor did they assess perceived effort or symptoms of dehydration.

The physiological mechanism(s) responsible for deterioration of mood and related factors due to dehydration is not known. Hypothalamic neurons detect dehydration (27) and may signal higher-order cortical brain regions regulating mood when initial physiological indicators of dehydration appear, resulting in adverse mood and symptoms. In humans, dehydration induced by thermal stress in the same range as this study modified fronto-parietal blood oxygen level-dependent response assessed by functional MRI without affecting cognitive performance (26). Given the critical physiological importance of maintaining hydration, adverse changes in mood and related perceptions may serve as a signal that evolved to alert humans before more severe consequences occur, such as degradation in performance. Once cognitive or physical performance is degraded, survival may be affected, because the ability to find water or respond to threats is diminished.

TABLE 4 T_{gi}, heart rate, and plasma constituents in female volunteers at the end of each experimental session while at rest[1]

Physiological measurements	EU	≥1%	*P* value[2]
Postexercise T_{gi},[3] *°C*	37.8 ± 0.3	38.1 ± 0.2	<0.001
Postexercise heart rate,[3] *bpm*	152 ± 15	161 ± 15	<0.001
Resting T_{gi},[4] *°C*	37.8 ± 0.4	38.1 ± 0.4	0.004
Resting plasma osmolality change,[5] *mOsm/kg*	3.5 ± 7.9	10.1 ± 6.1	0.006
Resting plasma lactate,[5] *mmol/L*	1.5 ± 0.9	1.2 ± 0.5	0.12
Resting plasma glucose,[5] *mmol/L*	4.8 ± 0.4	4.9 ± 0.3	0.15
Resting plasma cortisol,[5] *nmol/L*	92.7 ± 43.9	105.4 ± 39.2	0.11

[1] Values are means ± SD, $n = 25$ (resting and postexercise T_{gi}), 24 (heart rate, lactate, glucose, and cortisol, due to inability to complete a venipuncture), or 22 (osmolality, due to equipment malfunction). DD, dehydration with diuretic treatment condition; DN, dehydration with no diuretic treatment condition; EU, euhydrated treatment condition; T_{gi}, gastrointestinal temperature.
[2] Paired *t* tests compared EU trials to the corresponding mean of DN and DD trials achieving dehydration of ≥1%.
[3] At the end of the third 40-min exercise bout (27.6°C air temperature).
[4] At rest, immediately before cognitive test administration (23.0°C air temperature).
[5] At rest, immediately after cognitive test administration (23.0°C air temperature).

This study has a number of practical implications. Although cognitive performance was not substantially impaired in healthy, young females who were mildly dehydrated, key mood states including vigor, fatigue, perception of task difficulty, concentration, and headache were adversely affected by a small change in hydration. All these adverse effects were present during rest and moderate exercise. Therefore, at least in females, maintenance of optimal hydration is essential to ensure optimal mood and reduce symptoms, both at rest and during moderate exercise. Healthy females may lose only 1.36% of body mass during daily activities if they are not actively and regularly hydrating or are participating in exercise or sports, especially in a warm or hot environment (28,29). Females may also be more readily affected by modest levels of dehydration during phases of the menstrual cycle that disrupt fluid balance and alter mood (30,31). Changes in mood associated with premenstrual syndrome may be influenced by fluid shifts and the present data support this hypothesis (32). In addition, individuals at risk of dehydration due to age, infirmity, or medical conditions associated with dehydration such as diabetes may experience adverse moods, increased perception of effort, and headache when minimally dehydrated (33–35).

The findings of the present investigation are unlikely to result from confounding factors, such as an expectation of adverse effects of dehydration by volunteers or duration of exposure to exercise and stress, because these were carefully controlled. Procedures were implemented to ensure that volunteers and investigators were unaware of each test condition, including an active dehydrating drug treatment and placebo, as well as administration of a small volume of mineral water in all experiments. During a poststudy interview, volunteers could not identify test conditions. The within-participant design compared a woman's dehydrated behavioral data to her own hydrated experiment and controlled for the confounding effects of exercise duration or time of day. The effectiveness of the experimental manipulations to induce dehydration was confirmed by substantial increases in plasma osmolality during dehydration (Table 4). Osmolality is a widely used physiological marker of hydration state in research studies and clinical settings (28,36). However, other physiological changes due to mild dehydration (T_{gi} change of 0.3°C, heart rate change of 9 bpm) (Table 4) were minimal, making it unlikely that these factors affected mood (37).

In conclusion, this study demonstrates that, in healthy young women, mild levels of dehydration result in adverse changes in key mood states such as vigor and fatigue as well as increased headaches and difficulty concentrating, without substantially altering key aspects of cognitive performance. Future studies should determine the level of dehydration (i.e., >1.36% mass loss) at which cognitive performance initially is degraded in females and which aspects of cognition are most readily affected. We also recommend that the effects of dehydration on cognition be examined in young men and at-risk populations such as children, elderly individuals, and those with diabetes or stroke, because those medical conditions can result in dehydration (33–35,38).

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