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VOLUNTARY DEHYDRATION AND COGNITIVE PERFORMANCE IN TRAINED COLLEGE ATHLETES[1,2]

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Summary.—Cognitive and mood decrements resulting from mild dehydration and glucose consumption were studied. Men and women (total $N = 54$; M age = 19.8 yr., $SD = 1.2$) were recruited from college athletic teams. Euhydration or dehydration was achieved by athletes completing team practices with or without water replacement. Dehydration was associated with higher thirst and negative mood ratings as well as better Digit Span performance. Participants showed better Vigilance Attention with euhydration. Hydration status and athlete's sex interacted with performance on Choice Reaction Time and Vigilance Attention. In a second study, half of the athletes received glucose prior to cognitive testing. Results for negative mood and thirst ratings were similar, but for cognitive performance the results were mixed. Effects of glucose on cognition were independent of dehydration.

Adequate fluid intake is critical for performance, not to mention survival (Lamb, 2002; Shirreffs, Armstrong, & Cheuvront, 2004). The increased physical exertion during athletic performance may make fluid consumption particularly important, given the relationship between dehydration and increases in heat-related illness and decrements in physical performance (American Academy of Pediatrics, 2000; Lamb, 2002). Failure to replace lost fluids following physical exertion or heat exposure is known as "voluntary dehydration." In these cases, adequate fluids may have been ingested to satisfy the thirst response, but not sufficient to restore normal fluid balance (Greenleaf & Sargent, 1965). Fluid loss of as little as 2% of body weight increases fatigue and impairs physical performance (Lamb, 2002). It is common for athletes to lose between 2 to 4 kg of sweat during a game (Buskirk, 1977). For a 90-kg athlete, this fluid loss is

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roughly equivalent to 2 to 4% of body weight (Lamb, 2002). Further, during a particularly strenuous sporting activity such as marathon running, even greater sweat loss may occur, often in the range of 6 to 10% of body weight (Buskirk, 1977). Considerable attention has been given to adequate hydration and performance in athletes (Shirreffs, *et al*., 2004).

While physical performance decrements due to dehydration have been documented (Buskirk, 1977; Lamb, 2002), less research has focused on other performance such as cognitive ability. Though this topic is largely unexplored, the few studies to date suggest that moderate dehydration, losses as low as 2% of body weight, can impair performance on vigilance attention, short-term memory, perceptual discrimination, arithmetic ability, visuomotor tracking, and psychomotor skills (Gopinathan, Pichan, & Sharma, 1988; Cian, Koulmann, Barraud, Raphel, Jimenez, & Melin, 2000; Cian, Barraud, Melin, & Raphel, 2001; Baker, Conroy, & Kenney, 2007). Several experiments in controlled environments have examined the relative role of activity, humidity, and temperature on cognitive performance with varying extents of dehydration. Sharma and colleagues (Sharma, Pichan, & Panwar, 1983) observed that cognitive performance on a variety of tasks declined with increasing ambient temperature in young, heat-acclimatized Indian men. In dehydration sessions followed by physical exercise, primary dehydration to 2 or 3% loss in body mass resulted in a significant decline in cognitive performance (Sharma, Sridharan, Pichan, & Panwar, 1986). Gopinathan, *et al*. (1988) also induced moderate dehydration of 2 to 4% body mass loss using a combination of water restriction and exercise in a heated room, finding hydration-dependent decreases in short-term memory, arithmetic efficiency, and attention. The authors argued that performance on cognitively demanding tasks may be negatively affected when the dehydration stress diverts attention. Cian and colleagues also examined the effects of heat stress and dehydration on cognitive functioning (Cian, *et al*., 2000; Cian, *et al*., 2001). In these studies, participants were dehydrated by approximately 2.8% body weight either through heat exposure or treadmill exercise. They found impaired performance on perceptual tasks, short-term memory tasks, and psychomotor skills with dehydration.

Few studies have examined how fluid reintroduction may alleviate dehydration's negative effects on cognitive performance and mood. One study (Neave, Scholey, Emmett, Moss, Kennedy, & Wesnes, 2001) examined how water ingestion affected arousal and cognitive performance in young people following a 12-hr. water restriction. While cognitive performance was not affected by either water restriction or water consumption, water ingestion affected self-reported arousal. Participants reported increased alertness as a function of water intake. Rogers and coworkers

(Rogers, Kainth, & Smit, 2001) observed a similar increase in alertness following water ingestion in both participants with high and low thirst. Water ingestion, however, had negative effects on cognitive performance as a function of thirst. Participants' performance on a cognitively demanding task improved following water ingestion if thirst was high, but if thirst was low, performance declined. These studies indicate that low to moderate dehydration may alter cognitive performance. However, most of these studies combined heat and exercise to induce dehydration, making it difficult to disentangle effects of heat stress from those of dehydration. Further research is needed to assess the effects of dehydration on cognitive performance in temperate conditions.

Many of the physical effects of dehydration are readily reversed following water intake. However, various products purportedly enhance athletic performance more than water alone. Research examining the efficacy of sports beverages indicates that their intake results in better fluid balance restoration following exercise in comparison to water (Shirreffs, Aragon-Vargas, Keil, Love, & Phillips, 2007), but other drinks such as milk are also effective (Watson, Love, Maughan, & Shirreffs, 2008). Aside from water, the primary ingredient in sports beverages is dietary carbohydrates such as sucrose or glucose, and additional ingredients such as electrolytes and flavorings. Both electrolytes and carbohydrates appear to be important for recovery of blood volume, but it is not known how these ingredients may affect recovery of cognitive abilities following dehydration. Intake of dietary sugar appears to positively affect cognition (for a review see D'Anci & Kanarek, 2006). The notion that modest increases in circulating blood glucose concentration enhance learning and memory has gained considerable recognition (Gold, 1986, 1995; Lee, Graham, & Gold, 1988). Previous research indicates that such positive effects apply across age groups, including children (Benton, Owens, & Parker, 1994; Busch, Taylor, Kanarek, & Holcomb, 2002), young adults (Benton, Brett, & Brain, 1987; Benton & Owens, 1993; Mahoney, Taylor, & Kanarek, 2007), and older adults (Gonder-Frederick, Hall, Vogt, Cox, Green, & Gold, 1987; Hall, Gonder-Frederick, Chewning, Silveira, & Gold, 1989; Parsons & Gold, 1992; Manning, Stone, Korol, & Gold, 1998).

The present research explores cognitive and mood effects of dehydration and possible amelioration of these effects with sugar consumption. This research is particularly relevant to college athletes who frequently engage in physical exertion (placing them at higher risk for dehydration than nonathletes), followed by cognitive activity such as studying, reading, or problem solving. In other words, college athletes not only need to be able to follow plans and form strategies on the athletic field, but after practice, they must engage in activities pertinent to academics. The present experiment was designed to examine more fully the effects of dehydration on several cognitive indices. It was expected that mild dehydration would be associated with impairments in cognitive performance. Cognitive functioning was examined following team athletic practices under two conditions: euhydration and mild dehydration (losses of between 1% and 2% of body weight). A second experiment examined the interaction of dietary glucose and dehydration. It was hypothesized that the provision of dietary glucose would reduce the effects of dehydration on cognitive performance. Combined dehydration and sugar consumption is a realistic scenario for today's college athletes given the beverages and energy bars heavily marketed to them for use during and after vigorous workouts.

STUDY 1

Method

Participants

Thirty-one Tufts University athletes (16 men, *M* age = 19.9 yr., *SD* = 1.0; 15 women, *M* age = 20.6 yr., *SD* = 1.4) participated. Volunteers were recruited from teams engaging in high levels of aerobic activity and included men's and women's crew (rowing) and women's lacrosse. All participants had their annual athletics physical and had been cleared for athletic participation. Volunteers taking medication of any type, except oral contraceptives, were excluded. Participants received $100 compensation and participating teams received $500 for assistance in coordinating research time with team practice. All procedures were approved by the Tufts University–New England Medical Center Institutional Review Board.

Procedure

To ensure adequate hydration prior to team practice and prepractice weigh-in, participants received guidelines on fluid and food intake for study-participation days. The guidelines advised them to refrain from alcohol use for 24 hr., from caffeine for 6 hr., and from tobacco products for 2 hr. prior to testing. In addition to these guidelines, participants received one liter of water to be consumed, as a minimum, on the testing day. Participants weighed in (both nude and clothed) prior to, during (clothed), and following (nude and clothed) practice to assess body water loss (dehydration status). Participants in the dehydration condition were not given fluids during practice. Participants in the euhydration condition were given water throughout practice. All individuals participated in both hydration conditions; participants were randomly assigned first to either the euhydration or dehydration condition. Test sessions were scheduled on days when teams had heavy practices. For the crew team, this entailed 60 min. of high-intensity rowing on an ergometer machine with one break for weighing at 30 min. For the lacrosse team, this entailed about 75 min. of drills including sprints, passing, and defense work with one break for weighing at about 30 to 40 minutes.

After practice, participants provided a final nude weight and completed several computer and pen-and-paper cognitive tests assessing Vigilance Attention, Short-term Memory, Simple and Choice Reaction Time, Map Planning, Visual Perception, and Mathematical Addition (see below). These tasks have been validated in the literature to assess a wide range of cognitive processes and are sensitive to nutritional changes (Gopinathan, *et al*., 1988; Busch, *et al*., 2002; Mahoney, *et al*., 2007; D'Anci, Watts, Kanarek, & Taylor, 2009). Participants also completed standard thirst and mood questionnaires (Engell, Maller, Sawka, Francesconi, Drolet, & Young, 1987; McNair, Lorr, & Droppleman, 1994). At the end of testing, participants received food and water.

Athletes participated in a second session approximately a week later in the opposite hydration condition. Debriefing took place immediately following the last testing session.

Clothed body weights were taken in the presence of an experimenter, and participants were instructed at this time on use of the scale. For the greatest accuracy of pre- and postexercise body weights, participants provided nude body weights. To do this, they weighed themselves on a digital scale in complete privacy using instructions provided and then reported body weight to the researcher. Clothed and nude weights were compared to assess potential discrepancies in reporting weights.

Subjective Ratings

Thirst Sensation Scale (Engell, *et al*., 1987).—This scale provides a subjective measure of hydration and was administered prior to cognitive testing. Participants rated a series of thirst-related adjectives on a 10-point scale with anchors 1: Not at all and 10: Severe, using the response set of "How you feel at this moment." Example questions include "I feel thirsty," "I feel weary," and "My throat feels dry." Higher scores indicate a greater feeling of thirst. This scale has been shown to provide reliable and valid results in studies examining thirst and dehydration.

Profile of Mood States (McNair, *et al*., 1994).—This questionnaire is an inventory of subjective mood states. Each participant rated a series of 65 mood-related adjectives on a 5-point scale with anchors 0: Not at all to 4: Extremely, using the response set of "How are you feeling right now?" Example adjectives include "lively," "bitter," "sluggish," and "alert." Previous research has shown that the adjectives factor into six mood subscales: Tension, Depression, Anger, Vigor, Fatigue, and Confusion. Since self-perceived performance on cognitive tasks can influence mood, the questionnaire was administered prior to all cognitive tasks.

Cognitive Tasks

Short-term Memory.—Short-term memory was assessed using the Digit Span Forward task. Participants saw groups of numbers on a computer screen and then typed them from memory in the order presented. Each time the participant repeated a series correctly, the next series included one more number. If the participant could not correctly repeat the series, he saw a new series of the same length. If, again, he could not correctly repeat the set, the test was terminated. The participant's Short-term Memory Span equaled the length of the longest series of digits correctly recalled.

Simple Reaction Time.—A red square appeared at random intervals on the computer screen and the participant pressed a response key as quickly as possible when it appeared. The computer timer began when the shape appeared and ended when the participant responded. The dependent measure was reaction time.

Choice Reaction Time.—Either a red square or a blue circle appeared and the participant pressed a response key designated for each shape as quickly as possible. Timing began when the stimulus appeared and stopped with the participant's response. Dependent measures were reaction time and errors.

Map Planning.—Participants completed a map-planning test from the Kit of Factor-Referenced Cognitive Tests (Eckstrom, French, Harman, & Derman, 1976). They saw a grid-like map marked with letters along each side, and with buildings and roadblocks within it. They had to find the shortest route between two lettered places on the map as quickly as possible, avoiding roadblocks and passing along the sides of buildings.

Mathematical Addition.—Participants received a sheet of addition problems and had 5.0 min. to solve as many as possible (Gopinathan, *et al.*, 1988). There were more problems than could reasonably be completed in the allotted time. Dependent measures included the number of questions attempted and the number correctly solved.

Vigilance.—A Continuous Performance Task assessed the vigilance component of attention (Busch, *et al.*, 2002). Participants watched letters flashing on a computer screen at a rate of approximately one per second for 15 min. They looked for a particular letter target combination, e.g., "X" immediately followed by "B," and hit the space bar when they saw it. The dependent measures included overall accuracy, accuracy over time, type of error, and RT.

Visual Perception.—Participants performed a Mental Rotation task (Shepard & Metzler, 1971). Two shapes, made up of individual blocks put together at varying angles, appeared on the computer screen. Participants responded whether the two objects were a perfect rotation of one another, or a mirror image, by pressing designated keys. Dependent measures included accuracy and RT.

Data Analysis

Data were analyzed using paired *t* tests (euhydration versus dehydration) or two-way (hydration status × sex) analysis of variance (ANOVA). Hydration status (euhydration, dehydration) served as a within-participants measure and sex served as a between-participants measure. In tasks where measurements were taken at different time points, time was analyzed as a within-groups measure. In the visual perception task, angle of rotation was analyzed as a within-groups measure. Outliers, defined as scores greater than three standard deviations from the mean, were eliminated. Additional analyses included testing order, to check for learning effects in the crossover design. Only one test showed such an effect, Digit Span, so this effect is discussed in the results. Effect sizes for *t* tests are reported as *r* and for ANOVA as partial eta-squared (η^2_p). Alpha was set at $p < .05$.

Results

Two women did not complete the hydration portion of the experiment; data analysis reflects this unequal *n*.

Effects of water restriction

Loss of body weight (%) and Perceived Thirst were analyzed as a function of hydration status as checks on the manipulation of water restriction. Water restriction resulted in significantly greater body weight loss relative to water replacement ($F_{1,27} = 195.1$; $p < .001$; $\eta^2_p = 0.88$). Results also showed a significant hydration by sex interaction ($F_{1,27} = 6.72$; $p < .05$; $\eta^2_p = 0.20$). Men lost a greater percent body weight under the restricted condition relative to women ($t_{29} = -2.75$; $p < .05$; $r = .45$; see Table 1). Water restriction also resulted in significantly higher Perceived Thirst scores relative to water replacement ($t_{27} = -9.219$; $p < .001$; $r = .87$).

TABLE 1

Percent Body Mass Change (kg) Under Dehydrated and Euhydrated Conditions For Both Study One and Study Two; Data Are Expressed as Means (±*SD*)

	Dehydrated			Euhydrated		
	M	*SD*	*n*	*M*	*SD*	*n*
Study 1						
Men	–2.00	0.38	16	0.09	0.92	16
Women	–1.65	0.33	15	–0.23	0.40	13
All	–1.82	0.40	31	–0.05	0.74	29
Study 2						
Men	–1.44	0.03	13	–0.12	0.34	13
Women	–0.99	0.37	11	0.42	0.40	12
All	–1.23	0.41	24	0.14	0.52	25

Mood Scores

Scores on the Profile of Mood States varied as a function of hydration condition. Anger (t_{28}=–4.03; $p<.001$; $r=.61$), Fatigue (t_{28}=–3.19; $p<.005$; $r=.52$), Depression (t_{28}=–2.72; $p<.05$; $r=.46$), Tension (t_{28}=–3.27; $p<.005$; $r=.53$), and Confusion (t_{28}=–3.30; $p<.005$; $r=.53$) scores were all higher in the dehydrated condition, and Vigor (t_{28}=2.52; $p<.05$; $r=.43$) was significantly lower in the dehydrated condition. While there were no significant interactions between hydration condition and sex, there were some sex effects. Women scored higher on the Tension scale ($F_{1,27}=6.08$; $p<.05$; $\eta^2_p=0.18$).

Cognitive Tests

There were no overall effects of hydration condition on Digit Span performance. The data did show a learning effect across testing sessions. To offset this learning effect, an additional analysis examined first-session data, using hydration condition as a between-participants variable. This analysis showed that participants in the dehydrated condition performed better relative to those in the euhydrated condition ($F_{1,27}=5.55$; $p<.05$; $\eta^2_p=0.17$; see Table 2). There were no effects for sex alone or for sex and hydration status.

TABLE 2

Performance on Digit Span Forward and Choice Reaction Time (Reaction Time in msec. and Number of Errors)

	Dehydrated			Euhydrated		
	M	*SD*	*n*	*M*	*SD*	*n*
Choice Reaction Time (msec.)						
Men	484.12	67.32	16	499.95	80.85	16
Women	489.53	73.13	13	516.25	125.54	13
Total	486.55	68.79	29	507.26	101.61	29
Choice Reaction Time Errors						
Men	2.00	1.26	16	3.25	2.14	16
Women	2.77	1.69	13	1.62	1.71	13
Total	2.34	1.49	29	2.52	2.10	29
Digit Span						
Men	8.63	0.52	8	7.25	1.49	8
Women	8.14	1.22	7	7.50	1.31	8
Total	8.40	0.91	15	7.38	1.36	16

There were no effects of hydration status or sex on either Simple or Choice Reaction Time. However, the analysis showed an interaction between hydration status and sex for Choice Reaction Time errors ($F_{1,27}$= 9.59; $p<.01$; $\eta^2_p=0.26$). *Post hoc* analysis showed that men made fewer errors while under the dehydrated condition (Table 2).

There were no effects of hydration status on Map Planning or Mathematical Addition.

Continuous Performance Task data were divided into 5-min. intervals across the 15-min. test time. Reaction time increased over the successive 5-min. blocks ($F_{2,52} = 7.06$; $p < .01$; $\eta^2_p = 0.21$), showing decreased Vigilance over time. There was a hydration status-by-time interval interaction for reaction time ($F_{2,52} = 3.88$; $p < .05$; $\eta^2_p = 0.13$). Reaction time was stable over the 15-min. test for the euhydration condition, but increased over time in the dehydration condition (see Table 3). There was also a three-way interaction between time, sex, and hydration status ($F_{2,52} = 5.67$; $p < .01$; $\eta^2_p = 0.18$). Reaction time was stable for men over the entire test regardless of hydration status, but was higher overall in the dehydration condition. Reaction time for women was stable for the euhydration condition, but increased over time in the dehydration condition (see Table 3).

Due to experimental error, Mental Rotation data from three men were lost. Thus, the analysis includes 13 men. Mental Rotation data were analyzed as a function of angle of rotation (0–180 degrees in 30-degree increments). There were no effects of hydration status on the number of errors or RT. The results did show the typical Mental Rotation pattern with performance varying as a function of the angle of rotation ($F_{6,144} = 9.48$; $p < .001$; $\eta^2_p = 0.28$ for errors; and $F_{6,144} = 40.56$; $p < .001$; $\eta^2_p = 0.63$ for RT).

TABLE 3

Reaction Time For Hits in Seconds on the Continuous Performance Task Over Successive 5-Min. Response Intervals; Data Are Expressed as Means (±*SD*)

Interval	Dehydrated			Euhydrated		
	M	*SD*	*n*	*M*	*SD*	*n*
Men						
First 5 min.	1.10	0.03	16	1.06	0.02	16
Second 5 min.	1.10	0.03	16	1.07	0.02	16
Third 5 min.	1.10	0.03	16	1.07	0.02	16
Women						
First 5 min.	1.08	0.03	15	1.08	0.02	13
Second 5 min.	1.10	0.03	15	1.08	0.02	13
Third 5 min.	1.13	0.03	15	1.08	0.02	13
All						
First 5 min.	1.09	0.02	31	1.06	0.02	29
Second 5 min.	1.10	0.02	31	1.07	0.02	29
Third 5 min.	1.12	0.02	31	1.08	0.02	29

STUDY 2

Method

In Study 1, negative mood scores were elevated in the dehydrated condition. There were also effects of mild dehydration on cognitive performances. A slight decrement was seen in Vigilance Attention, as measured by the Continuous Performance Task, and a slight improvement seen with

Short-term Memory in the dehydration condition. The Vigilance Attention procedure in Study 1 was one of the more mentally taxing procedures, requiring sustained attention for 15 min. It was hypothesized that cognitive performance on more demanding tasks would be more greatly affected than performance on less demanding tasks (Busch, *et al.*, 2002). Study 2 follows up on these results, examining the additional effect of glucose intake on cognitive performance in college-aged individuals. Research has shown positive effects of glucose on cognition (Benton, *et al.*, 1987; Benton & Owens, 1993; Mahoney, *et al.*, 2007), and sports drinks including sugars have been heavily marketed to this age group. Changes in tests and procedures from Study 1 are noted below.

Participants

Twenty-four Tufts University athletes (12 men, *M* age = 19.7, *SD* = 1.4; 12 women, *M* age = 19.1, *SD* = 1.1) participated. All participants had undergone their annual athletics physical and were cleared for athletic participation by Tufts. Participants were recruited from University athletic teams and compensated as outlined in Study 1. Selected teams included men's and women's crew and football. None of the participants had participated in Study 1.

To assess the effects of mild dehydration and glucose consumption on cognitive performance, the athletes were recruited to participate in cognitive testing following regular team practice. Hydration procedures followed those outlined in Study 1. After practice, participants provided a final nude weight. Immediately after weighing, half of the participants received a palatable sugar candy (Pixy Stix: primary ingredient, dextrose with citric acid for flavoring) equivalent to 25 g dietary glucose. This amount has been used in other studies and has been successfully shown to have acute, positive effects on cognition (Busch, *et al.*, 2002).

Participants then completed several computer and pen-and-paper cognitive tests, including Vigilance Attention, Short-term Memory, Choice Reaction Time, Visual Perception, and Spatial Memory (see below for descriptions of the tasks that were changed from Study 1). Participants also completed thirst and mood questionnaires. At the end of testing, participants received food and water.

Athletes participated in a second session, approximately a week later, in the same glucose-consumption condition, but in the opposite hydration condition. Debriefing took place immediately following this second session.

Cognitive Tasks

Short-term Memory.—Short-term Memory was assessed using both backward and forward versions of the Digit Span task. The forward version followed the procedures described in Study 1. The backward task was added to increase task difficulty and required the participant to repeat the numbers in the reverse order. For the above example, if "3 9 7 2" appeared on the screen, the participant would type "2 7 9 3." The dependent variable for the digit span task was the number of digits correctly repeated.

Spatial Memory.—Spatial Memory was assessed using a Map Memory Test (Mahoney, *et al.*, 2007). A map with four fictitious continents divided into between 18 and 25 countries was shown on the computer. Country names appeared one at a time on the blank map. Each country name appeared for 4 sec. and then disappeared and another name appeared. The complete set of country names was cycled through twice in the same order. Then participants received a paper copy of the blank map and had 5 min. to fill in the country names.

Vigilance and Divided Attention.—The Continuous Performance Task was again used to assess the Vigilance component of attention. A simultaneous secondary distractor task added a Divided Attention component, and increased overall task difficulty. The primary task followed the procedures described in Study 1. For the secondary task, participants listened to a tape recording of beeps presented through headphones to their left and right ears. Participants were instructed to place a tick mark on a sheet of paper when they heard three beeps in a row in their left ear. The secondary task was intended as a distractor, and data were not analyzed.

Data Analysis

Data were analyzed using three-way (hydration × sex × glucose) analysis of variance. Hydration status (euhydration, dehydration) served as a within-participant measure and sex and glucose served as between-participants measures. In tasks where measurements were taken at different time points, time was analyzed as a within-groups measure. In the visual perception task, angle of rotation was analyzed as a within-groups measure. Outliers, defined as scores greater than three standard deviations from the mean on a given task, were eliminated from analysis. Analyses were conducted on order of testing, to assess whether there were learning effects in the crossover design. No tests showed learning effects in this study. Effect sizes for ANOVA are reported as partial eta-squared (η^2_p). Alpha was set at $p < .05$.

Results

One woman in the glucose-consumption condition did not complete the dehydration portion of the experiment. Data for one man in the no-glucose, hydration condition for Continuous Performance Task reaction time were lost. Data analyses reflect these unequal *n*.

Effects of Water Restriction

The hydration manipulation and all body weight measurements took place prior to glucose consumption, so glucose was not included in the body weight analysis. Water restriction resulted in greater percent body weight loss ($F_{1,22} = 200.77$; $p < .001$; $h_p^2 = 0.90$). There was a hydration status by sex interaction ($F_{1,22} = 13.6$; $p = .001$; $h_p^2 = 0.38$; see Table 1). Women lost less weight in the dehydration condition than men, and in the euhydrated condition, women tended to increase slightly in body weight with fluid replacement even though the amount of fluid they ingested was intended to match the amount lost. In the present study, participants lost less weight, compared to Study 1, under virtually identical testing and exercise conditions, suggesting that mild dehydration under temperate conditions can vary.

Water restriction resulted in significantly higher Perceived Thirst scores ($F_{1,22} = 13.25$; $p = .001$; $h_p^2 = 0.38$). Intake of a powdered glucose candy did not further affect thirst scores either in the presence or absence of water to drink.

Mood Scores

Scores on the Profile of Mood States varied as a function of hydration status. These data replicated Study 1. Scores for Anger ($F_{1,20} = 5.48$; $p < .05$; $h_p^2 = 0.22$), Depression ($F_{1,20} = 8.67$; $p < .01$; $h_p^2 = 0.30$), and Tension ($F_{1,20} = 10.19$; $p = .005$; $h_p^2 = 0.34$) were all higher in the dehydrated relative to the hydrated condition, and Vigor ($F_{1,20} = 5.92$; $p < .05$; $h_p^2 = 0.23$) was significantly lower in the dehydrated condition. There were no mood differences as a function of sex or glucose condition.

Cognitive Tests

There were no effects of hydration condition, sex, or glucose on Digit Span, Mental Rotation, or Choice Reaction Time performance. There were no main effects of hydration status on map memory, although there was a three-way interaction between sex, hydration condition, and glucose condition on the total number of countries left blank ($F_{1,20} = 10.38$; $p < .005$; $h_p^2 = 0.34$; Table 4). There was an interaction between sex and glucose con-

TABLE 4

Number of Blanks Left in the Map Recall Task; Data Are expressed as Means (±*SD*)

	Dehydrated			Euhydrated		
	M	*SD*	*n*	*M*	*SD*	*n*
Men						
No Glucose	7.57	1.68	6	5.86	1.63	6
Glucose	5.80	1.98	6	8.20	1.93	6
Women						
No Glucose	4.60	1.98	6	8.20	1.93	6
Glucose	9.57	1.68	5	7.57	1.63	6

dition for errors on the map memory task ($F_{1,20}=4.66$; $p<.05$; $h_p^2=0.19$). While men made similar numbers of errors in both conditions, women made fewer errors in the glucose relative to the no-glucose condition (Table 5).

TABLE 5
Number of Errors Made in the Map Recall Task as a Function of Glucose Intake; Data Are Expressed as Means (±*SD*)

	No Glucose			Glucose		
	M	*SD*	*n*	*M*	*SD*	*n*
Men	0.25	0.12	12	0.29	0.11	12
Women	0.58	0.12	12	0.10	0.13	12

There were no effects of hydration condition, sex, or glucose condition on Continuous Performance Task reaction time, total misses, or false alarms. Analysis over 5-min. blocks similarly yielded no effects of hydration, sex, or glucose on reaction time or total misses. When looking at false alarms, there was an interaction of glucose by time interval for inversion errors (GT instead of TG, for example; $F_{2,38}=3.59$; $p<.05$; $h_p^2=0.16$) over 5-min. test blocks (Table 6). As time increased, fewer inversions were made in the glucose relative to the no-glucose condition.

TABLE 6
Number of Inversion Errors on the Continuous Performance Task Over Successive 5-min. Response Intervals as a Function of Glucose Intake

	No Glucose			Glucose		
	M	*SD*	*n*	*M*	*SD*	*n*
First 5 min.	2.16	0.47	24	1.20	0.44	23
Second 5 min.	2.52	0.91	24	1.41	0.86	23
Third 5 min.	2.61	0.48	24	0.54	0.48	23

Discussion

In the present studies, dehydration was achieved in college athletes by restricting access to fluids during team practice. Dehydration was defined as a decrease in body weight, due to fluid loss, between the beginning and end of team practice. Under temperate indoor conditions (~23° C; ~45–55% humidity), only mild dehydration (1.5–2.0%) was achieved in active, physically fit young adults. Men were more dehydrated after restriction and exercise than were women.

In Study 1, mild and varied effects of hydration status were observed. These included slight decrements in Vigilance Attention and slight enhancements in Short-term Memory as a result of mild dehydration. For some tasks, hydration status had differential effects as a function of sex, as seen in the Choice Reaction Time: men made more errors while under the dehydrated condition, and women made more errors when under the euhydrated condition. Negative mood scores on all subscales of the Profile of Mood States were significantly elevated under dehydrated conditions, and Vigor scores were significantly lower under dehydrated conditions.

In Study 2, the same dehydration levels obtained in Study 1 were not achieved, despite using different athletes from the same team with similar environmental and exercise conditions and at the same time of year. In Study 2, the low levels of dehydration appeared to have little effect on cognition. Under dehydrated conditions, women who ingested glucose left more blanks on the Map Memory Task. Men in the dehydrated condition tended to do to the opposite. However, overall women made fewer errors on the Map Memory Task following glucose ingestion whereas men performed the same with and without glucose. For all participants, fewer inversion errors were made on the Continuous Performance Task following glucose intake relative to no glucose. As in Study 1, negative mood scores on all subscales of the Profile of Mood States , except for Confusion, were elevated under dehydrated conditions, and Vigor scores were significantly lower under dehydrated conditions.

In Study 2, it was hypothesized that more difficult cognitive tasks, such as Divided Attention and Map Memory, would be affected more by dehydration. Moreover, as previous research suggests that performance on more difficult tasks can be enhanced by glucose intake, it was expected that glucose intake would produce cognitive benefits on these tasks, and possibly offset dehydration-induced decrements. There were no consistent effects of glucose intake on cognition. Men and women had varied performances following glucose intake in Map Memory, and in the Divided Attention task glucose intake was only associated with a reduction of inversion errors. The only task to show differences as a function of both hydration status and glucose intake was Map Memory, and these differences also varied by sex. Men in the no-glucose condition left more blanks under the euhydrated than under the dehydrated condition, but in the glucose condition left more blanks under the dehydrated, relative to euhydrated, condition. Women's performance was the reverse of men's and more consistent with the predictions, despite women having lost less water weight. The differential response by sex to glucose and dehydration status deserves further attention.

Typically, dietary sugar intake produces greater improvements on difficult cognitive tasks relative to easy ones (Sünram-Lea, Foster, Durlach, & Perez, 2001, 2002; Kennedy & Scholey, 2004; Benton, 2005). Kennedy and Scholey (2004) reported that glucose enhanced performance more on tasks participants rated as difficult. Additionally, these researchers (Scholey, Harper, & Kennedy, 2001) found that blood glucose fell more sharply following more demanding tasks. On the basis of these and similar findings, it is hypothesized that difficult cognitive tasks require the brain to work harder than easier tasks. This mental work leads to a depletion of glucose and is reflected in a measurable drop in peripheral blood glucose (Scholey, *et al*., 2001). By consuming a food or beverage containing sugar, the resulting elevation in blood glucose levels enhances cognitive performance. Indirectly supporting this hypothesis, glucose does not typically increase performance in lower-demand cognitive tasks. The absence of a facilitating effect on easier cognitive tasks may represent a floor effect.

In these two experiments, the only consistent effect of mild dehydration was elevations of negative mood scores for all subsets of the Profile of Mood States scale: Fatigue, Confusion, Anger, Depression, and Tension, while Vigor was significantly suppressed with dehydration. These data suggest that mild dehydration influences cognition, but that mood may be more sensitive to negative fluid balance than cognitive performance. These data are consistent with other research examining mood in dehydrated participants. In an early study, Strydom and colleagues (Strydom, van Graan, Viljoen, & Benade, 1968) examined well-conditioned, young mens' physical performance under a variety of hydration conditions over several days. The men in the most restricted condition reported being "lethargic" and "morose" and that these symptoms worsened with increasing dehydration. In contrast, men given *ad libitum* access to water displayed "high morale and vigor" throughout the study.

The present studies had some methodological limitations imposed by the institutional review board and by the athletic teams. While the researchers were permitted to run the study and take body weights throughout practices, they were not permitted to disrupt athletes' concentration with specific questions about perceived exertion, or to ask the athletes to increase or decrease exertion. It was arranged to run the study during "hard practice" days, and the experiment was scheduled around these practices. It was also arranged that the same type of practice was used on both days of testing. The observations relating to hydration status were thus constrained to body mass changes and to the subjective thirst questionnaire, both of which gave consistent results with respect to hydration status within the bounds of the experiment. Body mass changes have come under criticism as an index of hydration status (Maughan, Shirreffs, & Leiper, 2007): absolute changes in body mass may not reflect true hydration status due to production of metabolic water, changes in the distribution of water in body water compartments, and fat oxidation. However, changes in body mass are still a useful and commonly used tool for field observations where more complicated measures of body composition are impracticable. In the present studies, the convergence of body mass change and perceived thirst adds additional validity to the use of such measures.

It should also be noted that these studies were conducted within an hour or two of high levels of aerobic activity. The literature examining exercise and cognitive performance is mixed, with some studies reporting decrements in performance, no effects of exercise, or improvements in performance following exercise (for a review, see Anish, 2005). It is possible that there were some carryover effects of exercise on mood and cognition in the present studies, and it is not known to what extent exercise and hydration status may interact. However, all participants engaged in similar amounts of activity, to which they were accustomed, under both euhydrated and dehydrated conditions. Additionally, while previous research shows that mood is significantly elevated after exercise (Osei-Tutu & Campagna, 2005), in the present studies, mood varied significantly as a function of hydration condition within one hour of physical activity, and cognitive testing occurred after moods were assessed.

Taken together, the available empirical evidence for the role of mild dehydration suggests a negative influence of dehydration on mood and cognitive performance. Indeed, mood appears to be particularly sensitive to hydration status and may be a useful index for mild dehydration in both experimental and real world conditions. Although there has been considerable interest in the effects of mild dehydration on both physiological and psychological performance, to what these effects may be attributed is still largely unknown. The support for diminished cognitive performance with mild dehydration alone is weak and, in some cases, conflicting (D'Anci, 2005). Studies differ widely in the means of inducing dehydration and the duration of dehydration, as well as in measuring dehydration status. Furthermore, "mild" and "moderate" dehydration are somewhat difficult to quantify, and little is understood about how hydration status across different ages affects cognitive behavior. Very little research has directly examined cognitive effects of dehydration in children (D'Anci, Constant, & Rosenberg, 2006). While older adults may be more susceptible to dehydration resulting from reduced thirst and hypodypsia, they may also be more sensitive to dehydration-related decrements in cognitive performance (Ainslie, Campbell, Frayn, Humphreys, MacLaren, & Reilly, 2002). Little research is available in this population as well. Future research using well-controlled methods for achieving dehydration is needed in both children and older adults.

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