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Cognitive Performance May be Impaired by Exercise in a Hot, Humid Environment: A Preliminary Investigation

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Abstract: The purpose of this study was to examine the effects of acute active dehydration by exercise in a hot, humid environment on cognitive performance. Our findings were inconclusive compared to previous studies that reported decreased cognitive performance in manual laborers and military personnel working in extreme environmental conditions.

Dehydration, or the loss of body water, negatively affects physical performance (Sawka, 1992). Limited research (Cian, Barraud, Melin, & Papel, 2001; Cian et al., 2000; Gopinathan, Pichan, & Sharma, 1988; Sharma, Sridharan, Pichan, & Panwar, 1986) suggests that cognitive performance may also be impaired; however, methodological flaws limit the applicability of these findings to the physically active population. Normal cognitive function is important for peak sport performance, particularly during high speed, high risk sports such as football, soccer, rugby, or auto racing. Small decrements in one or more components of cognitive performance such as concentration, attention, reaction time, and cognitive processing speed may affect individual and team performance and may predispose an individual to injury.

A recent literature review (Sawka, 1992) establishes that dehydration commonly ranging between 2 – 8% body weight loss negatively impacts physical performance by decreasing muscular strength, power, and endurance. Previous studies (Jimenez et al., 2002; Weiskopf et al., 2000) have demonstrated that exercise in the heat commonly results in moderate dehydration of 3 – 4% of body weight loss. During moderate dehydration, plasma volume is diminished by as much as 17%, resulting in decreased stroke volume and cardiac output and inducing cardiovascular strain. Although clinicians are trained to identify mental confusion, impaired memory, or reduced attention as signs of dehydration (Cian et al., 2000), limited understanding of the physiological mechanisms causing these mental deficits exists. It is possible that this reduced blood volume results in decreased the blood flow through the brain resulting in some level of cognitive impairment. Increased levels of the stress hormone cortisol have been reported during dehydration and may be related to impaired cognition and memory functions (Weiskopf et al., 2000). Unfortunately, the physiological mechanisms explaining the cognitive impairments associated with dehydration remain largely theoretical.

A paucity of studies examining subjects' cognitive performance before and after dehydration exists and no studies to our knowledge examine athletes. Initial results suggest that dehydration negatively affects mental performance (Cian et al., 2000; Gopinathan et al., 1988; Sharma et al., 1986) in manual laborers, military personnel, and volunteers dehydrated up to 5% body mass loss. Previous studies have demonstrated that cognitive performance impairment was proportional to the degree of dehydration and significant differences were found at 2 – 3% dehydration for all neuropsychological tests administered. Peak sport performance in extreme environments is more demanding and requires more physical resources than occupational activities. The physically active population has not yet been studied and few studies have used the latest technological advances in neuropsychological testing to identify the effects of active dehydration by exercise in a hot, humid environment on cognition. Therefore, the purpose of this study is to identify the effects of dehydration on cognitive performance in physically active individuals using an Internet-based neuropsychological testing system.

Method

Research Design

Physically active males were tested before and after performance of a heat stress trial constituting a within subjects test-retest design. We measured cognitive performance on the Headminder™ Cognitive Stability Index (CSI) test in ten participants in two physiological conditions: euhydrated (normally hydrated) control condition and dehydrated (fluid deficit) experimental condition. The day prior to testing, each participant attended a familiarization session during which he was instructed on the proper use of a computer keyboard and mouse, familiarized with the Headminder™ CSI test, and baseline anthropometric measures were recorded. The following day, each participant reported to the Florida International University (FIU) Sport Science Research Laboratory wearing an athletic supporter, mesh shorts, a cotton t-shirt, sweat socks and running shoes. Each participant was asked to completely void urine and body mass data was recorded using a digital calibrated physician's scale. A euhydration body mass was confirmed at less than ±1% (or 0.4 kg) of baseline body mass. Each participant was then administered the euhydrated condition Headminder™ CSI test. Results were recorded, and each participant performed the heat stress trial consisting of 45-120 min of treadmill exercise in a hot and humid environment with limited fluid intake.

Immediately following the exercise trial, participants removed all clothing and towel dried for measurement of dehydrated condition nude body mass. After achieving the target body dehydration of a minimum of 3% body mass decrease, the recovery period consisted of participants relaxing in an air-conditioned environment to allow the effects of heat exposure and exercise to subside. The dehydrated condition Headminder™ CSI test was then administered, and results were recorded. Physiological measures were recorded throughout the study (e.g. heart rate, body temperature, blood pressure). At the conclusion of the data collection session participants were required to orally rehydrate with cool water until they returned to within 2% of their pre-exercise body mass.

Participants

Prior to participation in the study, potential participants completed a health history questionnaire and informed consent form approved by the Institutional Review Board. Participants were 10 healthy male volunteers (mean age = 25.6 ±1.6 years, weight = 80.3 kg ±4.3 kg) recruited from FIU and the surrounding community who had no history of heat-induced illness or head injury within the past year. Participants were screened for use of prescription medications, history of neurologic illness, and any motor or sensory impairment that would prevent reliable operation of the computer. Males were selected to reduce the variability of ovarian hormone levels and substrate utilization between genders during exercise (Cleary, Kimura, Sitler, & Kendrick, 2002). During a familiarization session the day preceding testing, participants were instructed to abstain from ingestion of alcohol, caffeine, non-prescription medication, and dehydrating behaviors (sauna, diuretics, sweat suits, etc.) for the duration of the study.

Instruments and Procedures

Mood ratings. Motivation and fatigue were assessed prior to each administration of the Headminder™ CSI test to identify confounding variables that may have affected cognitive performance on the Headminder™ CSI test. Motivation level was determined by administering a visual analog scale designed to present to the respondent a rating scale with minimum constraints

(Hocking, 2001). The visual analog scale consisted of a 13 cm line with the left side labeled "No Motivation At All" and the right side labeled "Highest Possible Amount of Motivation." Participants marked the location on the line corresponding to the amount of motivation experienced at that time. The mark on the line was measured from the left to the nearest 0.1 cm and recorded for data analysis. Fatigue severity was determined using a question reading "At this moment what is your severity of fatigue?" with a 9-point Likert scale response. The response scale consisted of 1 = not at all, 3 = mild, 5 = moderate, 7 = severe, 9 = worst imaginable.

Cognitive performance testing. Participants were tested on the Headminder™ CSI computerized cognitive test administrator (Headminder Inc., New York, NY). The Headminder™ CSI test is a 30-min internet-based test including: (a) questions about patient background, pertinent medical history, and computer familiarity; (b) neurocognitive subtests of reaction time, processing speed, memory, and attention/executive functioning; and (c) an optional mental status examination completed at the investigator's discretion. These cognitive tests are designed to detect statistically significant, clinically meaningful change in central nervous system functioning. All tests are administered and scored online via an Internet browser and results are accessible only to the test administrator who is responsible for interpreting and discussing test results with the participant. The Headminder™ CSI is designed for routine monitoring of healthy and/or at-risk individuals for detection of significant changes in memory, executive, or other cognitive functions consistent with various neurologic conditions. Using this "baseline" model, in which an individual's scores are compared to his/her own prior scores, even relatively small decreases in cognitive function can be identified as statistically significant. (Headminder, 2002)

The Headminder™ CSI is highly reliable and has concurrent validity with paper-and-pencil-type neuropsychological tests. The intra-test correlations for each of the moderately independent cognitive factors are: response speed r = .80, processing speed r = .78, memory r= .68, and attention r = .73. Cognitive factors and subtests measure of reaction time, processing speed, memory, and attention/executive functioning have moderate to large concurrent validity (ranging from .30 to .74) with the trail making test, symbol digit modalities test, symbol search, Bushke test, and digit span test. Current cognitive functioning on the Headminder™ CSI was reported as raw scores for response time on each of the subtests were used for data analysis.

Statistical Analysis

Statistical analyses were conducted on the participants' mood ratings and cognitive performance response time raw scores. Dependent t-tests were used to identify differences between the euhydrated and dehydrated conditions on raw scores of processing speed, response speed, memory, and attention and each associated subtest. Dependent t-tests were also used to analyze the hydration measures before and after the heat stress trial and recovery. Data were analyzed using the SPSS 11.0 for Windows Statistical Package (SPSS, Chicago, IL). Significance was set at $P \leq .05$ for all statistical analyses.

Results

Mood ratings. Participants rated motivation and fatigue prior to each cognitive performance test. Motivation ratings were not significantly different ($t_9 = 2.181$, $P = .057$) between conditions; however, motivation ratings did reveal a 17.86% decrease from the euhydrated (8.4 $\pm$1.8 cm) to the dehydrated condition (6.9 $\pm$2.9 cm). Fatigue severity ratings were significantly ($t_8 = -5.774$, $P = .001$) increased 62.48% from the euhydrated (2.00 $\pm$1.41) to the dehydrated (5.33 $\pm$1.73) condition.

Cognitive performance measures. Cognitive performance consisted of four factor scores with associated subtest response times (Table 1). The Headminder™ CSI processing speed factor composite raw score means revealed a significant (t_9 = -3.329, *P* = .009) 8.33% decrease (improvement) in the dehydrated condition (2.78 $\pm$.43) compared to the euhydrated condition (3.03 $\pm$.32). The symbol scanning subtest response time was significantly (t_9 = 6.692, $P \leq .001$) decreased 16.16% in the dehydrated (3.16 $\pm$.57 ms) compared to the euhydrated (3.76 $\pm$.17 ms) condition. No other factor scores were significantly different between the euhydrated and dehydrated conditions. The response direction 1 response time was significantly (t_9 = 6.692, $P \leq .001$) increased 4.59% in the dehydrated (.54 $\pm$.01 ms) compared to the euhydrated (.51 $\pm$.01 ms) condition. Although not significant (t_9 = 2.257, *P* = .051), the response direction 2 response time was decreased 5.05% in the dehydrated (.63 $\pm$.08 ms) compared to the euhydrated (.66 $\pm$.10 ms) condition.

Hydration measures. Measures of hydration status were compared between the pre- and post-heat stress trial periods. Body mass was significantly decreased (t_9 = 15.348, $P \leq .001$) as a result of the heat stress trial with participants losing an average of 3.27% or 2.56 kg. Urine color was significantly (t_9 = -6.128, $P \leq .001$) increased 26.0% in the dehydrated (mean = 6.34 $\pm$1.2) compared to the euhydrated (mean = 4.7 $\pm$1.5) condition. Urine specific gravity was not significantly (t_9 = -2.039, *P* = .072) different between conditions.

Discussion

This experiment was designed to identify the effects of heat stress trial-induced active dehydration on cognitive performance. Based on our limited sample, our results were inconclusive compared to previous investigations (Cian et al., 2000; Gopinathan et al., 1988; Sharma et al., 1986) that reported impaired cognitive performance on paper-and-pencil type tests with various confounding variables. Two previous investigations (Gopinathan et al., 1988; Sharma et al., 1986) concurrently stated that impairment recorded in mental performance was proportional to the degree of dehydration and was significant at 2-3% dehydration. In contrast with past research, our results found there to be both improvements and decrements in the level of cognitive performance functioning with an average dehydration of 3.27%. Previous studies (Gopinathan et al., 1988; Sharma et al., 1986) have examined trained soldiers and manual labor workers, whereas our study examined all ranges of people from the surrounding community not attributed to a nominal group. Trained individuals may have been prepared to perform their duties in a similar matter perhaps accounting for the similarities in test scores. Previous investigations (Gopinathan et al., 1988; Sharma et al., 1986) used traditional pencil and paper cognitive tests to determine level of functioning.

As technology has advanced, so has the means to administer neuropsychological testing. The Headminder™ CSI test is a robust neuropsychological examination tool that is very sensitive to small changes in outcomes. The Headminder™ CSI test was designed to measure cognitive functioning in a neurologically impaired individual or one that is recovering from a concussion. Test administration may occur over a time period of weeks or months. In the current study, participants were administered two tests within a short period of about 3 hours allowing the possibility of improvement as a confounding learning effect. Many participants openly expressed that they better understand the examination during the second administration, making it easier to perform the tasks associated with the test. To confound this limitation in the future, a preliminary practice administration of the Headminder™ CSI test should be performed prior to the prior to testing day.

The Headminder™ CSI test was administered to participants in a dehydrated condition following an exercise heat stress trial lasting up to 2 hours. Upon completion of the heat stress trial, participants relaxed in a thermoneutral environment for an average of 50.2 $\pm$17.05 min (range = 28 – 80 min). The recovery period was provided to allow participants' core body temperature to return to baseline and to reduce the effects of exercise fatigue from the heat stress trial. Nonetheless, participants' motivation level ratings were decreased and fatigue severity ratings were significantly increased prior to the second administration of the Headminder^{TM} CSI. Therefore, we must conclude that although participants had ample time to reach baseline core body temperature, cognitive performance on the Headminder^{TM} CSI may have been affected by the mental and physical effects of the heat stress trial.

To an individual or athlete involved in a high risk activity, the constructs of cognitive performance that are important are the ability to process information quickly and then respond accordingly as soon as possible. Participants in our study presented unexpected findings on these measures of processing and response speed. Processing speed revealed an improvement in the dehydrated condition compared to the euhydrated condition. This may be explained by the participants' interest and willingness to complete the second trial of cognitive testing. However, response speed data revealed a decrement from the euhydrated to the dehydrated condition. These finding are clinically important although processing speed may not change or perhaps even improve, if the response to the stimulus cannot be completed normally, the potential for negative outcomes increases.

Physiologically, the basis for decreased cognitive performance may be attributed to a variety of mechanisms, all of which remain largely theoretical. More research is necessary to identify specific physiological mechanism to explain brain function in an exercise heat stress environment. Hocking, Silberstein, Lau, Stough, and Roberts (2001) theorized the existence of a "cognitive reserve," whereby subjects have at their disposal a certain amount of neural resources that can be allocated to the performance of cognitive tasks and activities when resources are diminished. Cognitive performance may deteriorate when the amount of resources necessary to deal with the tasks and the thermal stress is lacking, such that subjects will be able to maintain performance level until the resources are overloaded. We can speculate that participants the current study where able to utilize their cognitive reserve for part or all of the cognitive testing resulting in improvements on several of the subtest scores.

We sought to add to the body of evidence that acute bouts of steady-state exercise and heat induced dehydration affect cognition. Prolonged exercise leading to dehydration and its accompanying metabolic changes are associated with impaired information processing and cognition. Few researchers have attempted to determine the combined effects of exercise and heat stress-induced dehydration on cognitive performance in a well-designed and controlled study. The current knowledge is still at a general level and many questions remain. It is important for athletic trainers, coaches, nutritionists and other medical professionals to understand the how active dehydration and heat stress affect both the physical and psychological performance of the athlete. Much more research is needed to determine the impact of dehydration on cognitive performance.

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Table 1
Headminder[TM] CSI Cognitive Factors and Subtests Response Time Raw Score Means and Standard Deviations

Cognitive Factor	Condition	Mean ± sd	Subtests	Condition	Mean ± sd
Processing Speed* (*n* = 9)	Euhydration	3.03 ±.32	Animal Decoding (response time)	Euhydration	2.30 ±.35
				Dehydration	2.41 ±.53
	Dehydration	2.78 ±.43	Symbol Scanning* (response time)	Euhydration	3.76 ±.34
				Dehydration	3.16 ±.57
Response Speed (*n* = 10)	Euhydration	95.60 ±12.00	Response Direction 1 (response time)	Euhydration	84.30 ±11.30
				Dehydration	79.00 ±10.39
			Response Direction 2 (response time)	Euhydration	93.40 ±12.33
				Dehydration	97.30 ± 9.52
	Dehydration	93.60 ±14.06	Incidental Learning 1 (response time)	Euhydration	101.70 ±10.87
				Dehydration	97.40 ±16.64
			Incidental Learning 2 (response time)	Euhydration	99.90 ±12.12
				Dehydration	98.60 ±15.49
Attention (*n* = 10)	Euhydration	103.8 ±12.81	Number Recall (number correct)	Euhydration	100.10 ±14.09
				Dehydration	99.10 ±16.04
	Dehydration	104.30 ±15.84	Number Sequencing (number correct)	Euhydration	105.50 ±10.06
				Dehydration	107.40 ±16.78