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Effects of hydration status on cognitive performance and mood

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Abstract

Although it is well known that water is essential for human homeostasis and survival, only recently have we begun to understand its role in the maintenance of brain function. Herein, we integrate emerging evidence regarding the effects of both dehydration and additional acute water consumption on cognition and mood. Current findings in the field suggest that particular cognitive abilities and mood states are positively influenced by water consumption. The impact of dehydration on cognition and mood is particularly relevant for those with poor fluid regulation, such as the elderly and children. We critically review the most recent advances in both behavioural and neuroimaging studies of dehydration and link the findings to the known effects of water on hormonal, neurochemical and vascular functions in an attempt to suggest plausible mechanisms of action. We identify some methodological weaknesses, including inconsistent measurements in cognitive assessment and the lack of objective hydration state measurements as well as gaps in knowledge concerning mediating factors that may influence water intervention effects. Finally, we discuss how future research can best elucidate the role of water in the optimal maintenance of brain health and function.

Key words: **Hydration: Cognitive performance: Mood: Water consumption**

Growing evidence suggests that the food and drink that we consume affect mental and physical performance[1]. Food and food components that exhibit physiological and mental effects have been dubbed 'functional foods' or 'nutraceuticals' and are proposed as ways to help sustain good health and protect against illness, disease and pathological ageing[2]. Despite water constituting 60–80 % of the human body, it is often overlooked as a significant nutrient that can affect not only physical performance, but also mental performance. In this review, we evaluate evidence from studies that investigated how cognitive performance is affected when water intake levels are low (i.e. during dehydration) or optimal and beyond (i.e. during acute water consumption). (To ensure that the review was comprehensive, we carried out literature searches using databases 'Web of Science' and 'Google Scholar' and obtained published studies that investigated dehydration and its effect on cognitive performance using search terms such as 'dehydration & cognition', 'dehydration & performance', and 'dehydration & mental'. To obtain studies that investigated water consumption and how it influences cognitive performance, search terms such as the following were used: 'hydration & cognition'; 'hydration & performance'; 'hydration & mental'; 'water consumption & performance'; 'water consumption & cognition'; 'drinking water & cognition'.) In addition to reviewing published research findings, we also discuss previously proposed mechanisms of action as well as new ones. Finally, based on the current state of the research area, we propose avenues for future investigations.

Voluntary dehydration

Evidence from public surveys[3,4] and experimental investigations[5,6] has indicated that the general public and particularly groups such as children and older adults are at a risk of voluntary dehydration[7,8], such that individuals are drinking insufficient amounts of fluid resulting in sustained dehydration. Voluntary dehydration is likely to occur due to a lack of awareness of how much fluid consumption is required for a balanced hydration state (euhydration), especially when not taking into account the amount of daily activity; other external factors such as weather also contribute to this day-to-day variability in hydration requirements. Examples of voluntary dehydration have been reported in school children living in hot climates[5,6] and also in a group of experienced runners who, although aware that they should rehydrate after exercise, drank insufficient amounts of water due to an underestimation of their hydration state, resulting in sustained dehydration[9].

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Fluid balance within the body is maintained via homeostatic mechanisms[10]; water conservation occurs via the renal system, modifying urine production. Water intake is encouraged by thirst sensation. Although these mechanisms are intrinsic in homeostatic maintenance, they are also fallible, particularly in vulnerable groups such as children and older adults who maintain their hydration state inadequately. Inadequate hydration in young children and older adults may be due to dependency on carers, making self-motivation to seek fluid consumption difficult. There are also physiological issues of interpreting the thirst response, prompted by homeostatic mechanisms, which may be problematic due to inexperience in children[11,12] and due to the deterioration of osmoreceptor sensitivity in older adults[13–15]. These factors preventing fluid consumption will over time result in individuals sustaining dehydration. Older adults are also more likely to have reduced kidney filtration function, resulting in less efficient water conservation when dehydrated, further exacerbating difficulties in recognising a dehydrated state[14].

Sustained dehydration is associated with poor health[16,17]; chronic dehydration greatly increases the chances of kidney stones and urinary tract infection[16,18], whereas prolonged vasoconstriction, as a result of chronic dehydration, can increase the chances of hypertension and stroke[10]. These physical consequences highlight the importance of preventing voluntary dehydration and make it a public health issue. Authoritative bodies such as the European Food Safety Authority (EFSA) support the scientific opinion that water contributes to the maintenance of normal physical and cognitive function[19] and therefore have set recommended guidelines of 2000 ml of fluids for females and 2500 ml for males to be consumed per day[20]. These guidelines were set to encourage more fluid consumption and reduce the risk of sustained dehydration. There is some debate regarding the guidelines and the apparent lack of empirical evidence concerning the amount of additional fluids that individuals should actually consume[21,22]. Based on the high individual variability regarding fluid requirements, it is argued that the emphasis should be on encouraging individuals to monitor their own hydration levels using markers such as urine colour[23] and to be aware of variables that may influence the amount of water they need to consume, such as climate and physical activity. To identify the best strategy for improving public water consumption, it is important to understand the factors that lead to the widespread neglect of water intake, as well as the impacts of inadequate water intake on both physical and mental performance.

Dehydration and cognitive function

Investigations into dehydration and mental performance were first systematically carried out in a military population[24]. Soldiers were exposed to extreme heat, inducing varying severities of dehydration. Cognitive abilities such as short-term memory, numerical ability, psychomotor function and sustained attention were assessed to establish any particular deficits as a result of changes in hydration status. Cognitive deficits were dependent on the severity of dehydration, which affected performance in all cognitive tasks when soldiers were in a severe state of dehydration (>2 % body mass loss). This study was the first to emphasise that cognitive abilities were sensitive to a suboptimal hydration state.

Subsequent studies both in a military population and in the general population supported this initial evidence of detriments in cognitive abilities with induced dehydration[25–32]. However, relative to the study carried out by Gopinathan *et al.*[24], the cognitive deficits were more modest and only found in particular cognitive domains such as short-term memory and perceptual abilities, with preservation of other cognitive abilities such as working memory and executive function. Other studies[33–38] found no support of cognitive impairment due to dehydration. These inconsistencies across empirical studies make it difficult to conclude whether, and how, dehydration affects cognitive performance (see Table 1 for all the dehydration and cognition function studies). Indeed, some experts have questioned where there is sufficient evidence to suggest that dehydration significantly affects cognitive performance[39].

Studies measuring self-reported changes in mental state have consistently found associations between dehydration and mood, in conjunction with changes in performance[27,30] or with limited to no performance changes[35–37,40,41]. Despite variability in rating methods used, similar mood states were reported such as ‘less alert’, ‘difficulty in concentrating’, ‘fatigue’ and ‘tension’[27,35,36,40–42]. Some studies also reported that participants found completing the experimental tasks more difficult[35,36] when in a dehydrated state. These findings highlight that self-reported mood states are sensitive to changes in hydration state and can occur independently from any cognitive performance changes.

One possible source of the heterogeneity in the profile of cognitive effects during dehydration may be the diversity in methods used to induce dehydration and to measure cognitive performance[43]. Early investigations used heat stress independently[24] as well as a combination of strenuous exercise and heat stress to create a severe dehydration state[25–27,35,40,44], whereas more recent investigations have used fluid restriction to ascertain how mild dehydration influences performance[32,36,45–47]. These methods vary in the degree of dehydration severity, which is probably a key determining factor of deficits in cognitive performance[24]. This is supported by recent mild dehydration investigations reviewed above, which found self-reported mood changes but the preservation of cognitive abilities[35,38,40]. The use of different methods also results in interpretive confounding factors. Specifically, evidence suggests that exercise alone improves cognitive performance[48], which could counteract any potential deficit caused by dehydration. Increased core temperature via heat stress has also been shown to cause cognitive deficits, more so than dehydration[44]. Therefore, studies that use exercise and heat stress to induce dehydration may confound the mechanisms responsible for any effect found, placing into question whether these methods are optimal to investigate the influence of dehydration on cognitive performance.

Studies that have used fluid restriction to induce dehydration[32,36,45–47] are comparatively free of such

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Table 1. Characteristics of dehydration and cognitive function and/or mood studies

Authors	Sample size (*n*)	Sample age	Design	Dehydration method	Self-reported measures	Other measures	Cognitive tasks	Cognitive performance/MRI change	Self-reported changes
Sharma *et al.*[49]	8 men	21–24 years old	Repeated-measures cross-over	Heat chamber with moderate activity Targeted varying severities of dehydration (1–3 % BMC)	–	%BMC	Symbol substitution test – processing speed Concentration test – WM Eye–hand coordination test – psychomotor function	Slower processing – speed at 3 % Reduced psychomotor function	–
Gopinathan *et al.*[24]	11 men	20–25 years old	Repeated-measures cross-over	Heat chamber with moderate activity Targeted varying severities of dehydration (1–4 % BMC)	–	%BMC	Word recognition – STM Serial addition – mathematical efficiency Trail-making test – visuomotor processing	Global deficits at 2 %: STM Mathematical efficiency Visuomotor processing	–
Cian *et al.*[25]	8 men	Mean age: 27·4 years	Repeated-measures cross-over	Cond 1: heat chamber – passive hyperthermia to approximately 2·8 % BMC Cond 2: 60 % VO_{2max} exercise to approximately 2·8 % BMC	VAS: fatigue and mood	%BMC; heart rate; blood samples; core body temperature	Pictures recall – long-term memory task Four-choice serial RT – visual attention Perceptive discrimination – perceptual processing Digit span memory – STM Unstable tracking – psychomotor skills	Slow perceptual discrimination RT Reduced STM recall Psychomotor errors	Increased fatigue
Cian *et al.*[26]	7 men	Mean age: 25 years	Repeated-measures cross-over	Cond 1 and 2: heat chamber – passive hyperthermia with or without FR to approximately 2·8 % BMC Cond 3 and 4: 65 % VO_{2max} exercise to approximately 2·8 % BMC	VAS: fatigue and mood	%BMC; heart rate; core body temperature	Pictures recall – long-term memory Judgement of line length – perceptual discrimination RT – processing speed Digit span test – STM Unstable tracking – psychomotor skills	Slower perceptual RT Impaired STM performance	Increased tiredness
Ainslie *et al.* [86]	17 men: 9 younger and 8 older	Mean age: 24 years Mean age: 56 years	Independent sample – YA *v.* OA	Exercise – 10 d walking activity	–	Uosm; %BMC; daily dietary record; energy expenditure; blood samples	Choice RT Grip strength – motor function Flexibility and vertical jump –muscle power	OA progressive dehydration over 10 ds YA sustained euhydration Psychomotor function deficit for OA	–
Suhr *et al.*[46]	28 adults	Mean age: 63·7 years	Correlational	FR approximately 12 h	–	%BMC – bioelectrical impedance	RBANS – range of cognitive abilities Trail-making task – psychomotor function Grooved Pegboard Test – manual dexterity	Slower psychomotor processing speed with low %BMC	–
Shirreffs *et al.*[41]	15 adults	Mean age: 30 years	Repeated-measures cross-over	FR for 37 h	VAS: thirst, mouth dry, mouth pleasant, headache, concentration, tiredness and alertness	%BMC; Uosm; blood samples	–	–	Increased headaches Reduced concentration and alertness at 24 and 37 FR
Bar-David *et al.*[45]	51 children	Mean age: 11 years	Independent samples, $>$800 mosm/kg H_2O (dehydrated) *v.* $<$800 mosm/kg H_2O (euhydrated)	No intervention, natural hydration state for comparison	–	Uosm	Hidden figures – visual attention/ perceptual speed Auditory number span – WM Making groups – semantic flexibility Verbal analogies – semantic memory Number addition – perceptual speed and numerical reasoning	Reduced STM at afternoon testing for dehydrated children	–

Table 1. *Continued*

Authors	Sample size (*n*)	Sample age	Design	Dehydration method	Self-reported measures	Other measures	Cognitive tasks	Cognitive performance/MRI change	Self-reported changes
Szinnai *et al.*[36]	16 adults	Mean age: 26 years	Repeated-measures cross-over	FR for 28 h	VAS: thirst, effort and concentration Likert scale: tiredness and alertness	Blood samples; Uosm; auditory ERP	Choice RT task – sustained visual attention Auditory serial addition task – sustained/divided attention Stroop task – verbal response time Smooth pursuit rotor task – manual tracking	No cognitive differences	Increased tiredness Less alertness
Petri *et al.*[32]	10 men	Mean age: 25 years	Repeated measures	FR for 24 h	10-point Likert scale mood: depression, working energy, anxiety and self-confidence	–	Complex Reactionmeter Drenovac: light signal position discrimination STM Simple visual orientation Simple arithmetic Complex motor coordination	Slower total solving time found from 9 h of FR and onwards	–
Patel *et al.*[28]	24 men	Mean age: 21·9 years	Repeated-measures cross-over	FR for 15 h plus 45 min 65–70 % VO_{2max} exercise	Concussion measures Sleep scale test – fatigue measure	Balance error scoring system NeuroCom sensory organisation test – postural stability USG	ANAM Simple RT Mathematics processing test Match-to-sample test Sternberg memory test	Reduced visual memory performance	Increased fatigue, 'feeling slowed down' and 'difficulty in concentrating'
Baker *et al.*[30]	11 males	Mean age: 21·3 years	Repeated measures	Cond 1: exercise + placebo drink Cond 2: exercise + carbohydrate drink Cond 3–6: degrees of dehydration 1–4 %	VAS lightheadedness, hotness and total body fatigue	%BMC; blood samples; core body temperature	Test of Variables in Attention – continuous performance test Two versions: first half frequent targets and second half infrequent.	Slower RT and increased errors compared	Increased fatigue, lightheadedness and overheating
Adam *et al.*[34]	8 adults	Mean age: 24 years	Repeated-measures cross-over	Cond 1: exercise-induced dehydration Cond 2: passive heat dehydration Cond 3: exercise plus fluids and cold environment Cond 4: exercise plus fluids and temperate environment	POMS; NASA-TLX	%BMC	Sentry duty simulation – marksmanship simulation with weapon Scanning visual vigilance	No cognitive differences	Not reported
Ackland *et al.*[30]	52 adults	Mean age: 62 years	Independent measures: colonoscopy surgical patients *v.* sigmoidoscopy surgical patients	Medical procedure – bowel preparation	Quality of life – SF8 Spielberger State-Trait Anxiety Inventory Subjective cognition scale	%BMC – bioelectrical impedance	Trail-making test A and B Rey Auditory Verbal Learning Test	No cognitive differences	Colonoscopy patients more anxious
D'Anci *et al.*[27]	54 adults; study 1: 31 adults	Mean age: 19·8 years	Repeated-measures cross-over	Study 1 Cond 1: 60 min exercise plus FR Cond 2: 60 min exercise plus water	Thirst sensation scale; POMS	%BMC	Digit span forward task – STM Simple RT Choice RT Kit of Factor-Referenced Cognitive Test – map planning Mathematical addition Continuous performance task Mental rotation task – visual perception	STM improvement Decreased vigilance over time	Increased anger, fatigue, depression, tension and confusion

Table 1. *Continued*

Authors	Sample size (*n*)	Sample age	Design	Dehydration method	Self-reported measures	Other measures	Cognitive tasks	Cognitive performance/MRI change	Self-reported changes
Kempton *et al.*[87]	7 men	Mean age: 23·8 years	Repeated-measures cross-over	Thermal – exercise-induced dehydration	–	Uosm; %BMC; structural MRI	–	Ventricular expansion following dehydration %BMC correlated with ventricular volume	–
Serwah & Marino[88]	8 men	Mean age: 24·5 years	Repeated-measures cross-over	Heat chamber plus exercise and varying fluid replacement	Perceived exertion and thermal comfort	%BMC; heart rate; skin temperature	Choice RT: one, two or four choices – varying complexities processing speed	Reduced accuracy while performing complex processing	Increased exertion due to exercise
Bandelow *et al.*[44]	20 men	Mean age: 20 years	Repeated-measures cross-over	Exercise-induced dehydration with or without fluid replacement	–	%BMC; core temperature; blood samples	Visual sensitivity – visuomotor RT Corsi block design test – visuospatial WM Sternberg test – WM Finger-tapping test – fine motor speed	Improved fine motor speed and complex WM RT during dehydration Slower RT for simple WM task	–
Suhr *et al.*[47]	21 women	Mean age: 60·3 years	Correlational	No intervention, natural hydration state	–	%BMC – bioelectrical impedance; blood pressure	Auditory consonant trigrams – WM Auditory verbal learning – declarative memory	Worse hydration state related to worse declarative memory ability	–
Ganio *et al.*[40]	26 men	Mean age: 20 years	Repeated-measures cross-over	Cond 1: exercise-induced dehydration plus diuretic Cond 2: exercise plus placebo Cond 3: exercise with fluid replacement	VAS: task difficulty, concentration and headache; POMS	%BMC; USG	Psychomotor vigilance test – simple RT Four-choice visual RT test Match-to-sample test – short-term spatial memory Repeated acquisition test – learning and STM Grammatical reasoning – logical reasoning.	Increased false alarms in vigilance task and slower RT for spatial WM	Increased tension and fatigue
Kempton *et al.*[38]	10 adolescents	Mean age: 16·8 years	Repeated measures	Two conditions: exercise-induced dehydration or euhydration. Structural and functional MRI at baseline and after thermal exercise protocol to induce dehydration	VAS: physical sedation and mental sedation	Uosm; %BMC; body core temperature; structural MRI BOLD functional MRI; ASL MRI	Tower of London task – executive function	No cognitive performance change Ventricular enlargement due to dehydration BOLD MRI increased activation for task-related areas after exercise	Physical and mental sedation increased due to exercise irrespective of dehydration condition
Armstrong *et al.*[35]	25 women	Mean age: 23 years	Repeated-measures cross-over	Cond 1: exercise-induced dehydration plus diuretic Cond 2: exercise plus placebo Cond 3: exercise with fluid replacement	VAS task difficulty, concentration and headache; POMS	%BMC; USG	Psychomotor vigilance test – simple RT Four-choice visual RT test Match-to-sample test – short-term spatial memory Repeated acquisition test – learning and STM Grammatical reasoning – logical reasoning	Increased false alarms in vigilance task	Increased anger, vigour and fatigue, difficulty in concentrating, headaches and difficulty in doing task
Smith *et al.*[31]	7 adults	Mean age: 21·1 years	Repeated-measures cross-over	FR for 12 h	–	%BMC; Ucol	Motor performance task – golf simulation Golf shot distance judgement and perceptual depth judgement	Impairments in shot distance and target accuracy Increased errors in distance judgement	–
Lindseth *et al.*[29]	89 adults	Mean age: 20·3 years	Repeated-measures cross-over	Fluid diet intervention: low-fluid diet *v.* high-fluid diet	–	%BMC; sleep activity	General aviation trainer – flight simulator Vandenberg mental rotation test – spatial WM Sternberg Item Recognition Test	Impairments in spatial WM for those who reached 1–3 % BMC	–

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Table 1. *Continued*

Authors	Sample size (*n*)	Sample age	Design	Dehydration method	Self-reported measures	Other measures	Cognitive tasks	Cognitive performance/MRI change	Self-reported changes
Pross *et al.*[42]	20 women	Mean age: 25 years	Repeated-measures cross-over	FR for 23 h or euhydration	POMS Bond Lader scale VAS: thirst Karolinska sleepiness scale	Uosm; plasma measures; saliva	(Cognitive data not included in the paper) Driving simulator Mackworth Clock Test Rey Auditory Verbal Learning Test		Increased ratings of sleepiness, fatigue, reduced vigour, alertness and confusion After *ad libitum* water states reversed
Ely *et al.*[37]	32 adults	Mean age: 22 years	Mixed design	Exercise–heat procedure with varying temperatures (10–40°C) with or without fluid replacement	POMS	%BMC; USG	Psychomotor vigilance task Four-choice RT test Match-to-sample test Grammatical reasoning	No cognitive differences	Increased anger, confusion, depression and fatigue when dehydrated

%BMC, body mass change; WM, working memory; STM, short-term memory; Cond, condition; VAS, visual analogue scale; RT, reaction time; FR, fluid restriction; YA, younger adults; OA, older adults; RBANS, Repeatable Battery for the Assessment of Neuropsychological Status; Uosm, urine osmolality; ERP, event-related potential; ANAM, Automated Neuropsychological Assessment Metrics; USG, urine specific gravity; POMS, profiles of mood states; NASA-TLX, National Aeronautical Space Administration, task load index; SF8, Health Survey by QualityMetric Inc.; BOLD, blood oxygen level-dependent; ASL, arterial spin labelling; Ucol, urine colour.

confounding factors. Interestingly, these studies tend to show modest cognitive deficits, if any, possibly reflecting that the participants were less severely dehydrated, although this is speculative; to date, no objective hydration state measure has been used to establish whether dehydration was induced. However, fluid restriction closely resembles routine voluntary dehydration behaviour found in the general population. Future research should focus on the extent to which fluid restriction may influence cognitive performance and ideally include objective measures of hydration state; this would not only advance the field of dehydration research but also benefit public health initiatives to encourage adequate fluid consumption.

As with any assessment of cognition, the tests chosen have a profound impact on the sensitivity to observe effects of the manipulation. There has been a propensity within the current collection of studies investigating dehydration and cognitive performance[28,44,46,49] to either use broad cognitive measurements from neuropsychological batteries or to select cognitive measurements based on previous use. These include batteries such as the Repeatable Battery for the Assessment of Neuropsychological Status and the Automated Neuropsychological Assessment Metrics. These neuropsychological tests often show little sensitivity to performance changes due to nutritional intervention, have inherently large variability in the detection of these performance differences and therefore lack validity in nutrition research. These issues with general neuropsychological tests that were not specifically designed for nutritional studies may lead to subtle effects being overlooked and an increase in false-negative reports. To avoid such issues, a number of researchers in this field, including Lieberman[43,50] and Edmonds *et al.*[51,52], have recommended that standardised cognitive measures, i.e. those that have previously shown sensitivity to nutritional interventions, should be utilised in future studies. Cognitive batteries that were designed for nutritional interventions such as phytochemicals have in recent years become popular[53], and the identification of sensitive cognitive measurements in nutritional intervention contexts can be found in published reviews (see Macready *et al.*[54]). Standardising the method of cognitive testing would also make it easier to corroborate evidence across different empirical studies in the future.

Mechanisms of action

Despite the inconsistent evidence of the impact of dehydration on cognitive performance, sustained dehydration is characterised by specific physiological changes. These physiological changes are part of a highly complex and variable system, making it particularly difficult to establish a unified baseline for hydration states across individuals. This issue perhaps underlies the variability in the findings of the influence of dehydration on cognition. Nevertheless, these physiological mechanisms of action may further inform us as to which aspects of mental performance are probably affected by dehydration. Reflecting on the homeostatic responses of dehydration, when the body is in a state of dehydration, many substrates and neurotransmitters are influenced by circulating vasopressin (also known as antidiuretic hormone) and angiotensin II[17,55]. These are key hormones involved in the homeostatic response of fluid imbalance[10]. One possible mechanism, proposed by researchers in this field[6,11,17], for cognitive deficits during dehydration could be increased levels of cortisol, often released during a stress response. It has been shown that higher levels of cortisol can lower memory function and processing speed[56] and consequently cause memory-related cognitive deficits[57].

Other neurotransmitter systems have been shown to act differently as a consequence of dehydration, potentially mediating the cognitive deficits reported. Serotonergic and dopaminergic systems modify blood–brain barrier permeability, which, if sustained, causes central nervous system dysfunction[58]. Findings also indicate that δ-aminobutyric acid and glutamate levels increase during chronic dehydration, influencing both inhibitory and excitatory activities of the brain[59]. These modulations due to dehydration, however, are still unclear in relation to how they may influence functional brain activation and therefore cognitive performance. To better understand the mechanisms of action of dehydration on cognitive performance, studies directly manipulating dehydration and measuring the impact on neurotransmitter function should be carried out. For instance, positron emission tomography or magnetic resonance spectroscopy can be employed to uncover how the functioning of these neurotransmitter systems changes as a result of dehydration.

As described above, mild dehydration studies so far have failed to show a replicable impact on cognitive performance. Whether this is due to insufficiently sensitive cognitive measurements and issues of variability, discussed previously, or due to a genuine lack of impact of mild dehydration on cognitive performance remains unclear. The evidence for reported mood state changes is more consistent across studies. Despite the lack of behavioural changes in cognition, neural activity in brain regions involved in attention and executive function has been shown to increase when individuals are mildly dehydrated than when they are euhydrated[38]. One explanation is that individuals compensate for dehydration at both the neural and behavioural levels through investing greater effort and mental energy[60], thus producing no net performance changes. Others suggest that NO production is increased during dehydration[61,62]. Indeed, studies have shown that NO production is associated with increased cerebral blood flow and vasodilation[63] and could ultimately counteract any potential impairment to cognitive performance, leading to a sustained level of ability. These theorised processes need to be investigated further, focusing on the critical point at which the brain can no longer compensate for dehydration and at what point cognitive deficits begin.

Acute water intervention and cognitive function

With evidence to suggest that individuals are routinely at a risk of mild dehydration day to day[8], particularly vulnerable populations such as children and older adults, there has been an increased interest in studying whether additional water consumption might benefit cognitive performance. The small collection of published water intervention studies involving either young adults or school children report consistent positive effects of water intervention on particular cognitive abilities.

Acute water intervention and visual sustained attention

Visual sustained attention has shown sensitivity to water consumption: the first study to investigate this[64] employed a between-group design randomly allocating young adults to a no-water, 120 ml water or 330 ml water condition. Using a sustained attention task (rapid visual information-processing task), the participants were asked to locate target numbers among successive sequences. The researchers found a dose-related improvement in performance, with those in the 330 ml water condition performing the best of the three groups and the no-water group performing the worst. However, this response was only found for those participants who reported thirst before the water intervention. These results suggest that visual sustained attention was sensitive to water consumption depending on the baseline hydration state of the individual. Interestingly, the task used in this study (rapid visual information processing) has not shown consistent results with acute water intervention. A subsequent study[65] using a repeated-measures design and an overnight fast – the latter to minimise variability in baseline hydration – included this task and found no improvement in sustained attention or in other cognitive performance measures after a water intervention. The inconsistencies found between these two studies could be due to the differences in experimental design: Rogers *et al.*[64] employed a between-group design, whereas Neave *et al.*[65] used a within-subjects design controlling for baseline hydration state. Due to repeated exposure to the cognitive tasks, within-subjects designs are likely to suffer from practice effects, which can diminish the sensitivity of the cognitive measurements. As discussed above, insensitive cognitive assessments can increase false-negative reports and make it difficult to ascertain whether there is a genuine effect of water intervention. Further investigation is still needed to understand these inconsistencies and how the role of experimental design may interact with any influence that water consumption has on cognitive abilities.

Other water intervention studies have reported similar sustained attention performance changes without a dependency on prior thirst/hydration state. In a mixed design[66], young adults were given 200 ml of water and performance was found to increase from baseline in a sustained attention task (letter cancellation), which involved searching for a target letter within a grid. This was the only task to show improvement out of a battery of tasks including working memory assessments and simple reaction time. Other studies carried out by the same research group[67–69] have replicated these improvements in visual sustained attention after water consumption in groups of school children. Despite these studies varying in the amounts of water ingested and experimental design, consistently these studies have shown visual sustained attention to improve after acute water consumption.

The corroborating evidence regarding visual sustained attention improvement after water intervention clearly

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highlights this as a key cognitive domain sensitive to water intervention. Further empirical studies should establish what particular component of this cognitive ability is benefiting from water intervention. One question that remains is whether attentional processes in other modalities such as auditory sustained attention would be similarly affected by acute water consumption. These recommendations have been made by researchers in the field[39,50,51,66], but have thus far not been implemented in empirical research. Testing these different sensory modalities would help teasing apart whether water intervention improvement is specific to the visual system, as has been found in some flavonoid intervention studies, for example[70], or whether higher-level, cross-modal attentional mechanisms are affected.

Acute water intervention and short-term memory

Short-term memory has also been shown to improve after water consumption. Short-term memory improvements after water consumption were found by three studies that investigated acute water intervention in school children[6,68,71]. The study carried out by Benton & Burgess[71] used a repeated-measures design with school children, assessing changes in the cognitive domains of short-term memory and sustained attention (using the recall of objects task and an auditory reaction time task). Interestingly, the authors failed to replicate water-induced performance improvements in the sustained attention task observed in other studies, possibly due to the task relying on auditory sustained attention rather than on visual sustained attention. However, the researchers did find that the children's short- and long-term recall of a list of objects improved after water consumption compared with no-water condition. A study carried out by Edmonds & Burford[68] testing 7–9-year-old children in London schools found that water consumption improved visual attention and visual memory. Using a 'spot the difference' task, the researchers found that water intervention significantly influenced children's visual memory: children who consumed water were able to identify more differences between two pictures compared with those who did not consume water. When taking into account the dosage of water consumed (250 *v.* <250 ml), they also found that short-term memory performance was improved, but only for those who drank more water (250 ml). The differential effect of dosage highlights that there may be a minimum amount of water consumption required to cause a significant impact on particular cognitive abilities and this no doubt will be related to the baseline hydration state of the children. Future studies should consider whether water dosage might have any differential effect on performance between various cognitive domains. Relatedly, a study that investigated Italian school children[6] found that children who were less hydrated were more likely to perform worse in an auditory number memory task, also implying that optimal hydration leads to better performance in the auditory number memory task. This study further highlights the importance of including metrics of baseline hydration state of children, in this case urine osmolality, which is an objective hydration state measure. Inclusions of hydration state markers such as urine osmolality provide valuable information related to the day-to-day hydration levels of individuals and the extent to which these levels change after acute water consumption. Taking these measurements into account when assessing cognitive performance after water ingestion would contribute towards the understanding of the underlying mechanisms at work.

Acute water intervention and simple reaction time

A recent study carried out by Edmonds *et al.*[52] has found improvements in simple reaction time after acute water intervention. The study consisted of thirty-three adults within a repeated-measures design. Cognitive performance changes were measured using the Cambridge Neuropsychological Test Automated Battery. When taking into account prior thirst of individuals, the researchers found that performance in the simple reaction time task was different between those who were thirsty and those who were not thirsty, with non-thirsty individuals exhibiting a relatively similar performance independent of water intake, whereas thirsty individuals performed significantly worse in the no-water condition. Even though thirst was measured subjectively, these results suggest that such subjective reports provide valuable information regarding hydration state; individuals who reported being thirsty during the experiment and were not provided with water supplementation were potentially mildly dehydrated, resulting in slower reaction times. This study helps us to understand how experienced variations in hydration state may interact with changes in cognitive performance. The majority of previous studies on this topic have lacked a measurement of baseline hydration status of their participants[52,64–69,71], and with the findings from this study highlighting that thirst mediates the performance change in specific cognitive abilities, it is evident that we need to further our understanding of the relationship between hydration state and change in cognitive performance in future work.

Acute water intervention and real-world settings

The importance of an optimal hydration state for adequate cognitive performance has been highlighted by a range of studies reviewed above, all of which have been carried out within a laboratory setting testing individuals' performance using relatively controlled neuropsychological tasks that are impoverished in comparison with real-life demands. Therefore, it is important to test the effects of changing hydration states in real-world settings that require a complex array of cognitive abilities. Such studies have already been carried out, testing the effects of dehydration on performance in real-life tasks such as airplane piloting and playing golf[29,31]. An attempt has been made by one study to investigate how drinking-water may be related to performance in examinations in university students: Pawson *et al.*[72] observed the number of people who took drinks to university examination sessions and compared the performance of these students with that of those who sat the same examination but did not take a drink. The results revealed a positive relationship between water taken to the examination session and performance in examination. Although these findings are correlational and do not include a measure of students' prior hydration state or of the amount of water consumed during the examination, these results support the notion that water consumption, or preventing dehydration, can have cognitive benefits. Further studies should investigate how drinking habits influence real-world settings, particularly for tasks that require a multitude of cognitive processes at once, such as driving and airline traffic control.

Acute water intervention and mood

Self-reported mood has been reported to show particular sensitivity to water consumption. One study that tested young adults on a range of cognitive tasks, including attention and working memory[65], failed to find any significant impact of water consumption on cognitive performance. However, mood ratings were shown to significantly change when individuals were given water. Individuals reported feeling more 'calm' and 'alert' immediately after water consumption. These results are in line with those of other young adult studies that found similar reports of 'alertness' after water consumption[64]. The recent study carried out by Edmonds *et al.*[52], which found that thirst mediated cognitive effects, also tested mood using visual analogue mood scales. The authors found that particular mood states were influenced by the counterbalanced order of water conditions. An example is that individuals were more confused when exposed to the control condition first, in which they did not receive any water, compared with when they were given water in the experimental condition. Interestingly, this relationship was moderated by drinking, indicating that water consumption was associated with lower reported confusion levels, irrespective of the condition order. This perhaps highlights that self-reported mood may be influenced by the expectancy of the experimental procedure itself and may have consequences for cognitive performance; therefore, it is important that participants are blind to the aims of the study to avoid such issues. Keeping participants blind in water intervention studies is particularly difficult when explicit instructions to consume water are provided. Considerations should be made to mask the true intentions of water consumption in such studies; one novel study was carried out by Edmonds *et al.*[66], in which the experimenter had a drink her/himself and provided an additional cup of water without explicitly instructing the participants to consume the drink. The participants still consumed an adequate amount of water (approximately 167 ml) that was enough to exert a significant impact on cognitive performance.

The majority of studies that have investigated acute water intervention in children have either not included a mood measure or asked children to rate their 'happiness', which provides a measure of mood similar to standardised mood assessments, and yet have so far failed to show any change after water consumption. This is possibly because self-reported happiness may not be sensitive enough, particularly as happiness does not usually capture a state of arousal that has shown sensitivity to water intervention[64,65]. A more recent study involving children has used an adapted version of the Profiles of Mood State questionnaire designed for children[6] and found a significant correlation between better hydration and reports of 'vigour', further supporting young adult mood reports. Studies that have included mood measures of alertness and other arousal states reveal that water consumption does have a significant impact on alertness and arousal; however, the extent to which this consumption sustains these mood changes is still inconclusive. Current findings suggest that these mood effects are short-lived and occur immediately after water consumption[64,65]. Future studies should consider investigating the temporal pattern of mood changes before and after water consumption.

Mediating factors

Despite only a relatively small collection of published empirical studies, evidence on acute water intervention hydration and cognition suggests that both cognitive performance and self-reported mood benefit from water consumption. As the field of water intervention is still in its infancy, there is some uncertainty as to how mediating factors such as water temperature and time of cognitive testing can influence subsequent intervention effects. To date, no water intervention studies have standardised water temperature and a majority of them have failed to report water temperature, despite evidence suggesting that particular chilled water temperatures (5°C) are most pleasant and thirst quenching[73–75]. This may be a critical mediating factor, as individuals have shown preference for chilled water when deprived for a period of time[76]. This preference for chilled water may result in improved motivation and mood after consumption, more so than room temperature, potentially resulting in different outcomes due to water intervention.

Water temperature has also been shown to influence the rate of water absorption into the bloodstream from the gut[77]. This change in absorption could mediate the critical time at which cognitive performance measures should be taken. Based on the current evidence, water absorption in the gut reaches its peak into the bloodstream between 20 and 60 min after ingestion[78,79]. Water intervention studies thus far have found cognitive performance changes within a critical window of 20–45 min[64,66,68,69,71]. This window is closely related to the peak absorption rates, suggesting that the critical time for cognitive testing should be in conjunction with this peak absorption point. Should water temperature vary, this peak absorption window is likely to be shifted and subsequently cognitive testing time would need to be altered. These are important considerations that need to be further investigated and considered in future empirical studies to truly identify how important these mediating factors are for water intervention effects.

Mechanisms of action

Despite the expansion of this research area, we still do not have a clear understanding as to how acute water intervention may influence mental performance and its associated neural activity. Researchers have suggested psychological mechanisms related to limited attentional resources during thirst[51,52,80]. However, evidence has also highlighted the importance of physiological mechanisms, with findings that the expectancy of water alone does not influence cognitive performance[66]. Herein, we not only discuss previously proposed mechanisms but also introduce new potential physiological mechanisms that we think have been previously overlooked.

Psychological mechanisms have been commonly proposed[51,52,80] to explain the effect of water consumption on cognitive abilities and mood states. The global workspace model[81] is a well-known generalised model of cognitive processes that postulates that there are limited amounts of cognitive resources and parallel processes often compete to obtain these resources. Applied to the topic at hand, states such as thirst and dehydration compete for these resources, resulting in limited capacity for other mental processes[80]. Within the context of acute water intervention, by alleviating the state of thirst and dehydration, these states no longer require allocation of resources, thus allowing parallel processes to recruit the required resources. This shift in cognitive resource allocation may provide the mechanism for performance change in cognitive tasks after water consumption. Support for this mechanism can be found in studies that demonstrated improvements in cognitive performance after hydration, with the level of thirst mediating the effect[52,64]. However, an alternative interpretation is that the state of thirst could be an indication of mild dehydration that could subsequently induce physiological changes, similar to those observed in brain imaging data[38] such as total brain volume shrinkage. Future studies focusing on this potential mechanism will help us to decipher whether it is the influence of thirst itself or the consequence of dehydration that underlies any changes in cognitive performance.

Potential physiological mechanisms for performance improvements after water intervention are based on theorised physiological changes as a result of water consumption. To date, researchers have not explored these mechanisms. The importance of physiological mechanisms, in addition to psychological mechanism, is underscored by a recent study carried out by Edmonds *et al.*[66]. The researchers manipulated expectancy by informing half of the participants about the beneficial effects of water consumption on cognitive performance during either a no-water or water consumption period. Cognitive improvements were found after water intervention, with no influence of expectancy. The authors posit that these findings reveal the lack of influence that expectancy has on cognitive improvements after water intervention and provide support for physiological mechanisms. To date, it is still unclear as to what hydration state participants in empirical studies reviewed above actually experience. With a lack of objective measurement, it is not known whether individuals experience mild dehydration at baseline or a euhydrated state. With evidence to suggest that even mild dehydration states are associated with significant changes at the neural level, such as total brain volume shrinkage and over-recruitment of specific brain areas during cognitively demanding tasks[38], it may be possible that providing mildly dehydrated participants with water may be reversing this effect. With a lack of data related to baseline hydration states of individuals and no further published work using imaging techniques to examine hydration state, these proposed mechanisms are merely speculative.

Another physiological mechanism to consider is the reactivity of the cardiovascular system after acute water consumption[82]. Reduced heart rate and vasodilation have been found in young adults after drinking 500 ml of water, whereas a significant blood pressure increase has been observed in healthy older adults[83]. This cardiovascular reactivity probably promotes cerebral blood flow, which will encourage the circulation of substances such as oxygen and glucose known to stimulate neural activity and associated behavioural performance[84], a mechanism similar to that suggested for cognitive function improvements due to physical exercise[85]. Future studies should consider using neuroimaging techniques such as functional MRI and perfusion to understand how cardiovascular changes can be related to neural activity changes and thus how these influence cognitive performance.

Conclusion

Accumulating evidence supports the notion that hydration state affects cognitive ability and mood. Severe dehydration has been shown to cause cognitive deficits such as short-term memory and visual perceptual abilities as well as mood disturbance, whereas water consumption can improve cognitive performance, particularly visual attention and mood. This research field is still in its infancy and fundamentally there is still a high amount of variability with regard to cognitive findings in both dehydration and acute water intervention studies. Researchers should investigate why this variability occurs and what the optimum conditions are for hydration state to affect cognitive performance. In this review, we have highlighted the importance of controlling for any potential confounding factors that may occur due to experimental design, exercise/heat stress protocols used in dehydration studies or conditions related to acute water intervention such as water temperature. Other advancements include taking into account the mechanisms that may underlie the observed performance changes: conducting behavioural studies with physiological markers to monitor hydration state such as urine indices and neuroimaging studies to discover the underlying neural events during hydration state change. Standardising cognitive testing would also help advance knowledge in this field. The topic is highly relevant for public health and engages with a wide audience, and this research has the potential to pave the way for intervention programmes in public arenas, improving people's quality of life.

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