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ORIGINAL CONTRIBUTION

Water intake and post-exercise cognitive performance: an observational study of long-distance walkers and runners

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Abstract

Purpose The impact of diet on endurance performance and cognitive function has been extensively researched in controlled settings, but there are limited observational data in field situations. This study examines relationships between nutrient intake and cognitive function following endurance exercise amongst a group of 33 recreational runners and walkers.

Methods All participants (mean age of 43.2 years) took part in a long-distance walking event and completed diet diaries to estimate nutrient intake across three-time periods (previous day, breakfast and during the event). Anthropometric measurements were recorded. Cognitive tests, covering word recall, ruler drop and trail making tests (TMT) A and B were conducted pre- and post-exercise. Participants rated their exercise level on a validated scale. Nutrient intake data were summarised using principal components analysis to identify a nutrient intake pattern loaded towards water intake across all time periods. Regression analysis was used to ascertain relationships between water intake component scores and post-exercise cognitive function, controlling for anthropometric measures and exercise metrics (distance, duration and pace).

Results Participants rated their exercise as 'hard-heavy' (score 14.4, ±3.2). Scores on the water intake factor were associated with significantly faster TMT A ($p = 0.001$) and TMT B ($p = 0.005$) completion times, and a tendency for improved short-term memory ($p = 0.090$). Water intake scores were not associated with simple reaction time (assessed via the ruler drop test).

Conclusion These data are congruent with experimental research demonstrating a benefit of hydration on cognitive function. Further field research to confirm this relationship, supported with precise measures of body weight, is needed.

Keywords Cognitive function · Memory · Reaction time · Trail making test · Hydration

Introduction

Experimental evidence as to the effects of dehydration on cognitive function is unclear. Gopinathan et al. [1] reported a decline in cognitive performance with water restriction and exercise; as dehydration increased from 1 to 4 % loss in body weight, there was a corresponding decline in scores on several cognitive tests, including trail making test (TMT), completion speed, word recall and serial addition. Similarly, Cian et al. [2] demonstrated impairment in short- and long-term memory, visual-spatial function, perceptive discrimination and reaction time in dehydrated subjects. Recently, Ganio et al. [3] reported that exercise-induced mild dehydration (1.6 % loss in body weight) without hyperthermia resulted in detriment in some aspects of

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cognitive performance, specifically visual vigilance and visual working memory response time, compared to a control condition that comprised equivalent exercise with fluid replenishment.

However, not all research is in accord in this area. Mild dehydration in young women did not result in decrements in cognitive performance [4] unlike men [3]. Sharma et al. [5] reported a dose-dependent decline in hand–eye coordination with increasing dehydration (1–3 % body weight loss) in a hot–dry environment, but dehydration had less impact in a humid or thermo-neutral environment, indicating an independent impact of heat on cognition [6, 7]. Indeed, Cian et al. [8] noted that cognitive performance rebounded after a 3.5-h period of recovery following exercise-induced dehydration even when fluid balance was not fully restored, although presentation of data in this study did not allow confirmation of this assertion. Furthermore, Szinnai et al. [9] found no effects of dehydration, induced through water deprivation alone, on manual tracking, paced auditory, serial addition or Stroop test performances. However, in this study, caffeine withdrawal, known to affect cognitive performance detrimentally [10–12], may have confounded the results, as caffeine was not completely restricted in the control condition. Interpretation of these studies is difficult given that there is often residual confounding from fatigue and heat stress. A recent detailed review by Benton [13] concluded that there was no evidence for dehydration per se having a detrimental effect on cognition in adults.

Caffeine has specifically been shown to improve reaction time [14, 15] and attention [14, 16], but not memory scanning or delayed free word recall [15]. There have been contradictory reports of positive [16] and no effects of caffeine on measures of sustained attention [17]. Also, excessive intakes of caffeine can have a negative impact on cognitive performance [10, 11], whilst low doses (<100 mg) have been shown to have no impact on short-term memory.

Exercise per se can have an impact on cognitive function, independent of its ability to induce hypoglycaemia [18] or dehydration [19]. Moderate-intensity aerobic exercise improves choice reaction time (CRT) during exercise [20]. In addition, both CRT [21] and simple reaction time (SRT) have been shown to improve following exercise [22].

Research on diet and cognitive performance has typically attempted to test the influence of a single nutrient through controlled experimentation. This study examined the influence of multiple nutrient factors in relation to time of consumption through principle components analysis, in order to gain a holistic view of relationships between nutrient intake, exercise and cognitive performance in an observational setting.

Methods

Subjects

Thirty-five recreational runners and walkers, of whom 22 were men and 13 were women, were recruited from six different long-distance walking events in England and Wales throughout the summer of 2010. Most participants ($n = 25$) were recruited through the Long Distance Walking Association (LDWA), having registered to compete in their summer events. The remainder of the sample were recruited via local posters throughout the University of Sheffield. Interested individuals received an information pack, which gave an overview of the study and explained exactly what was involved to participate. People who were happy to take part returned a questionnaire covering information on demographics, general health, prior experience of long-distance events and usual activity level and also completed a written statement giving informed consent. The study was approved by the University of Sheffield Research Ethics Committee (SMBRER160).

Over half of the sample (20; 56 %) were members of running and walking clubs. Over half of the sample (19; 55 %) had more than 10 years' experience of long-distance walking or running. All subjects considered themselves to be in a state of good health, although two participants reported metabolic conditions (Type 2 diabetes, gastritis and colitis). Four subjects were smokers.

Data collection process

On the morning of the event, prior to the walk, participants made themselves known to one of the two investigators (MDB and RS), and anthropometric measuring and cognitive testing were carried out. Self-reported height and weight information was collected, and percentage of body fat was assessed using the *Omron BS 306 Body Fat Monitor Compact* (Omron Health Care Limited, Milton Keynes*)*. Such body composition devices have been reported to have accuracy of between 1 and 4.8 % [23]. Body Mass Index was calculated as body weight (kg) over height squared (m^2). Fully loaded bag weight was assessed using *Design Go Luggage Scales (Design Go, London)*, which measures weights up to 22 kg, and is accurate to 500 g.

Immediately following the event, subjects completed the Borg scale [24], which assessed perceived levels of exertion, and cognitive testing was again carried out. Participants provided information on distance covered in accordance with the event entered. The research team recorded times of event completion.

All events were held under similar weather conditions; maximum area temperatures varied from 20 to 25 °C. Because of this homogeneity and the crudeness of measurement, we did not include temperature data in the analysis.

Cognitive tests

Simple reaction time (SRT) was assessed via the ruler drop test [25]. A ruler was placed between the outstretched forefinger and thumb of the participant around the 0 cm mark. The investigator then dropped the ruler and participants reacted by seizing the ruler as it fell. Reaction time was represented as the point along the ruler in cm where it was caught. Misses were scored as 30 cm. The test was conducted on five occasions in succession and an average calculated.

Short-term memory (STM) was assessed via word recall of 28 abstract four-letter words [26]. Participants were given a list of 28 abstract words to study for 1 min and were then given 1 min to recall as many of these as possible. Different words were used in pre- and post-event tests.

Trail making tests (TMT) A and B were used to assess visual attention, scanning and speed of processing [27]. Both tests require participants to join the dots on a sheet of paper as quickly as possible; TMT A requires participants to join numbers 1–25, whereas TMT B involves joining numbers 1–13, interspersed with letters A-L. Performance was recorded in seconds and number of errors was noted.

Prior to use in the field, all cognitive tests were validated in 17 non-athletic subjects for learning effect. SRT showed no learning effect, as did STM and TMT A. For TMT B, a learning effect was noted; to counteract this, the post-exercise test was presented as an inverted mirror image of the baseline test.

Dietary intake

Before the event all participants were mailed a food diary, a food portion size booklet [28] and instructions on how to complete an estimated food record. All food and drink consumed on the day previous to the walking event, that consumed on the morning of the walk and all food and drinks brought to the event for intended consumption were recorded in the diary. Participants estimated food quantities using the photographic food portion size booklet [28], household measures and packet/bottle sizes. At the outset of the walk, following cognitive testing, participants returned these food diaries to the research team. These were scrutinised for missing detail whilst participants were competing. At the finish of the event following cognitive testing, investigators clarified food detail, portion size and possible missing items in the diary, noted how much of the recorded food and drink had been consumed over the duration of the walk, and estimated additional consumption made at occasional food and drink stations during the event. Nutrient analysis of diet diaries was performed using *NetWisp version 3.0* software (Tinuviel Software, Warrington), which uses the UK Nutrient databank (McCance and Widdowson's Composition of Foods Integrated Dataset) to give intake estimates for the following nutrients: energy (kJ), total water from food and beverages (ml), carbohydrate (g), sugar (g), non-milk extrinsic sugars (NMES) (g), glucose (g), protein (g), fat (g), saturated fatty acids (g), alcohol (g), caffeine (mg) and sodium (mg). Nutrient intake was calculated by the time period of consumption: previous day, breakfast and during the event. Therefore, for each subject, we had 36 nutrient intake measures.

Statistical analysis

Principle components analysis with Varimax rotation was carried out on the entire nutrient intake data matrix, with the exception of alcohol intake which was omitted from the analysis because very few subjects consumed alcohol, and those that did consumed very little. Principal components analysis is a statistical technique, which produces linear combinations of the variables that account for as much of the variance as possible, and thus describes major patterns in the data. The first component is the linear combination that explains as much of the variance as possible, the second component is the linear combination of the variables which is independent of the first component and explains as much as possible of the remaining variance, and so on. The coefficients in these linear combinations are called the factor loadings, and by looking at the loadings of the variables represented in a component, we build up a picture of the pattern, which the component is describing. The chief advantage of the technique is that it summarises a large number of variables into a small number of underlying patterns.

Five components were extracted explaining 94.8 % of the variance. Table 1 shows the loadings above 0.2 for each of the components and the amount of the variation explained by each component. Component 4 indicated a positive water intake, hereafter referred to as *water intake.* This *water intake* component had positive factor loadings of >0.2 for the following variables: previous water intake (0.883), breakfast water intake (0.505) and during the event water intake (0.428). Breakfast NMES intake and breakfast caffeine intake had negative factor loadings (−0.274 and −0.271, respectively) in the *water intake* component. The *water intake* component accounted for 7.5 % of total variation of nutrient intake. A *water intake* component score was calculated for each participant based on intakes of previous water, breakfast water, during the event water, breakfast NMES and breakfast caffeine.

All pre-exercise cognition scores were adjusted for *water intake* component score, in order to exclude the

Table 1 Factor loadings (>0.2) of various nutrients for each component (percentage of variation explained by each component in parentheses)

Component 1 (54.4 %)		Component 2 (4.1 %)		Component 3 (22.0 %)		Component 4 (7.5 %)		Component 5 (6.9 %)	
Nutrients	Loading	Nutrients	Loading	Nutrients	Loading	Nutrients	Loading	Nutrients	Loading
Previous energy (kJ)	0.978	Breakfast energy (kJ)	0.929	During carbohydrate (g)	0.902	Previous water (ml)	0.883	Previous sodium (mg)	0.672
Previous fat (g)	0.885	Breakfast fat (g)	0.717	During energy (kJ)	0.865	Breakfast water (ml)	0.505	Breakfast sodium (mg)	0.462
Previous saturated fatty acids (g)	0.785	Breakfast carbohydrate (g)	0.701	During sugars (g)	0.814	During water (ml)	0.424	During caffeine (mg)	0.321
Previous protein (g)	0.777	Breakfast protein (g)	0.691	During non-milk extrinsic sugars (g)	0.686	Breakfast non-milk extrinsic sugars (g)	−0.274	During sodium (mg)	0.308
During fat (g)	0.724	Breakfast sugars (g)	0.645	During glucose (g)	0.631	Breakfast caffeine (mg)	−0.271	Breakfast saturated fatty acids (g)	0.217
Previous sodium (mg)	0.68	Breakfast sodium (mg)	0.62	During water (ml)	0.57			Previous carbohydrate (g)	−0.260
During protein (g)	0.676	Breakfast saturated fatty acids (g)	0.587	During protein (g)	0.46			Previous sugars (g)	−0.264
During saturated fatty acids (g)	0.658	Breakfast glucose (g)	0.501	During sodium (mg)	0.458			Previous glucose (g)	−0.286
During sodium (mg)	0.561	Breakfast non-milk extrinsic sugars (g)	0.438	During fat (g)	0.373				
Previous carbohydrate (g)	0.552	Previous carbohydrate (g)	0.344	During saturated fatty acids (g)	0.309				
Previous non-milk extrinsic sugars (g)	0.305	During water (ml)	0.283	Previous carbohydrate (g)	0.209				
Previous sugars (g)	0.249	Previous sugars (g)	0.257	Previous saturated fatty acids (g)	−0.208				
		Breakfast water (ml)	0.226	Previous sodium (mg)	−0.236				
		Previous glucose (g)	0.212						

influence of water intake on pre-exercise score, and address specifically the influence of diet on cognitive performance after exercise. Regression analysis was used to model influences on cognitive function. The dependent variable in all analyses was post-exercise cognitive score. The final model was developed in stages: firstly by forced entry of adjusted pre-exercise cognitive scores, secondly by forward stepwise entry of other possible covariates (age, gender, height, body weight, bag weight, % body fat, Body Mass Index, distance (km), duration (hours) and pace (km/h) and thirdly by forced entry of *water intake* score. Residuals from the final model were checked for normality. Alpha was set at 0.05 for all analyses. The analysis was carried out using the statistical software package *SPSS for Windows version 18.0.1*.

Results

Subjects characteristics

One participant failed to provide comprehensive dietary information and one participant did not complete the walk due to injury, giving a final sample size of 33. Participants had an average age of 43.2 years. The average distance covered was 31.6 km (±9.7), over a time period of 6.11 h (±1.65) carrying a mean bag weight of 3.8 kg (±1.7) (Table 2). Mean water intake was 3,199 ml (±1,313) on the previous day, 654 ml (±404) at breakfast and 1,727 ml (±962) during the event (Table 3). Ratings of perceived exertion (RPE) were recorded immediately after exercise. A mean RPE of 14.4 (±3.2) reflected a perception of 'hard-heavy' exercise on the Borg 6–20 scale.

Cognitive performance

Ruler drop performance was not altered by exercise (Table 4). Word recall deteriorated after exercise by 1.0 (±3.6) word. This change was statistically significant (paired *t* test, $p = 0.028$). TMT A completion time improved following exercise by 2.1 s (±3.6). This change was statistically significant (paired *t* test, $p = 0.003$). There was a trend for improvement on TMT B score by a margin of 4.1 s (±12.7) following exercise (paired *t* test, $p = 0.072$).

A final regression model showed that ruler drop performance was not related to *water intake score* ($p = 0.895$); pre-exercise score ($p = 0.001$) and pace ($p = 0.012$) were positively related to final score (Table 5). For word recall, the final regression model showed that performance was positively related to *water intake* score; however, the relationship fell short of statistical significance ($B = 0.564$, $p = 0.090$). *Water intake* score accounted for 4.7 % of the variation in word recall performance. TMT A performance (completion time) was associated with *water intake* score; there was an inverse relationship ($B = -2.257, p = 0.001$). In this model, *water intake score* accounted for 12.4 % of the variation in TMT A performance after controlling for pre-exercise score and body weight. Similarly, TMT B completion time was inversely related to *water intake* score ($B = -6.334, p = 0.005$); *water intake score* accounted for 13.6 % of the variation in performance after controlling for pre-exercise score and BMI.

Table 2 Participant characteristics: demographic, anthropometric and event metrics ($n = 33$)

	Mean	SD
Age (years)	43.2	14.89
Height (m)	1.73	0.09
Body weight (kg)	70.8	11.81
Bag weight (kg)	3.8	1.75
% Body fat	22.9	6.64
BMI (kg/m^2)	23.4	2.77
Distance (km)	31.6	9.70
Duration (h)	6.11	1.65
Pace (km/h)	5.40	1.69

Discussion

We assessed the effects of dietary intake on cognitive performance following endurance exercise using a statistical technique, which summarised a large number of nutrient intake variables collected across different time periods into a small number of patterns. This approach extends the research literature from investigations of

Table 3 Nutrient intake by time period ($n = 33$)

	Previous day		Breakfast		During event	
	Mean	SD	Mean	SD	Mean	SD
Energy intake						
kJ	9,275.1	3,112.4	1,675.7	850.0	4,912.3	2,392.9
Carbohydrate						
g	271.9	111.4	60.5	32.7	195.5	106.8
% Energy	47.2	15.6	60.3	17.7	63.9	15.2
Fat						
g	74.7	45.3	11.7	11.2	35.9	24.9
% Energy	28.8	9.9	23.0	14.4	27.3	13.1
Protein						
g	91.7	43.4	16.3	10.7	26.0	24.0
% Energy	16.8	4.7	16.7	6.9	8.4	4.9
Caffeine						
mg	321.9	302.3	97.5	85.4	32.7	70.8
Water						
ml	3,198.9	1,312.5	653.5	404.3	1,727.2	961.6

Table 4 Cognitive performance scores in relation to exercise ($n = 33$)

	Pre-exercise	Post-exercise	Change	p value[a]
Ruler drop (cm)	16.0 (3.7)	14.9 (3.2)	−1.1 (3.6)	0.088
Word recall (no.)	8.6 (3.5)	7.6 (2.6)	−1.0 (2.4)	0.028
TMT A (s)	23.9 (6.4)	21.8 (6.2)	−2.1 (3.6)	0.003
TMT B (s)	40.3 (15.9)	36.2 (16.5)	−4.1 (12.7)	0.072

[a] Paired *t* test

Table 5 Final regression models predicting cognition scores after exercise

Dependent variable	Independent variables	R^2 change	Coefficients		
			B	SE	*p* value
Ruler drop (cm)	Adjusted pre-exercise score	0.222	0.487	0.131	0.001
	Pace (km/h)	0.170	−0.786	0.292	0.012
	Water intake score	0.000	−0.065	0.484	0.895
Word recall (no.)	Adjusted pre-exercise score	0.491	0.526	0.093	<0.000
	Water intake score	0.047	0.564	0.322	0.090
TMT A (s)	Adjusted pre-exercise score	0.540	0.724	0.107	<0.000
	Body weight (kg)	0.061	0.086	0.055	0.129
	Water intake score	0.124	−2.257	0.623	0.001
TMT B (s)	Adjusted pre-exercise score	0.316	0.575	0.140	<0.000
	Body mass index (kg/m^2)	0.123	1.494	0.769	0.062
	Water intake score	0.136	−6.334	2.083	0.005

isolated effects of single nutrients [29, 30] and single meals [31, 32]. Critically, we identified a nutrient intake pattern orientated towards good hydration, being defined by high loadings for water intake across all time periods and a negative loading for caffeine and NMES intake immediately prior to exercise. This integrative approach to describe water intake rather than isolating the effect of a single factor as in intervention studies allows examination of combined effects of multiple factors in a field environment. Importantly, the method addresses the potential confounding effect of nutrient interrelationships.

Although our cognitive measures were pen and paper tests, which lack precision relative to equivalent computer-based tests, nevertheless, they were sufficiently sensitive to detect differences in performance for several measures in relation to water consumption. A learning effect was likely across the testing period as evidenced in test development with non-athletic subjects, and such an effect may relate to hydration. Indeed, the superior post-race cognitive performances of subjects with high *water intake* scores do not exclude a learning effect related to water intake, but if so, that raises interesting questions about hydration.

Word recall deteriorated following exercise, lending support to the post-exercise deterioration in STM reported in other studies [2, 8] but contradicting the research of Coles and Tomporowski [33] who reported an improvement in visual STM after exercise. Given that exercise duration was only 40 min in the Coles and Tomporowski study [33] relative to 6.1 h in the current study and 2 h in the study of Cian et al. [8], it is plausible that there is an inverted U in cognitive performance with exercise duration [18, 34]. The strong trend in the current study for high water intake combined with low breakfast caffeine content to benefit short-term memory supports a protective role of hydration against an exercise-induced decline in STM. Interestingly, impairments in STM observed in subjects dehydrated to −2.8 % of body weight [8] were no longer apparent 3.5 h post-exercise irrespective of whether or not subjects were actively rehydrated. It seems that, as observed in this study, the adverse effect of exercise on STM is better offset by the consumption of fluid during, as opposed to, after exercise.

The positive associations between a high water intake and superior performance in both TMT tests are concomitant with the dose-dependent decline in TMT performance in response to induced dehydration [1]. Although hydration status was not assessed in the current study, indeed, we lack an accurate biomarker for hydration in a field situation where variations in posture, food intake, muscle mass and total body water confound interpretation of both urine and plasma indices [35, 36], it is likely that hydration status was compromised given that exercise level was hard-heavy. The limitations of both blood and urine hydration biomarkers to assess changes in total body water and describe flux between intracellular and extracellular body compartments are recognised [37], and reliance on reported water consumption to assess hydration is justified in field situations.

Accurate measures of body weight to assess the level of dehydration would have been of value in the current study, as we would have been able to contextualise our findings in relation to other studies. Several reviews [13, 19, 38] have noted that a 2 % loss in body weight seems to be a threshold which invokes decrements in cognitive performance. It is possible that in our observational study that this threshold would have been reached for some subjects, as an average distance raced was 32 km over a 6-h period, exercise level was rated as hard-heavy, with a very variable total water intake during the event (mean 1,727 ml, ±962 ml).

No post-exercise change was seen in ruler drop performance offering no support for previously demonstrated exercise-induced improvements in SRT [22, 39]. We also observed no relationship between high water intake and ruler drop performance. These results support those of Jiménez-Pavón et al. [40] who found no change in SRT in subjects running for 50 min in a hot humid environment without water. They did, however, find improvements in choice reaction time, multiple reaction time and peripheral reaction time, which was attributed to improvements in complex tasks requiring a greater degree of processing and attention, in line with the theory that sub-maximal exercise increases arousal and beneficially narrows attention [19].

These results indicate water intake may have a positive role to play in maintaining effective cognitive functioning, adding to the body of evidence demonstrating that dehydration induced by exercise, water restriction and exposure to heat impairs cognitive function [19]. Field assessment of hydration through accurate body weight measures would strengthen this conclusion. The extent to which water restriction impacts on different aspects of cognitive functioning remains unclear, as does the complex relationship between exercise, core temperature, glycaemia and hydration [41]. It may be that task complexity interacts with hydration status, with less cognitively demanding tasks being unduly affected by exercise-induced dehydration [18]. Interaction between hydration status and status of other nutrients, including sugar and electrolytes, is also probable [41]. Further research to unravel these complexities is needed, as is confirmation of the benefits of water intake on cognition in the field.

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