Review

Cognitive Performance and Dehydration

Ana Adan, PhD

Department of Psychiatry and Clinical Psychobiology, School of Psychology, and Institute for Brain, Cognition, and Behavior, University of Barcelona, Barcelona, SPAIN

Key words: cognitive performance, dehydration, attention, psychomotor skills, memory, mood

No matter how mild, dehydration is not a desirable condition because there is an imbalance in the homeostatic function of the internal environment. This can adversely affect cognitive performance, not only in groups more vulnerable to dehydration, such as children and the elderly, but also in young adults. However, few studies have examined the impact of mild or moderate dehydration on cognitive performance. This paper reviews the principal findings from studies published to date examining cognitive skills. Being dehydrated by just 2% impairs performance in tasks that require attention, psychomotor, and immediate memory skills, as well as assessment of the subjective state. In contrast, the performance of long-term and working memory tasks and executive functions is more preserved, especially if the cause of dehydration is moderate physical exercise. The lack of consistency in the evidence published to date is largely due to the different methodology applied, and an attempt should be made to standardize methods for future studies. These differences relate to the assessment of cognitive performance, the method used to cause dehydration, and the characteristics of the participants.

Key teaching points:

- This paper reviews the existing findings about the impact of dehydration in the main cognitive skills explored so far.
- Children and the elderly are the populations most vulnerable to dehydration.
- Healthy young adults are also at risk of a decrease in their cognitive performance when hydration is not adequate.
- Attention, psychomotor, and immediate memory skills, as well as assessment of the subjective state, are the brain capabilities most vulnerable to mild or moderate dehydration.
- The relationship between hydration and cognitive performance is an emerging area of study of undoubted practical interest in which much research still need to be carried out.

INTRODUCTION

Severe dehydration inevitably leads to marked decline in overall functioning, including capacity to perform cognitive tasks, and can lead to delirium, coma, and death [1–3]. *Dehydration* is defined as a deficit of body water when fluid output exceeds intake and is classified as severe if the loss of body water is more than 5%. Although this state is rare in the general population, a state of mild or moderate dehydration can be reached easily, and this should be an important area for study. A state of *mild dehydration* is defined as a 1%–2% loss of body water, whereas *moderate dehydration* is when the loss is in the region of 2%–5%. The change of body water was usually measured by the change of body weight, because when an individual is in a caloric balance a body-weight loss essentially equals water loss.

Adequate hydration is an important factor in the prevention of accidents at work or the development of disease. This is because it enhances performance in both physical and mental tasks and improves the perception of well-being [4,5]. No matter how mild, dehydration is not a desirable condition because it means there is an imbalance in the homoeostatic function of the internal environment [3]. This can adversely affect cognitive capacity and interfere with adequate performance of work- or study-related activities that require the use of specific mental skills.

The risk of suffering from dehydration is greater among particular groups such as children, the elderly, pregnant women, infants, and athletes who, for different reasons, are

Address reprint requests to: Ana Adan, Department of Psychiatry and Clinical Psychobiology, School of Psychology, University of Barcelona, Passeig de la Vall d'Hebron, 171, 08035 Barcelona, SPAIN. E-mail: aadan@ub.edu

The study was funded by the author. The author declares that she has no competing interests.

Journal of the American College of Nutrition, Vol. 31, No. 2, 71–78 (2012)
Published by the American College of Nutrition

much more vulnerable to body-water loss [6–8]. Nevertheless, we should not ignore the fact that healthy young adults can also become dehydrated and suffer the negative consequences, even when not exposed to adverse environmental conditions, and we should, therefore, be aware of how to prevent it [3]. For example, it is estimated that the spontaneous drinking pattern among young adults who work in high temperatures or do strenuous exercise only replenishes two thirds of the total water lost. In such cases, it has been found that workers do not drink enough fluids during the working day and even arrive at work already dehydrated [5]. Although few studies have assessed the degree of hydration in schoolchildren or students—at all levels of education—the data all point in the same direction [7,9]. Recent initiatives, such as those in the United States, England, and Germany, that promote adequate hydration in schools during the school day, have resulted in better concentration and willingness to learn within class groups [7].

BACKGROUND

A large number of scientific studies have been conducted to determine the extent and duration of the impact of dehydration caused by physical exercise or sports activities. They examine the impact of dehydration on various skills such as strength, power, and speed [10,11] and the relationship with the factors that induced the dehydration, including the form of rehydration (if this was provided for in the design) and the environmental conditions [12]. Consequently, it is estimated that a 2% loss of body fluids causes a 20% decline in physical performance. Not many studies, however, have looked at the impact of dehydration on cognitive performance, and methodological limitations do not allow us to extrapolate results or derive robust conclusions.

This paper reviews the currently available findings on the effects of dehydration on cognitive performance with a brief reference to the possible underlying neurofunctional bases of the data gathered to date. Attention, psychomotor, and memory skills, the executive functions, and the subjective state of activation and mood are considered individually because these aspects have been the most widely studied. In addition, certain methodological aspects are discussed that need to be considered in future research with regard to the assessment of cognitive performance, the method of inducing dehydration, and the participants' characteristics, which would help to achieve greater understanding in this field.

DESCRIPTION OF SUBJECT

Neurofunctional Bases of Dehydration

Changes in the amount of electrolytes in the body that occur when dehydrated can alter brain activity and the functioning of some of the neurotransmitter systems involved in cognitive processing [1,13]. It has also been found that dehydration is associated with changes in blood-brain barrier permeability and decreases in the blood flow in some areas of the brain [2]. Most previous studies addressing this issue are reviews, and it is necessary to specify that the original data on aspects of brain function are circumstantial and were obtained indirectly.

Using positron emission tomography, Farrell et al. [14] found that a state of osmotic thirst induced with hypertonic infusions is related to changes in the blood flow in specific brain areas such as the primary somatosensory cortex, the motor cortex (motor control), the prefrontal cortex (executive functions, including planning and inhibitory control), the anterior cingulate cortex (emotions and decision making), and the superior temporal gyrus (auditory processing). These changes are more pronounced in the elderly than in young people. Younger subjects may exhibit cognitive compensating mechanisms for increased tiredness and reduced alertness during slowly progressive moderate dehydration through increasing subjective task-related effort [15].

The brain-stem monoaminergic systems are the neurotransmitter systems primarily involved [2]. Both the dopaminergic and noradrenergic systems are important in controlling attention, motivation, and fatigue, and there may be a decrease in transmission in these systems when the body is dehydrated. The serotonergic system has also been linked to a possible impact on performance, particularly on the subjective perception of dehydration, although findings have been contradictory. Dehydration impairs cholinergic neuromuscular transmission, with a negative influence on performance in psychomotor tasks [7,16].

A state of dehydration leads to the activation of the hypothalamic-pituitary-adrenocortical axis and to the subsequent production of stress hormones such as cortisol. Rehydration, however, is associated with significant decreases in cortisol levels. An increase in the cortisol level may be an underlying factor in the negative effects on various cognitive functions such as perception, spatial ability, and memory [7,17,18].

In response to dehydration, vasopressin (antidiuretic hormone) is also secreted. Elevated plasma levels of vasopressin can prove beneficial for learning and memory tasks [7,19,20]. Furthermore, proper hydration affects the levels of glycerol in the body and the adequate availability of glucose in the central nervous system [21–23], which is known to enhance learning and memory [24,25]. The production of neuronal nitric oxide as a result of glutamatergic hyperexcitation has also been dose-dependently associated with dehydration [13], which may explain the mixed evidence on the impact of dehydration on the performance of memory tasks.

Future studies need to include endocrine and biochemical measurements, functional neuroimaging data, the quantification of the state of dehydration, and assessments of cognitive performance. This will be key for clarifying the underlying biological aspects and to provide evidence to back previous findings by assessing performance in similar tasks.

Attention and Psychomotor Skills

The performance of simple attention tasks was not usually significantly impaired in states of dehydration of 1%–2% in cold environmental conditions when assessing both the processing rate or reaction time and accuracy or adequate performance [12,23,26,27]. In contrast, states of dehydration that exceeded 2% often negatively affected the attention and, consequently, the proper performance of these tasks by young subjects, even when evaluated at rest, when heat exposure or exercise are the methods of dehydration [12,21,22,28–30]. Speed is the most sensitive performance parameter, although the number of correct answers may not be affected. A recent study by D'Anci et al. [30] also found dehydration to have a greater negative effect on women's performance than that of men.

In tasks assessing reaction time to visual stimuli, no effect was observed on the response rate for dehydration states of 2% or higher, whether caused by fluid deprivation [15,27–30], exposure to physical activity [30,31], or both [20]. Moreover, dehydration increased the response rate to peripheral stimuli—a pattern that was more emotional than performance related—without affecting the rate of the central stimuli [26,32]. This effect has not been found in other studies, but it seems to disappear in motivated and trained participants [32]. The gender factor in the performance of these tasks is essential because in young dehydrated women, a significant decrease was observed in both the response rate [15] and the number of errors [30], whereas men were unaffected.

Studies with schoolchildren (6–12 years) in a state of voluntary dehydration caused by not drinking enough fluids despite having water available, whether environmental conditions were adverse or not, showed that those who did not drink water performed worse in tasks of visual attention and perceptual speed midmorning than those who drank water [8,9,33]. It is remarkable that only Bar-David et al. [9] formally assessed the hydration status of the children, whereas all the other studies assumed it without doing objective measurements.

Other findings that require further investigation come from the study by Rogers et al., [34], in which drinking a glass of water improved the performance of young healthy subjects who were thirsty in a task of simple reaction time to visual stimuli, whereas drinking a glass of water worsened the performance of those who were not thirsty but drank it anyway. The decrease in reaction time in the former and the increase in the latter is dose-dependent (they consumed 120 ml or 330 ml of water) and is maintained for 50 minutes postconsumption (measured at 2, 25, and 50 minutes). This suggests that overhydration is also not beneficial to the processing rate for visual information.

Loss of body water of 2% or more leads to a decrease in the performance of psychomotor tasks that require visuomotor or hand-to-eye coordination, regardless of the method used to induce dehydration. This has been found in both young healthy individuals [21,22,28,35] and in elderly people [6], with performance worsening as dehydration increased. The study by Devlin et al. [36] with cricketers with highly trained hand-to-eye coordination skills found that a 2.8% state of dehydration did not influence the velocity of bowling but did greatly affect its accuracy. Through the fluid deprivation method, the effect on psychomotor performance was noted as early as 9 AM in young, healthy subjects [35].

Studies evaluating different levels of dehydration have also shown a dose-response relationship with the deterioration in psychomotor task performance. In young subjects, there was a decrease in both speed and efficiency at 2% water loss, which increased if the level of dehydration was 3% [37] and 4% [38], regardless of environmental conditions. Furthermore, the effect was already apparent at 1% dehydration if the measurements were taken in a hot, dry environment (45°C and 30% humidity) [37]. Although there are still relatively few works in this area, motor pathways may be more sensitive to functional impairment in these environmental conditions than those involved in other attentional tasks.

Memory and Executive Functions

A level of dehydration greater than 2% decreased the ability of short-term memory for the presentation of verbal and numerical material in both young adults [20–22,28,37] and elderly people [6]. This was observed regardless of the method used to induce dehydration and of the environmental conditions in which the measurements were taken. Gopinathan et al. [38] found a significant detrimental effect on the short-term memory of verbal material (remembering words), with a higher number of incorrect answers at 1% water loss, which increased dose-dependently in dehydration states of 2%, 3%, and 4%. Schoolchildren in a state of voluntary dehydration also performed worse on a short-term memory task—number sequences—carried out at midday than did those who were hydrated [9]. The impairment of short-term memory due to fluid deprivation was evident from 9 AM in young, healthy subjects [35].

Data on the impact of dehydration on the working memory are more heterogeneous and appear to be mediated by the method used to induce dehydration. Using an arithmetic addition task of 5 digits presented orally, and with exposure to heat and fluid deprivation, Gopinathan et al. [38] observed a lower percentage of correct answers at 2% dehydration that increased at 3% and 4%. On the other hand, Sharma et al. [37], using moderate exercise and exposure to heat, found no significant differences in the performance of a very similar task with dehydration levels between 1% and 3%. Moreover, Patel et al. [20] did not find any negative effects in the Sternberg working memory test, using exposure to moderate exercise and fluid deprivation. Finally, Edmonds and Burford [8] found that a group of children who consumed water performed better on working memory tests compared with those who did not consume water.

In long-term memory tasks that assess learning at the same time, no negative effects were observed in mild or moderate dehydration caused by moderate physical exercise in young adults [21,22,30,39]. In elderly subjects, impaired mnemonic ability was observed after fluid deprivation during the night [6] using a battery of neuropsychological tests that included estimators of learning and spatial, verbal, and numeric memory. In contrast, the same method and the administration of a bowel preparation for diagnostic tests did not yield significant results in elderly subjects with a dehydration level of approximately 2% [40].

Moderate physical exercise in cold environments can have activating effects on cognitive performance in working and long-term (consolidation) memory tasks, thus compensating for performance deficits caused by mild to moderate states of dehydration [31,39,41]. This is particularly evident in the first 20 minutes following exercise and depends on the type of activity [42]. The increase in core body temperature produced by exercise and the increased activity of the dopaminergic, noradrenergic, and glutamatergic systems of the central nervous system (CNS) have been identified as factors that explain these benefits that temporarily compensate for the effects of dehydration [2,13,41]. However, with prolonged exercise at high temperatures, adverse cognitive effects can occur as a result of alterations in thermoregulation (reaching the level of hyperthermia), blood-brain barrier permeability, and cerebral blood flow [43].

The assessment of executive functions involves the implementation of various higher processes to accommodate new or complex situations in which the individual has to activate a process such as inhibition, planning, and problem solving [44]. In mild to moderately dehydrated young subjects, no decrease in performance was observed in a mental concentration test following physical exercise [45] or with fluid deprivation in the Stroop task, which measures response inhibition ability [15], or a planning task [30]. In contrast, Cian et al. [22] found that young subjects dehydrated following physical exercise performed worse on a decision-making task, although this was temporary with a duration of about 3.5 hours. Schoolchildren in a state of voluntary dehydration also performed worse on a verbal analogies task compared with those who were adequately hydrated [9]. A study of elderly subjects dehydrated by fluid deprivation found no negative effects on performance of the Trail Making Tests task, which measures inhibition ability and cognitive flexibility [40]. The few studies that have evaluated the impact of dehydration on executive functions tasks do not allow conclusions, although significant data obtained encourage the development of new studies.

Subjective Assessments

When fluid deprivation was used as a method to induce dehydration, young, healthy subjects showed a significant decline in subjectively assessed concentration ability and alertness with a 1% loss of body water at 13 hours, which increased after a 24-hour restriction (1.8% loss of body water) and at 37 hours (2.7% loss of body water). Moreover, marked subjective tiredness and headaches were evident from 24 hours onward [6,15,27,35,46].

A level of dehydration of more than 2% resulted in marked decreases in subjectively assessed alertness and concentration ability and increased fatigue, tiredness, and drowsiness, as well as headaches, in young subjects [20–22,30,37], regardless of whether the method to induce dehydration was exposure to heat, physical exercise, fluid deprivation, or any combination. Shirreffs et al. [46] found no significant gender differences in the subjective effects of dehydration.

The study by Rogers et al. [34] showed that drinking a glass of water improved subjective alertness and perception of revitalization in a similar way in both thirsty and nonthirsty subjects, contrary to what was observed with performance in information processing. The effect was greater after consuming 330 ml of water than after 120 ml, occurring just 2 minutes after consumption, but also dissipated quickly at 25 minutes postconsumption. In schoolchildren, drinking water during the school day had a positive effect on their subjective assessments of thirst and happiness compared with those who remained in a state of voluntary dehydration [33].

Methodological Issues

Assessment of Cognitive Performance. The complexity of assessing cognitive performance can be a problem when conducting studies in this research area. It encompasses many specific functions or skills (e.g., attention, motor control, learning, memory, and reasoning). Moreover, although there are hundreds of standardized neuropsychological tasks, even the simplest ones often require the use of more than one function, and there is not always a consensus on their sensitivity. The performance of a task can be assessed using estimates of the response rate and/or accuracy (correct answers, errors, and lapses). However, given that dehydration may not affect these elements equally, they should all be recorded.

Many of the standardized neuropsychological tasks for attention, memory, and executive functions are very useful for detecting pathological conditions in clinical examination. Nevertheless, this is not the case when they involve healthy individuals because their performance is often in the normal range of the available scales. The selection of specific tasks carried out in psychopharmacological research might be more useful and sensitive for detecting the effects associated with mild dehydration over the whole range of cognitive functions.

In addition, individual variability is important in estimations of performance and can result in a high dispersion of scores that does not provide significant results, even when controlling for the numerous socio-demographic and individual factors that are known to influence cognitive performance. Individual variability is minimized when designing repeated measurements, making this an excellent option for studies on biological parameters. Nevertheless, the use of these designs in the assessment of cognitive performance may lead to fatigue and/or learning effects that are impossible to determine *a posteriori*, which is a problem for obtaining reliable and valid results [44,47]. This explains why most studies use a small number of very simple tasks, but this makes it difficult to extrapolate the results to the social and occupational cognitive demands that people are subjected to in reality. In this regard, as an example, it seems something of a paradox that there has been no assessment of the effect of dehydration on attention or reaction-measuring tasks using somatosensory or auditory stimuli, even though these processing pathways can be even more sensitive than the visual routes [48], which in the main are those that are studied. The use of counterbalanced designs in the future may be an option to overcome these limitations.

It is a well-established fact that there are diurnal variations in both physical and cognitive performance associated with circadian rhythm expression, which also depend on the skill(s) required for a specific task to be performed [44,47]. It is estimated that intraindividual variation in cognitive test performance, depending on the time of day, may be 20% when comparing the best and worst moments of performance. However, only a few studies mention and/or control the time of day when the measurements are taken.

Method of Inducing Dehydration. The methodology selected to induce dehydration is a key element in the study of hydration and cognitive performance. The most common methods, due to their efficiency and speed, are exposure to heat (35°C–45°C, varied relative humidity) and sustained and controlled aerobic exercise—the active method of dehydration—that may be carried out exclusively or combined. The use of both methods requires a substantial degree of expertise in order to achieve reliable changes in the hydration levels of the participants, and their effects on the body may not be identical [1,11].

Another problem is the characteristics of the study participants when heat exposure or exercise are the methods of dehydration, which often do not allow for the extrapolation of the results to the general population. Athletes, people who regularly practice sports, and active soldiers are often selected to take part. These people are accustomed to both methods of dehydration and may have an accelerated general metabolism in order to meet increased energy needs. Consequently, they may present higher levels of dehydration compared with participants who perform more sedentary activities. Instead, those dehydration levels might not be associated with significant effects on cognitive performance on these people.

The passive dehydration method can also be used, which involves the deprivation of water or liquids and solids with high water content [46,49]. This requires a considerable period of time—at least 9–13 hours—which does not pose a problem for taking biological measurements but can be an issue for cognitive performance and subjective condition measurements because these measurements may be affected by the additional factors of changes caused by the duration of the study period, such as fatigue or boredom [1,32].

Moreover, if there is no control group that is also exposed to the dehydration method (exercise, heat exposure, and/or deprivation of fluids) but remains suitably hydrated, the experimental design introduces confounding factors that are impossible to identify *a posteriori* in the results [1,32]. As such, the comparison of premeasurements and postmeasurements does not allow us to determine whether the changes observed are the sole result of dehydration, exposure to the stress methods used to induce such dehydration, or a combination of both [3]. It is also necessary to clarify the relationship between intensity and duration of all the dehydration methods, individually and combined, in terms of biological parameters and, in particular, cognitive performance. The temperature of the environment in which the experiment recordings are made is another key element. A decrease in cognitive performance is been observed, particularly apparent in hot environments compared with thermoneutral or cold ones [31,50]. When the temperature of the environment is not specifically being studied in the field work, it is often excluded altogether, even though the results could be influenced by an environmental factor.

The few existing studies with dose-response designs have already found effects of 1% dehydration on some tasks. Because dehydration can occur in a range of many different levels and varies among subjects, the dose-response assessment of cognitive effects constitutes an appropriate strategy for internal control [1] if the selected cognitive tests allow for repeated measurements.

In addition, determining the level of dehydration by estimating the loss of body water is one of the most widely used in studies because it is the most universal, valid, inexpensive, feasible, and the quickest indicator. However, this causes bias in the real state of hydration of individuals due to the variability in body fat, and, moreover, there are no reference values for the general population [4]. Other biologic methods for a more precise dehydration diagnosis are available, for example, tracer techniques and plasma or urine osmolarity rates [51,52], that should be used in research on cognitive effects.

The type of drink used to rehydrate, if this is included in the study, is also a variable to take into account. The benefit of using only water to determine the effects of dehydration on cognitive performance has already been indicated [23] because it is the most widespread beverage. Nevertheless, the use of other beverages that are known to result in greater physiological and cognitive benefits for the participants should also be considered. The composition of commercial sports drinks allows for the rapid absorption of water and electrolytes. Moreover, their carbohydrate content (between 6% and 8%) increases glucose levels in the body, which is essential for correct physical and cognitive performance [24,29]. The consumption of low doses of caffeine with glucose, as contained in soft drinks, could also be a better strategy than drinking more water in order to boost performance in sustained attention, learning and memory tasks [25,53]. Last, energy drinks that contain both glucose and caffeine together with other psychoactive substances (e.g., taurine or ginseng) that improve cognitive performance [54,55], should also be assessed. However, regular consumption of these in large quantities is not recommended.

Participant Characteristics and Habits. Gender has been found to be a determining factor in relation to differences in levels of dehydration and their correlates with cognitive performance. On average, women have lower body-water content, and the use of the change in body-weight method that is based on water loss represents a higher percentage compared with men [46]. The impact of mild to moderate states of dehydration on cognitive performance is greater on women than on men, even when using body-weight estimates as detailed in the preceding sections. However, most studies include either only men in their samples or participants of both genders, without studying them separately [42]. In the future, more research is required on gender differences, and suitable control for menstrual cycle should also be included because this may be a modulating factor in the results. Hormonal changes have been associated with fluid retention in the luteal phase of the cycle and, consequently, with increases in body weight and effects on the state of hydration [28,56]. There is also evidence that the menstrual cycle affects cognitive task performance [57], which is better in the luteal phase in terms of attention tasks and in the ovulatory phase for visuospatial memory [58].

Over the last 20–30 years, circadian typology has been found to be the most important individual difference in the way people function, with 3 groups being considered: morning type, intermediate (or neither type), and evening type. This typology determines the differences in the optimum moments for biological and behavioral parameters that, for the performance of attention tasks, can be as much as 12 hours [59,60]. Circadian typology may be a decisive factor when analyzing the effects of hydration on cognitive performance, and the failure of previous studies to take this aspect into account may explain the contradictory results. Likewise, the normal sleep pattern—duration and quality—of the participants is another variable related to the quality of the waking period, although the studies that do consider it only analyze the night(s) immediately prior to the experimental measurements.

Although most studies check for the consumption of psychoactive substances (e.g., alcohol, nicotine, caffeine) for a few hours before and during the experiments, the participants' usual consumption is rarely taken into account and that could affect the results of performance and subjective state. Caffeine, owing to its widespread use in the population, is an example. Although caffeine does not adversely affect hydration, if the participants regularly consume large quantities, they could suffer from withdrawal during the measurements [60,61], especially in prolonged procedures such as fluid deprivation [1]. The use of medicines for a large number of different conditions could also influence the hydration state and have both positive and negative effects on cognitive performance. For example, the use of diuretics in hypertensive subjects or of laxatives causes dehydration [51], and antihistamines can impair performance. This, therefore, needs to be properly assessed and controlled when selecting participants. Moreover, it is very useful to include objective analytical measurements (urine, blood, and saliva) to confirm adherence to the dietary and/or pharmacological precautions requested in the studies.

Last, there are other participant-related variables that are known to influence the performance of cognitive tasks, such as the level of education, personality traits related to stress levels and the response to stress (i.e., anxiety), and the effects on motivation of receiving payment for taking part in the study. All of these should be specified in the relevant methodology sections of the research because they could be factors that explain the differences observed in the impact of dehydration on the performance of very similar tasks.

CONCLUSION

The relationship between hydration and cognitive performance is an emerging area of study, in which much research still needs to be conducted. Existing data show that, in the multivariate explanatory health model, good hydration is a factor of specific importance [3,4] that needs to be taken into account. Looking after hydration status, even when failing to perceive the warning signs of thirst, is important. This factor may affect physical and intellectual performance, even if people are sedentary or in optimal climate conditions. Children and the elderly are the population groups most vulnerable to dehydration; however, healthy young adults are also at risk of a reduction in their cognitive performance. Evidence suggests the tasks that require attention, immediate memory, and psychomotor skills, as well as assessment of the subjective state, are the most negatively affected. In contrast, working memory, long-term memory, and executive-function skills seem to be more preserved, especially if the method used to induce dehydration is moderate physical exercise. Campaigns are required to educate and promote awareness among the general population about the importance of looking after their hydration levels on a daily basis. Such campaigns require a solid base of new evidence, both scientific and clinical, from the study of large samples of participants of both genders, with suitable control of factors that are known to lead to biased results. This would enable a more in-depth understanding of the effects of dehydration on cognitive performance and allow a more reliable extrapolation of the results to the general population.

REFERENCES

1. Lieberman HR: Hydration and cognition: a critical review and recommendations for future research. J Am Coll Nutr 26:S555–S561, 2007.
2. Maughan RJ, Shirreffs SM, Watson P: Exercise, heat, hydration, and the brain. J Am Coll Nutr 26:S604–S612, 2007.
3. Popkin BM, D'Anci KE, Rosenberg IH: Water, hydration, and health. Nutr Rev 68:439–458, 2010.
4. Ritz P, Berrut G: The importance of good hydration for day-to-day health. Nutr Rev 63:S6–S13, 2005.
5. Kenefick RW, Sawka MN: Hydration in the work site. J Am Coll Nutr 26:S597–S603, 2007.
6. Suhr JA, Hall J, Patterson SM, Niinistö RT: The relation of hydration status to cognitive performance in healthy older adults. Int J Psychophysiol 53:121–125, 2004.
7. D'Anci KE, Constant F, Rosenberg IH: Hydration and cognitive function in children. Nutr Rev 64:457–464, 2006.
8. Edmonds CJ, Burford D: Should children drink more water? The effects of drinking water on cognition in children. Appetite 52:776–779, 2009.
9. Bar-David Y, Urkin J, Kozminsky E: The effect of voluntary dehydration on cognitive functions of elementary school children. Acta Paediatr 94:1667–1673, 2005.
10. Judelson DA, Maresh CM, Anderson JM, Armstrong LE, Casa DJ, Kraemer WJ, Volek JS: Hydration and muscular performance: does fluid balance affect strength, power, and high-intensity endurance? Sports Med 37:907–921, 2007.
11. Murray B: Hydration and physical performance. J Am Coll Nutr 26:S542–S548, 2007.
12. Shirreffs SM: Conference on "Multidisciplinary approaches to nutritional problems." Symposium on "Performance, exercise and health." Hydration, fluids and performance. Proc Nutr Soc 68:17–22, 2009.
13. Wilson MM, Morley JE: Impaired cognitive function and mental performance in mild dehydration. Eur J Clin Nutr 57:S24–S29, 2003.
14. Farrell MJ, Zamarripa F, Shade R, Phillips PA, McKinley MJ, Fox P, Blair-West J, Denton DA, Egan GE: Effect of aging on regional cerebral blood flow responses associated with osmotic thirst and its satiation by water drinking: a PET study. Proc Natl Acad Sci U S A 105:382–387, 2008.
15. Szinnai G, Schachinger H, Arnaud MJ, Linder L, Keller U: Effect of water deprivation on cognitive-motor performance in healthy men and women. Am J Physiol Regul Integr Comp Physiol 289:R275–R280, 2005.
16. Al Shuaib WB, Fahim MA, Davidson N: Dehydration affects synaptic transmission at flexor muscle in acute lead-treated mice. Cell Mol Biol 45:407–411, 1999.
17. Kirschbaum C, Wolf OT, May M, Wippich W, Hellhammer DH: Stress- and treatment-induced elevations of cortisol levels associated with impaired declarative memory in healthy adults. Life Sci 58:1475–1483, 1996.
18. Lieberman HR, Bathalon GP, Falco CM, Kramer FM, Morgan CA, Niro P: Severe decrements in cognition functions and mood induced by sleep loss, heat, dehydration, and undernutrition during simulated combat. Biol Psychiatry 57:422–429, 2005.
19. McEwen BB: Closing remarks: review and commentary on selected aspects of the roles of vasopressin and oxytocin in memory processing. Adv Pharmacol 50:593–654, 655–708, 2004.
20. Patel AV, Mihalik JP, Notebaert AJ, Guskiewicz KM, Prentice WE: Neuropsychological performance, postural stability, and symptoms after dehydration. J Athl Train 42:66–75, 2007.
21. Cian C, Koulmann N, Barraud PA, Raphel C: Influence of variations in body hydration on cognitive function: effect of hyperhydration, heat stress, and exercise-induced dehydration. J Psychophysiol 14:29–36, 2000.
22. Cian C, Barraud PA, Melin B, Raphel C: Effects of fluid ingestion on cognitive function after heat stress or exercise-induced dehydration. Int J Psychophysiol 42:243–251, 2001.
23. Serwah N, Marino FE: The combined effect of hydration and exercise heat stress on choice reaction time. J Sci Med Sport 9:157–164, 2006.
24. Food and Nutrition Board, Institute of Medicine: "Dietary Reference Intakes for Water, Potassium, Sodium, Chloride, and Sulfate." Washington, DC: National Academies Press, 2004.
25. Adan A, Serra-Grabulosa JM: Effects of caffeine and glucose, alone and combined, on cognitive performance. Human Psychopharmacol 25:310–317, 2010.
26. Leibowitz HW, Abernethy CN, Buskirk ER, Bar-or O, Hennessy RT: The effect of heat stress on reaction time to centrally and peripherally presented stimuli. Hum Factors 14:155–160, 1972.
27. Neave N, Scholey AB, Emmett JR, Moss M, Kennedy DO, Wesnes KA: Water ingestion improves subjective alertness, but has no effect on cognitive performance in dehydrated healthy young volunteers. Appetite 37:255–256, 2001.
28. Hall JA: "Hydration and Cognition In Young Adults" (master's thesis). College of Arts and Sciences, Ohio University, 2005. Accessed at: http://etd.ohiolink.edu/view.cgi?acc_num=ohiou1133195754
29. Bailey SP, Holt C, Pfluger KC, La Budde Z, Afergan D, Stripling R, Miller PC, Hall EE: Impact of prolonged exercise in the heat and carbohydrate supplementation on performance of a virtual environment task. Mil Med 173:187–192, 2008.
30. D'Anci KE, Vibhakar A, Kanter JH, Mahoney CR, Taylor HA: Voluntary dehydration and cognitive performance in trained college athletes. Percept Mot Skills 109:251–269, 2009.
31. Adam GE, Carter R III, Cheuvront SN, Merullo DJ, Castellani JW, Lieberman HR, Sawka MN: Hydration effects on cognitive performance during military tasks in temperate and cold environments. Physiol Behav 93:748–756, 2008.

32. Grandjean AC, Grandjean NR: Dehydration and cognitive performance. J Am Coll Nutr 26:S549–S554, 2007.
33. Edmonds CJ, Jeffes B: Does having a drink help you think? 6-7-year-old children show improvements in cognitive performance from baseline to test after having a drink of water. Appetite 53:469–472, 2009.
34. Rogers PJ, Kainth A, Smit HJ: A drink of water can improve or impair mental performance depending on small differences in thirst. Appetite 36:57–58, 2001.
35. Petri NM, Dropulic N, Kardum G: Effects of voluntary fluid intake deprivation on mental and psychomotor performance. Croat Med J 47:855–861, 2006.
36. Devlin LH, Fraser SF, Barras NS, Hawley JA: Moderate levels of hypohydration impairs bowling accuracy but not bowling velocity in skilled cricket players. J Sci Med Sport 4:179–187, 2001.
37. Sharma VM, Sridharan K, Pichan G, Panwar MR: Influence of heat-stress induced dehydration on mental functions. Ergonomics 29:791–799, 1986.
38. Gopinathan PM, Pichan G, Sharma VM: Role of dehydration in heat stress-induced dehydration in mental performance. Arch Environ Health 43:15–17, 1988.
39. Coles K, Tomporowski PD: Effects of acute exercise on executive processing, short-term, and long-term memory. J Sports Sci 26:333–344, 2008.
40. Ackland GL, Harrington J, Downie P, Holding JW, Singh-Ranger D, Griva K, Mythen MG, Newman SP: Dehydration induced by bowel preparation in older adults does not result in cognitive dysfunction. Anesth Analg 106:924–929, 2008.
41. Davranche K, Audiffren M: Facilitating effects of exercise on information processing. J Sports Sci 22:419–428, 2004.
42. Lambourne K, Tomporowki P: The effect of exercise-induced arousal on cognitive task performance: a meta-regression analysis. Brain Res 1341:12–24, 2010.
43. Nybo L, Nielsen B: Middle cerebral artery blood velocity is reduced with hyperthermia during prolonged exercise in humans. J Physiol 534:279–286, 2001.
44. Schmidt C, Collette F, Cajochen C, Peigneux P: A time to think: circadian rhythms in human cognition. Cogn Neuropsychol 24:755–789, 2007.
45. Edwards AM, Mann ME, Marfell-Jones MJ, Rankin DM, Noakes TD, Shillington DP: Influence of moderate dehydration on soccer performance: physiological responses to 45 min of outdoors match-play and the immediate subsequent performance of sport-specific and mental concentration test. Br J Sports Med 41:385–391, 2007.
46. Shirreffs SM, Merson SJ, Fraser SM, Archer DT: The effects of fluid restriction on hydration status and subjective feelings in man. Br J Nutr 91:951–958, 2004.
47. Adan A: Circadian variations in psychological measures. A new classification. Chronobiologia 20:145–162, 1993.
48. Jensen AR: "Clocking the Mind: Mental Chronometry and Individual Differences." Amsterdam: Elsevier, 2006.
49. Pedersen RS, Bentzen H, Bech JN, Pedersen EB: Effect of water deprivation and hypertonic saline infusion on urinary AQP2 excretion in healthy humans. Am J Physiol Renal Physiol 280:F860–F867, 2001.
50. Marrao C, Tikuisis P, Keefe AA, Gil V, Giesbrecht GG: Physical and cognitive performance during long-term cold weather operations. Aviat Space Environ Med 76:744–752, 2005.
51. Jéquier E, Constant F: Water as an essential nutrient: the physiological basis of hydration. Eur J Clin Nutr 64:115–123, 2010.
52. Cheuvront SN, Ely BR, Kenefick RW, Sawka MN: Biological variation and diagnostic accuracy of dehydration assessment markers. Am J Clin Nutr 92:565–573, 2010.
53. Serra-Grabulosa JM, Adan A, Falcón C, Bargalló N: Glucose and caffeine effects on sustained attention: an exploratory fMRI study. Human Psychopharmacol 25:543–552, 2010.
54. Smit HJ, Rogers PJ: Effects of energy drinks on mood and mental performance: critical methodology. Food Quality and Preference 13:317–326, 2002.
55. Scholey AB, Kennedy DO: Cognitive and physiological effects of an "energy drink": an evaluation of the whole drink and of glucose, caffeine, and herbal flavouring fractions. Psychopharmacology 176:320–330, 2004.
56. Lusseveld EM, Petery ETJ, Deurenberg P: Multifrequency bioelectrical impedance as a measure of differences in body water distribution. Ann Nutr Metab 37:44–51, 1993.
57. Hatta T, Nagaya K: Menstrual cycle phase effects on memory and Stroop task performance. Arch Sex Behav 38:821–827, 2009.
58. Solís-Ortiz S, Corsi-Cabrera M: Sustained attention is favored by progesterone during early luteal phase and visuo-spatial memory by estrogens during ovulatory phase in young women. Psychoneuroendocrinology 33:989–998, 2008.
59. Adan A, Natale V, Caci H: Cognitive strategies and circadian typology. In Léglise AL (ed): "Progress in Circadian Rhythm Research." New York: Nova Biomedical Books, pp 141–161, 2008.
60. Adan A, Prat G, Fabbri M, Sànchez-Turet M: Early effects of caffeinated and decaffeinated coffee on subjective state and gender differences. Prog Neuropsychopharmacol Biol Psychiatry 32:1698–1703, 2008.
61. Rogers PJ, Heatherley SV, Hayward RC, Seers HE, Hill J, Kane M: Effects of caffeine and caffeine withdrawal on mood and cognitive performance degraded by sleep restriction. Psychopharmacology 179:742–752, 2005.

Received July 30, 2011; revision accepted February 6, 2012.