



Hydration, mood state and cognitive function



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Introduction

If the human body is composed of about 60% water, the human's brain can contain about 75% water. Hydration is actually essential to human homeostasis and survival. As part of its body functions, water contributes to the maintenance of normal brain functions (*EFSA 2011; Lieberman 2007*). Cognition is involved in everything we do, including perceiving, thinking, remembering, as well as feeling emotions and exerting control over our environment. One can thus wonder how brain functions related to cognition can be influenced by hydration status. Several studies have investigated the effects of dehydration and of increased water intake on cognition.

This document aims at defining cognition and giving an overview of validated methods that allow the assessment of cognitive functions. Then, it offers the state of the art knowledge on hydration and cognition, and provides official recommendations for daily water intake.

I. Defining and measuring cognition

I.1. What is cognition?

The term “cognition” includes all mental processes allowing humans to perceive, think and remember, but also to feel emotions and exert control over their environment. It is involved in everything a human being might possibly do (*de Jager et al. 2014; Feist and Rosenberg 2009; Neisser 1967*). For the purposes of this document, cognition will be addressed in two main aspects, which are cognitive performance and mood state.

- **Cognitive function** refers to abilities such as attention, memory (short-term, long-term, and working memory), learning, language, executive functions (reasoning, planning, decision making), visual and psychomotor functions (*de Jager et al. 2014; EFSA 2011; IOM 2004; Neisser 1967; Schmitt et al. 2005*).
- **Mood state** includes feelings and emotions like happiness, tension, vigor or calmness. It can also include perceptions like overall mood, sensation of fatigue or headaches, perceived difficulty to concentrate or to perform a task (*IOM 2004; Masento et al. 2014; Neisser 1967*).

I.2. How is cognition measured?

Cognition includes many domains and functions that need to be evaluated separately even though they are all very much interlinked (*Schmitt et al. 2005*). To assess a performance regarding one specific cognitive function, a test needs to assess subjects’ ability to respond to the corresponding cognitive challenge. Tests need to be sensitive to differences between subjects, but also to differences between states within one individual (*de Jager et al. 2014; Lieberman 2012*). Depending on the time of the day for instance, factors such as hunger, physical discomfort or fatigue may impact the performance. Another point to consider is the learning effect that can occur after repeated measures (*de Jager et al. 2014; Lieberman 2007*).

For these reasons, assessing cognition is a difficult and complex task, and methods are numerous. Depending on the research aim and the parameter to be assessed, it can involve electrophysiological measures, neuroimaging, brain imaging technologies, behavioral tests or mood questionnaires. There is still no consensus on the best methods to use. Comparing results between studies is thus a substantial difficulty in this field (*Lieberman 2007*). Consequently, most of cognition assessments are performed with batteries of validated tests, meaning normalized tests that ensure a sufficient level of confidence (*de Jager et al. 2014; Lieberman 2007*). When studying nutrition and cognition, two types of tests are commonly used:

- **Objective performance tests:** these measure a specific cognitive function such as memory, learning or attention. In these tests, subjects are asked to execute a series of tasks. The assessment of performance is usually measured through speed and accuracy of response (*de Jager et al. 2014*).
- **Mood and behavioral subjective questionnaires and scales:** these are self-reported measurements of changes in mental state. Most of them are scales on which subjects self-rate their perceptions and emotions.

Neuroimaging technologies provide supportive evidence of a cognitive change, although they are not widely used in the field of cognition and nutrition. The latency of the P300 waveform for instance is one of the most widely used to measure reaction time (*Westenhofer et al. 2004*).

Figure 1 summarizes dimensions of cognition and main methods of assessment.

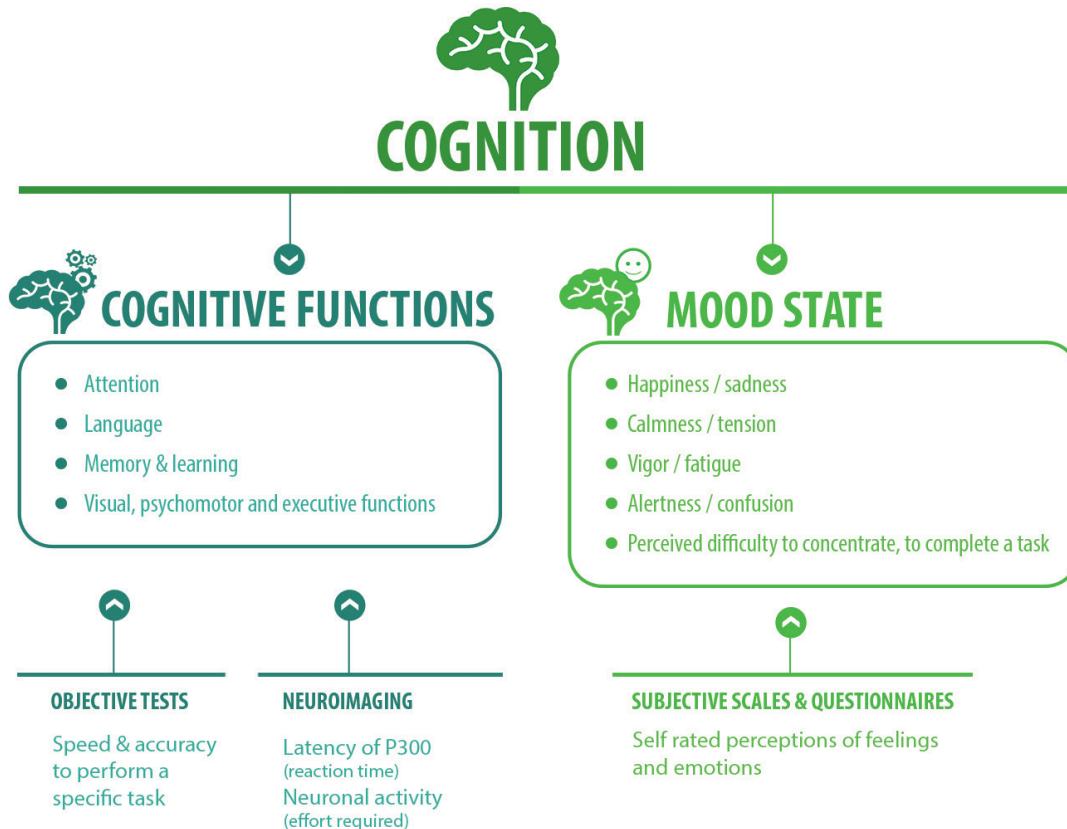


Figure 1. Main dimensions of cognition and methods of assessment.

I.3. Nutritional interventions in the field of cognition

Nutrition has an impact on both development and maintenance of brain structure and brain function. It could thus logically be associated with cognition (*Burkhalter and Hillman 2011*). Interest therefore rose regarding the associations between food and fluid intakes and cognitive performance (*de Jager et al. 2014*).

Assessing human cognitive function is however a difficult and complex task (*Lieberman 2007*). An important point to consider is that certain medications or diseases can have a great impact on cognition, while nutritional interventions will induce more subtle changes (*Lieberman et al. 2005; Lieberman 2007*). Tests used to assess the impacts of different food and nutrient intakes must then be carefully chosen as they need to ensure a sufficient sensitivity to the nutritional intervention (*Lieberman 2007*). Such tests have been developed over a century (*de Jager et al. 2014; Lieberman 2007*). However, a substantial difficulty in the analysis and comparison of different studies relies on the fact that many tests can be used, and they might not to be sensitive to the same nutrients (see **Figure 2**).

Regarding the impact of water on cognition, the European Food Safety Authority (EFSA) published in 2011 a report in which they supported the scientific opinion that water contributes to the maintenance of normal physical and cognitive function. It has actually repeatedly been reported that a water deficit can impair cognitive function (*EFSA 2011*). Despite the growing evidence of the deleterious impacts of dehydration on cognition (section III), only a few studies have focused on water supplementation (section IV), and even fewer have looked at habitual water intake and behavioral changes (section V). A possible explanation to this lack of evidence could be that accurate assessment of water intake and hydration status is another difficulty in the comparison of results (*Lieberman 2007*).

ASSESSING HYDRATION STATE



ASSESSING MOOD STATE AND COGNITIVE FUNCTION

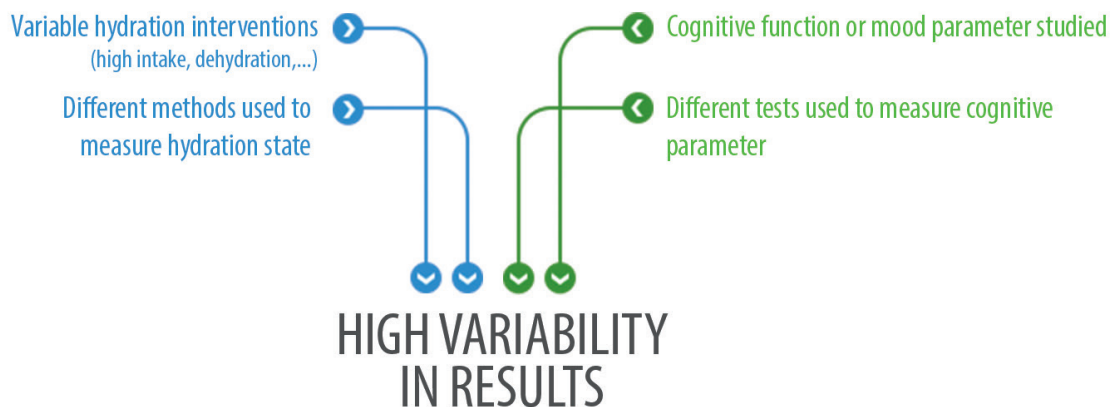


Figure 2. Challenges encountered when studying the impacts of hydration on cognition.

Cognition is involved in everything we do and includes many components that are all inter-connected.

It can be divided in two main dimensions:

mood, assessed through self-rated scales and questionnaires, and **cognitive performance** measured with objective tests.

II. Dehydration and cognition

There is growing evidence that cognitive functions are impaired in case of uncompensated body water loss (EFSA 2011). More generally, many studies have focused on cognitive impairment due to levels of dehydration of more than 2% body mass loss. The question of the impacts of mild dehydration ($\leq 2\%$ body mass loss) on cognition was only addressed in the last decade (Grandjean 2007; Masento et al. 2014).

II.1. Dehydration above 2% body mass loss

Impacts of dehydration on cognitive performance were first studied in extreme conditions, on soldiers or athletes. Levels of dehydration were usually higher than 2% body mass loss, achieved with intense physical exercise and/or extreme heat, sometimes combined with fluid deprivation (Grandjean 2007; Lieberman 2007; Masento et al. 2014).

In 1988, Gopinathan et al. studied the impacts of four levels of dehydration on cognitive performance. Their study was conducted on 11 young soldiers (aged 20-25 years) and involved dehydration induced through a combination of water deprivation, heat and exercise. When levels of dehydration induced were above 2% body mass loss, results show reduced short term memory, arithmetic efficiency, as well as motor speed and attention (Gopinathan et al. 1988).

Negative impacts due to dehydration above 2% body mass loss were repeatedly found both on subjective feelings and on cognitive performance. At these levels of dehydration, cognitive abilities affected include short term memory, attention, concentration, information processing, executive functions, coordination functions and motor speed (Baker et al. 2007; Cian et al. 2000; Epstein et al. 1980; Sharma et al. 1986). Above 2% body mass loss dehydration mood and feelings were also altered, including fatigue and perceived exertion, tension, confusion, anger, emotional state and global mood (Cian et al. 2000; Ely et al. 2013; McGregor et al. 1999; Sharma et al. 1986). This still has to be interpreted cautiously, as other studies have found no impact of dehydration on functions such as short term memory, grammatical learning, information processing, attention or alertness (Ely et al. 2013; Grego et al. 2005; Tomporowski et al. 2007).

These disparities and contradictions in results from one study to another may be due to the wide variety of methods involved. Many tests and questionnaires exist to assess cognitive performance and subjective feelings. Levels of dehydration can range from 2 to 4 percent of body mass loss and methods involved to induce dehydration also vary between studies. Finally, exercise in itself, as well as concurrent hyperthermia both induce changes in cognitive performance and can be confounding factors (Tomporowski and Ellis 1986). Also, in the control condition, ensuring euhydration through water intake to compensate for sweat loss makes it difficult for the study to be blinded (Grandjean 2007; Lieberman 2007; Masento et al. 2014).

Dehydration of 2% or more body mass loss can increase perception of fatigue, induce impairment in cognitive functions such as memory and attention, and alter mood.

II.2. Dehydration below 2% body mass loss

In the last decade, scientists began investigating the implications of mild dehydration (below 2% body mass loss) on cognition. Because water balance changes throughout the day, mild dehydration may be experienced in daily life, which explains the growing interest regarding cognitive consequences. Two types of experimental design are usually involved: either a combination of fluid restriction and exercise-induced sweat loss, or water deprivation alone.

II.2.1. Exercise-induced dehydration

In 2009, *D'Anci et al.* induced dehydration through exercise on 31 young athletes (16 men, 15 women, mean age 20). The exercise consisted of 60 minutes of intense rowing and was followed by a cognitive-test battery and self-rated mood and thirst assessments. Dehydration achieved was 2.0% body mass loss in men and 1.65% in women, and resulted in a deterioration of all POMS (Profile Of Mood State) parameters. None of the mood parameters differed according to sex except for choice reaction time and visual vigilance (*D'Anci et al. 2009*). Although the authors used validated tests, the study was not blinded and there was no control of body temperature. Inducing dehydration through exercise indeed implies some limitations: again, exercise, body hyperthermia, as well as water intake ensuring euhydration in the control condition, are known to be confounding factors (*Grandjean 2007; Lieberman 2007; Masento et al. 2014*).

More recently, *Armstrong et al.* and *Ganio et al.* published two well-controlled studies involving exercise-induced mild dehydration. They both considered hyperthermia as a possible confounding factor for cognitive performance and controlled that dehydration was achieved without any raise in body temperature. The studies were blinded with a diuretic condition. They involved three conditions: exercise-induced dehydration plus a diuretic, exercise-induced dehydration plus placebo, and exercise while maintaining euhydration. The exercise consisted of 40 minutes treadmill walks in a mild environment (27.7°C). In both of these studies, dehydration induced was above 1% body mass loss and led to an increase in urine specific gravity (*Armstrong et al. 2012; Ganio et al. 2011*). In men, mild dehydration of 1.6% body mass loss led to reduced visual vigilance and working memory, and to increased perception of fatigue and anxiety (*Ganio et al. 2011*). In women, mild dehydration of 1.4% body mass loss led to deterioration in vigor, to increased fatigue, to a greater total mood disturbance and to increased difficulty to complete cognitive tasks and to concentrate. Interestingly, women also reported an increased frequency of headaches. However, while mood was affected, the same study did not show differences in cognitive test performance (*Armstrong et al. 2012*). These two studies, carried out in the same conditions and using the same methods, suggest differences between men and women regarding the impacts of mild dehydration. While mild dehydration appears to affect mainly cognitive performance in men, in this study, women demonstrated little impact on cognitive functions and greater effects on mood. In most studies carried out on adults, mood appears to be affected by exercise-induced mild dehydration, while evidence regarding the impacts on cognitive performance is not consistent and varies between studies. This may be due to the fact that exercise in itself has cognitive impacts, and thus may confound or mask any effect of hydration. More carefully-controlled studies would be required to tease out the differential effects of mild dehydration from exercise on cognitive function.

Little has been done to evaluate the mechanisms by which dehydration may impact cognition, and this topic is addressed in part V. A study performed on adolescents provides some insight into potential physical changes in the brain as a result of mild dehydration. *Kempton et al.* induced dehydration of 1-2% body mass loss through exercise. Using brain imaging techniques, they measured neuronal activity while the subjects performed a cognitive task. While they observed no differences in task performance, they did observe increased brain activity in areas mediating executive functions (*Kempton et al. 2011*). The authors speculated that in the dehydrated condition, subjects may have had to increase the cognitive resources needed to complete the task, thereby suggesting that tasks may become more demanding when mildly dehydrated.

II.2.2. Mild dehydration achieved through water deprivation

Over the past few years, to avoid the possible confounding effect of exercise, water deprivation alone has been used to induce mild dehydration on healthy young subjects. As it is a new area of interest, only a few studies are available to date. Results vary between studies, probably due to differences in methods used to assess cognitive functions.

In studies that have shown results, the effects of water deprivation appear to be on the perception of sleep-wake feelings such as tiredness, fatigue or exertion are often reported (*D'anci et al. 2009; Shirreffs et al. 2004; Szinnai et al. 2005*). In a study carried out by *Pross et al.* on young women, authors found that a 24h fluid deprivation resulted in impaired mood, with several parameters affected, including fatigue and vigor, alertness, confusion, calmness and contentedness, tension and emotional state (*Pross et al. 2013*). In a study by *Shirreffs et al.*, inducing a 37h fluid deprivation, the 9 men and 6 women enrolled reported decreased alertness and ability to concentrate as of 10h. Subjects self-reported even greater difficulty to concentrate and to stay alert after 24 and 37 hours (*Shirreffs et al. 2004*). However, on 10 young men (mean age 25), *Petri et al.* found no effects of a 24h fluid deprivation on mood parameters (*Petri et al. 2006*). A plausible explanation to these differences in results could be the sex of subjects involved. Indeed, it appears that men and women may not be affected the same way by mild dehydration (*Armstrong et al. 2012; Ganio et al. 2011*). This hypothesis is supported by a study from *Szinnai et al.* who found a significant gender effect on several cognitive tasks (*Szinnai et al. 2005*).

II.2.3. Voluntary dehydration

Without any induced dehydration, some biomarkers can underline a suboptimal hydration. High urine osmolality can for instance occur when fluid intake is insufficient to adequately compensate water losses, leading to the conservation of body water through antidiuresis. This phenomenon is commonly called voluntary dehydration and has mostly been reported in children and elderly. In children this is mainly explained by the lack of available water in schools, while in elderly it may be due to decreased thirst sensation, and to incontinence (*Bar-David et al. 2005; Masento et al. 2014*).

Consequences of voluntary dehydration on cognition have not been thoroughly investigated. In children, *Bar-David et al.* found that voluntary dehydration affects immediate memory: children who had a morning urine osmolality above 800mOsm (dehydrated group) had lower scores at auditory number span test than hydrated children, defined as children whose urine osmolality in the morning was below 800mOsm (*Bar-David et al. 2005*). Some interest has been given to voluntary dehydration in the elderly, but in these studies the topic of cognition has been largely overlooked. *Suhr et al.* found correlations between hydration status and (a) psychomotor processing speed, attention and memory performance in healthy older adults, (b) declarative and working memory in postmenopausal women (*Suhr et al. 2004; Suhr et al. 2010*).

In adults, *Kenefick et al.* reported an increased rate of industrial accidents during summer months, suggesting that voluntary dehydration concurrent with high temperatures could affect cognitive performance and decision-making (*Kenefick and Sawka 2007*).

Even milder levels of dehydration (lower than 2% body mass loss) can increase fatigue and alter mood. There also is growing evidence that cognitive functions might be impaired.

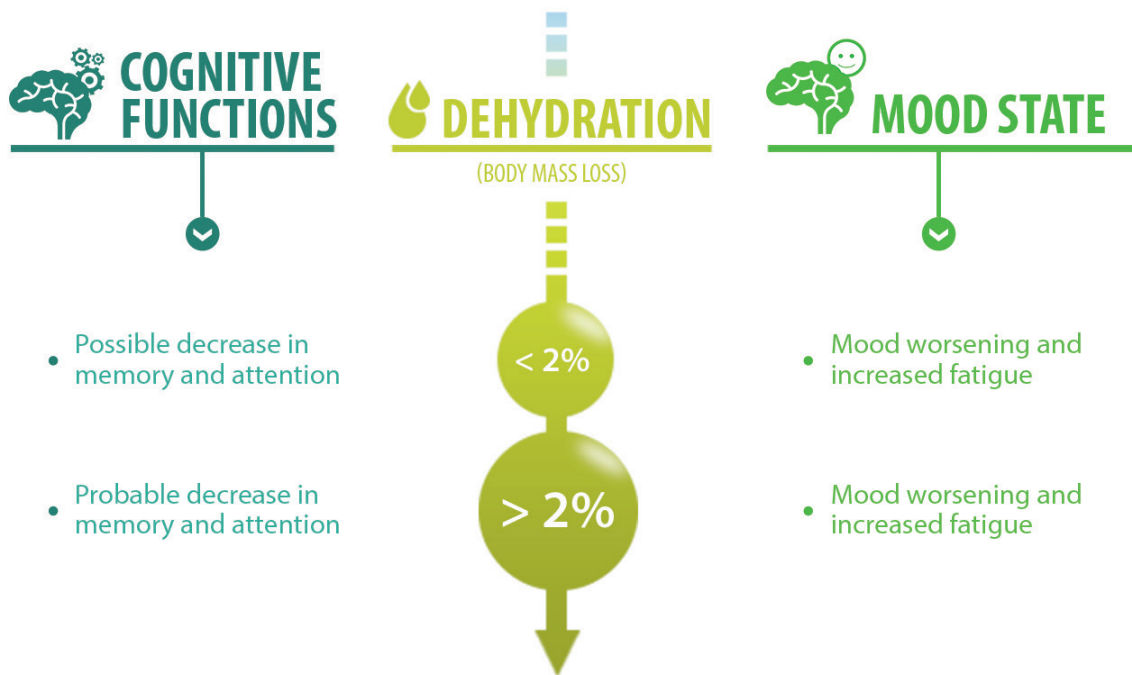


Figure 3. Commonly reported impacts of dehydration on mood state and cognitive function.

II.2.4. Recommendations for future research

Disparities in methods make it complex to compare results between studies and to conclude on the global effects of mild dehydration on cognition. Recommendations for future research include controls for exercise, for water intake and for other fluids consumed, as well as accurate measurement of hydration status using hydration biomarkers. More research is required to make further recommendations regarding cognitive tests sensitive to hydration and nutritional interventions (Lieberman 2007).

Overall, most of these studies found that mild dehydration altered several mood parameters. Conclusions are still unclear regarding cognitive performance for which results vary depending on the methods used, the parameters studied and for which there appears to be a gender effect (Lieberman 2007; Masento et al. 2014). As subjects often report increased difficulty to concentrate and to complete the cognitive tasks, a common hypothesis is that cognitive compensating mechanisms are involved (see V) (Szinnai et al. 2005).

Dehydration has deleterious impacts on cognition.
 Even below 2% body mass loss fatigue appears, mood is altered,
 and several cognitive functions might be impaired (memory, attention ...).
 Uncompensated water losses can thus lead to decreased cognitive functions.

III. Effect of water intake on cognition

Cognitive implications of water supplementation and immediate effects of water intake were mostly studied in children because they are known to be at particular risk of water deficit, and because it is ethically difficult to restrict water intake in children (Masento et al. 2014). In children, water intakes of 200 to 650mL have been shown to immediately reduce thirst and to increase subjective happiness, memory, motor skills, visual attention and visual search (Benton and Burgess 2009; Booth et al. 2012; Edmonds and Burford 2009; Edmonds and Jeffes 2009). Over the course of one class day, Fadda et al. asked children to increase their fluid intake with 1.0L of water (mean increase was actually of 625mL over the day). As compared to children who did not drink additional water, children who drank reported higher vigor and performed better at short-term memory tasks (Fadda et al. 2012). More recently, in their cohort study led on 447 undergraduates, Pawson et al. found that students who brought water to the exam performed better although they did not actually measure the water volumes consumed (Pawson et al. 2013).

In adults, water ingestion following a period of fluid restriction and/or fasting was repeatedly found to enhance state of arousal, increasing cognitive dimensions such as alertness, attention and reaction time, and decreasing perception of confusion (Edmonds et al. 2013b; Neave et al. 2001; Pross et al. 2013). When water intake occurs without previous fluid deprivation, water still appears to enhance alertness and visual attention (Edmonds et al. 2013a; Rogers et al. 2001). However, several studies found that the beneficial effect of water intake on state of arousal depends on whether or not subjects were thirsty before they drank water (Edmonds et al. 2013b; Rogers et al. 2001).

Headaches have been reported in subjects under induced dehydration (Armstrong et al. 2012). On recurrent migraine patients, Spigt et al. found that an increase in water intake of at least 0.8L per day can reduce headaches and increase patients' quality of life (Spigt et al. 2005; Spigt et al. 2012).

Immediate effects of water intake were repeatedly found on state of arousal, improving perceptions of vigor, as well as performance on task requiring attention and alertness. In children, water also appears to enhance short-term memory.

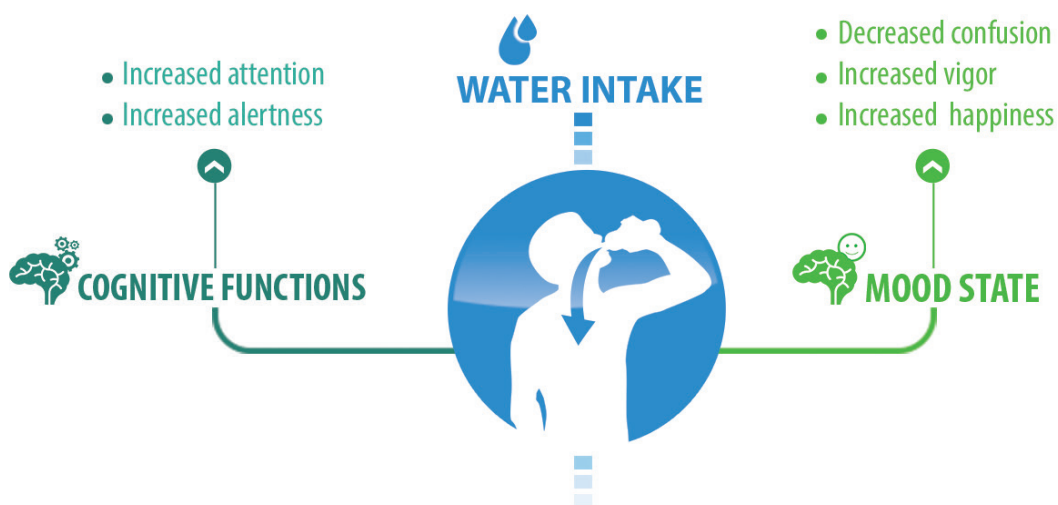


Figure 4. Commonly reported benefits of water intake on mood state and cognitive function.

IV. Can a change in water intake impact mood?

To our knowledge, only one study has looked at the effect of a change in water intake on mood. In this study carried out by *Pross et al.*, 52 healthy young subjects were asked to maintain their habitual water intake during two baseline days, and then to either increase or decrease their water intake over three intervention days. Groups were formed based on the average intakes of the French population: one third of subjects drinking less than 1.2L/day (low drinkers group), one third between 1.2 and 2L/day (excluded from the study), and another third drinking more than 2L/day (high drinkers group). Low drinkers subjects started from their habitual water intake of 1L/day and increased to 2.5L/day. The 22 high drinkers subjects started from 2.5L/day and decreased to 1L/day.

No differences in mood were observed at baseline between the two groups. After only three days of intervention, results showed increased thirst and decreased contentedness, calmness and positive emotions in high drinkers subjects who decreased their water intake. In the low drinkers group, increasing water intake resulted in decrease in thirst and confusion (*Pross et al. 2014*).

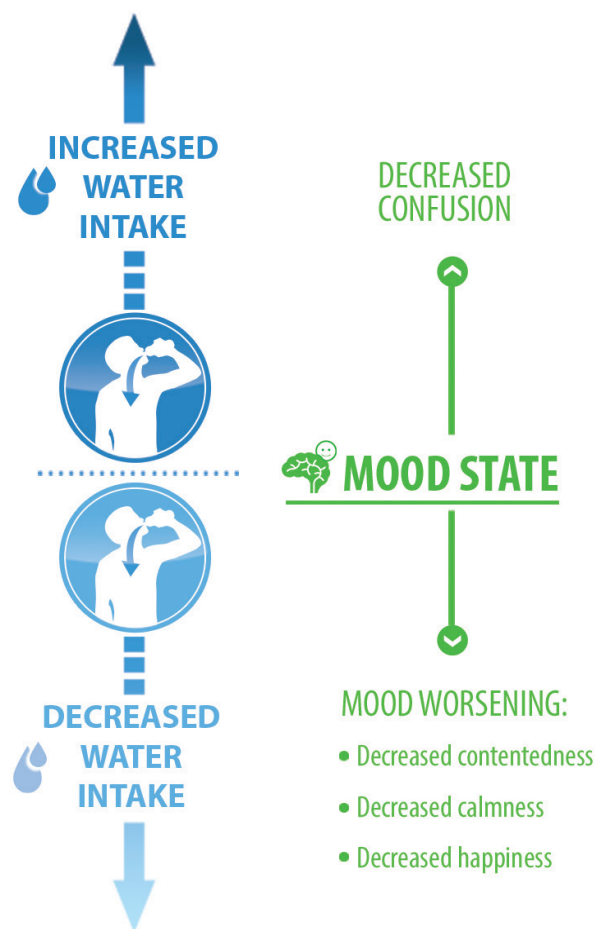


Figure 5. Reported effects of a change in daily water intake on mood state (*Pross et al. 2014*).

Scientific evidence is scarce regarding the effects of a change in daily water intake on cognition. Existing data suggest a change in mood after only 3 days: a decrease in water intake would alter mood, while an increase could decrease confusion thus enhancing state of arousal.

V. Hypothesized mechanisms linking water and cognition

It has been hypothesized that positive effects of water on cognition could be due to a psychological effect of expectancy. This hypothesis was however recently rejected when *Edmonds et al.* enrolled 47 adults among which some received water without knowing it was part of the experiment (subjects were given a drink during a conversation without notice). Some groups of subjects were informed that water could have an impact on their cognitive functions, and others were not. The authors found positive effects of acute water intake whether or not they were in the expectancy group (*Edmonds et al. 2013a*).

Several physiological mechanisms might be involved in the cognitive consequences of dehydration. The main mechanism known to follow dehydration involves the hormone vasopressin (or arginine vasopressin, AVP, also known as the Antidiuretic Hormone, or ADH). Dehydration causes a slight raise in blood osmolality, which is detected by specialized receptors that signal AVP release. The increase in circulating AVP may increase the synthesis of cortisol in the adrenal cortex of the kidneys. Hypotheses regarding how this could affect cognitive performance include animal studies that have shown an association between cortisol and reduced memory, poor processing speed and altered active learning (*Masento et al. 2014; Wilson and Morley 2003*). In parallel, AVP also induces thirst sensation. This is hypothesized to enter in competition with other cognitive tasks for resources, and might thereby decrease attention (*Masento et al. 2014*). These hypotheses are summarized in **Figure 6**.

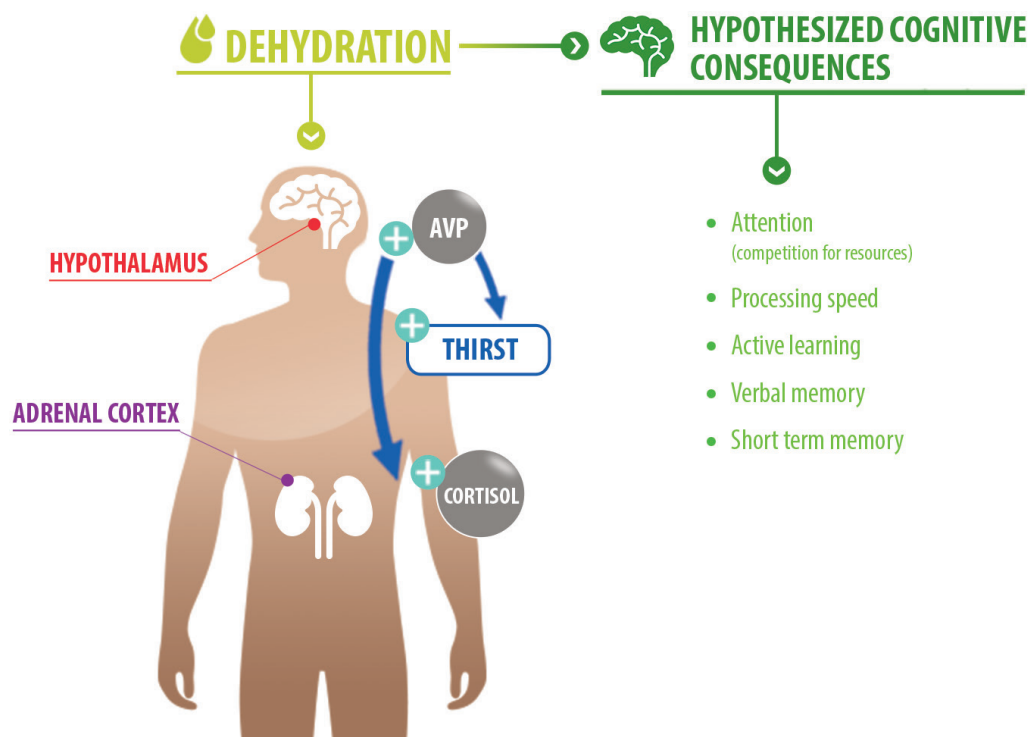


Figure 6. Physiological consequences of dehydration and hypothesized mechanisms involved in the cognitive consequences.

VI. Dietary reference values for water

Dietary reference values for total water intake (water coming from food and from fluids) have been established by several organizations (*EFSA 2010; IOM 2004*). Contrarily to many other nutrients, there is insufficient research regarding the amount of water required to prevent diseases or improve health. In 2010, the European Food Safety Authority established reference values for total water intake in the general population. These adequate intakes vary according to age and sex and are presented in **Table 1** (*EFSA 2010*).

	1-2 years	2-3 years	4-8 years	9-13 years	14-18 years	Adults	Pregnant women	Lactating women
Recommended TWI (EFSA 2010)	1.1-1.2 L/d	1.3L/d	1.6L/d	Girls 1.9L/d	Women 2L/d		2.3L/d	2.7L/d
				Boys 2.1L/d	Men 2.5L/d			

Table 1. Reference values for total water intake (water from food + water from fluid) per age group (*EFSA 2010*).

EFSA estimated that around 80% of total water intake come from fluids, and 20% from food (*EFSA 2010*). Adequate intakes are thus equivalent to drinking 1.6L of water per day for adult women, 2.0L per day for adult men, 1.8L per day for pregnant women and 2.2L per day for lactating women.

To set these adequate intakes, EFSA took into account data from multiple national intake surveys, corresponding osmotic load, and urine volumes necessary to achieve a desirable urine osmolality of 500mosm/L (*EFSA 2010*).

Later on, EFSA stated that water contributes to the maintenance of normal physical and cognitive performance. Along with this statement, and based on their previous scientific opinion on water intake, they approved the claim on water for a total water intake of 2.0L per day in adults (*EFSA 2011*).

According to the European Food Safety Authority, water contributes to the maintenance of normal physical and cognitive performance. In adults, EFSA considers 2.0L of water per day to be an adequate intake.

Conclusion

- Cognition is involved in everything we do and includes many components that are all inter-connected. It includes two main dimensions: mood, assessed through self-rated scales and questionnaires, and cognitive function measured with objective performance tests.
- Dehydration has deleterious impacts on cognition.
- Dehydration of 2% or more body mass loss can increase perception of fatigue, induce impairment in cognitive functions such as memory and attention, and alter mood.
- Even below 2% body mass loss fatigue appears, mood is altered, and several cognitive functions might be impaired (memory, attention ...).
- Uncompensated water losses can thus lead to decreased cognitive functions.
- Immediate effects of water intake were repeatedly found on state of arousal, improving perceptions of vigor, as well as performance on task requiring attention and alertness.
- In children, water also appears to enhance short-term memory.
- Scientific evidence is scarce regarding the influence of habitual water intake on cognition. Existing data suggest that a decrease in water intake can alter mood, while increasing water intake appears to reduce confusion.
- According to the European Food Safety Authority, water contributes to the maintenance of normal physical and cognitive performance.
- In adults, EFSA considers 2.0L of water per day to be an adequate intake.

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