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Research report

Hydration status moderates the effects of drinking water on children's cognitive performance

Clinton S. Perry III [a], Gertrude Rapinett [b], Nicole S. Glaser [a], Simona Ghetti [a, *]

[a] University of California, Davis, Davis, CA, USA
[b] Nestlé Research Centre, Nestec Ltd, Switzerland

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ABSTRACT

Changes in hydration status throughout the day may affect cognitive performance with implications for learning success in the classroom. Our study tested the hypothesis that the benefit of drinking water on working memory and attention depends upon children's hydration status and renal response to water intake. Fifty-two children aged 9–12 years old were tested under two experimental conditions. The treatment session (Water session) consisted of a standard breakfast with 200 ml water, a baseline test, consumption of 750 ml of water over a period of two hours and subsequently retested. No water was provided after breakfast during the control session. Changes in hydration were assessed via urine samples. Cognitive testing consisted of digit span, pair cancellation, and delayed match to sample tasks. Children who exhibited smaller decreases in urine osmolality following water intake performed significantly better on the water day compared to the control day on a digit-span task and pair-cancellation task. Children who exhibited larger decreases in urine osmolality following water intake performed better on the control day compared to the water day on the digit-span task and pair-cancellation task. These results suggest that focusing on adequate hydration over time may be key for cognitive enhancement.

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1. Introduction

Studies with adult populations suggest that consumption of water may be beneficial for cognitive functioning (Cian, Barraud, Melin, & Raphel, 2001; Edmonds, Crombie, Ballieux, Gardner, & Dawkins, 2013; Edmonds, Crombie, & Gardner, 2013; Rogers, Kainth, & Smit, 2001). These potential benefits have been examined less extensively in children. This is surprising given repeated indications that children are at greater risk for becoming dehydrated (D'Anci, Constant, & Rosenberg, 2006), that they suffer from inadequate fluid intake while in school (Bar-David, Urkin, & Kozminsky, 2005), and that a high percentage of children arrive at school in a dehydrated state (Bar-David et al., 2005; Bonnet et al., 2012; Fadda et al., 2012; Kaushik, Mullee, Bryant, & Hill, 2007; Molloy, Gandy, Cunningham, & Slattery, 2008).

Previous pediatric studies provided initial evidence that drinking supplemental water may benefit attention and working memory, but these findings are in part limited by lack of an assessment of baseline hydration status (Benton & Burgess, 2009; Booth, Taylor, & Edmonds, 2012; Edmonds & Burford, 2009; Edmonds & Jeffes, 2009) and cognitive performance (Benton & Burgess, 2009; Booth et al., 2012; Edmonds & Burford, 2009) measures. As such, one cannot exclude the possibility that the effects of supplemental water were due to pre-existing differences in either hydration status or cognitive performance. Furthermore, these studies were conducted using group assessments in a classroom setting thereby affording inadequate control of water intake prior to testing (Edmonds & Burford, 2009; Edmonds & Jeffes, 2009) and during the testing protocol (i.e., open access to water beyond that provided by the protocol water such as school water fountains or water bottles brought from home; Benton & Burgess, 2009). The effects of water intake cannot be fully assessed without accounting for these factors.

Further, individual differences in response to water supplementation appear to be an important factor for cognitive outcomes. A study with adults showed that provision of water improved or worsened visual attention depending on whether participants reported high or low subjective thirst prior to consuming water respectively (Rogers et al., 2001). While studies with children have

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* Corresponding author. Department of Psychology and Center for Mind and Brain, One Shields Avenue, Davis CA, 95616, USA.
E-mail address: sghetti@ucdavis.edu (S. Ghetti).

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collected thirst ratings and found that water both decreased ratings of thirst and also improved cognitive performance (Edmonds & Burford, 2009), there is no report of whether relative decreases in thirst were associated to relative increases in performance. In addition, while adults must suffer water loss of 1–2% of body mass to initiate thirst (Armstrong et al., 2010), the thirst response is immature in children (D'Anci et al., 2006) thereby limiting the possibility that children may accurately report changes in hydration as a function of thirst. Thus, a physiological measure may be a more accurate way to assess hydration status in children.

Urine concentrating ability has also been shown to vary considerably among individuals (Armstrong, 2005; Kavouras, 2002), indicating that urine osmolality alone is not an ideal indicator of hydration state (for a discussion of hydration assessment techniques see Armstrong, 2005). Changes in urine osmolality in response to water intake (renal response to water), when interpreted in the context of the initial osmolality, provide much more information about an individual's state of hydration. Persistently high osmolality after water drinking indicates continued dehydration with renal water retention whereas substantial declines in osmolality after water drinking indicate adequate or even excessive hydration (with the kidneys responding by eliminating excess water). Indeed, by focusing on change in osmolality, Fadda et al. (2012) found an association between larger decreases in urine osmolality following water supplementation and working-memory improvements in children. However, the amount of water intake in this study was highly variable among participants making it difficult to establish whether this correlation was driven by responses to water supplementation or, instead, by variations in water intake. Taken together these studies suggest that improvement in hydration status rather than water consumption in itself may enhance information-processing.

The goal of the present study was to examine the effects of water intake on working memory and attention in children and to establish whether these effects would be moderated by children's hydration state and subsequent renal response to water. We accounted for baseline differences in urine osmolality and cognitive performance because these factors affect the outcomes of interest, but have not been sufficiently accounted for in previous research. Finally, we selected cognitive measures that have showed sensitivity to water consumption.

2. Materials and methods

2.1. Participants

We recruited 58 (50% females) participants ages 9–12 years (M = 10.53 years, SD = 1.14). Participants were contacted via phone; contact information was obtained through general lab recruitment at local functions and from previous studies if participants indicated interest in participating in future studies. Exclusion criteria included kidney disorders, diabetes, inability or unwillingness to consume provided breakfasts and snacks (e.g., lactose intolerance and veganism), and if they were subject to any cognitive developmental disorders. Five participants voided their bladder prior to providing the first urine sample and one sample for the final collection time point was compromised during transit to the lab for analysis. These participants were excluded from analyses (N = 52). All participants were typically-developing children with English as their primary language and average IQ equal to 117.90 (SD = 12.92, range: 85–151; see Procedure). Children were from middle class families of various ethnicities (66% Caucasian, 17% Asian, 9% Hispanic; 8% declined to report). This convenience sample was recruited from the community. Of these participants, 6 failed to provide urine samples at awakening or at the end of the session; their cognitive data could not be analyzed based on the study design, resulting in a final sample of 52 children.

2.2. Design

All participants were tested under two experimental conditions, Water and Control condition based on the procedures described below and depicted graphically in Fig. 1. During the Water day participants consumed three treatments of 250 ml of water over a period of 2.5 h, during the Control day no water was provided. During both the water and control conditions, participant's cognitive performance was tested at three time points throughout the day (baseline, short-term assessment, long-term assessment). Response to Water intake was measured as the reduction in urine osmolality from awakening to the end of the testing session on the Water condition. A median split was used to identify participants who exhibited High-Change versus Low- Change in urine osmolality. Testing rooms were private with a one way mirror to allow parents to monitor sessions, and an ambient temperature of 72 °F was held constant by a thermostat in the lab.

Participants were assessed during three sessions conducted separately for each individual participant at the laboratory

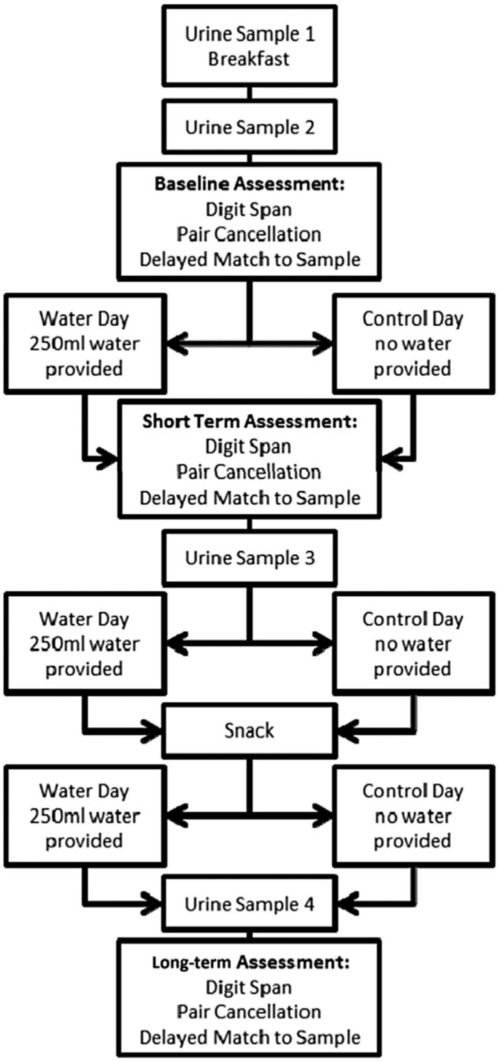

Fig. 1. Graphic representation of the experimental design.

following procedures approved by the UC Davis Internal Review Board. During Session 1, consent was obtained and the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999) was administered to verify that all participants fell in normative levels of intellectual ability. Children and their families were instructed to maintain habitual daily activities, diet, and sleep. Participants were instructed not to empty their bladder on the morning of Session 2 and 3. During these sessions, which were separated by approximately a 1-week delay, participants were tested under water intake and control conditions. Condition order was counterbalanced across participants.

On the morning of Session 2 and 3, participants were met at 7:30 A.M. at their residence and asked to provide a fasting urine sample, which was collected with the help, if necessary, of their parents or guardians. Children were then provided with a standard breakfast (250 ml of skim milk, 125 ml of water, 1 banana, and 1 cup of cereal). After breakfast, children and their parents were accompanied to the laboratory and were asked to provide a second urine sample about 30 min after breakfast. At approximately 8:40 A.M., participants completed a cognitive battery, which served as the Baseline for that testing day. This battery included a standard measure of working memory and sustained attention including forward and backward digit span (adapted from Wechsler, 1974), pair cancellation (adapted from Woodcock, McGrew, & Mather, 2001), and delayed-matched to sample (Owen et al., 1993; Sahakian et al., 1988). For digit span, participants listened to strings of single digits of increasing length and were asked to report them in forward order; then, they underwent the same procedure, but were asked to report the digits in backward order. The sum of correct forward and backward digit strings constituted the outcome measure based on previous studies (Bar-David et al., 2005; Fadda et al., 2012). For pair cancellation, participants were presented with a sheet of paper with a grid of three different image types (i.e., a dog, a ball, and a cup) and were instructed to locate all of the occurrences of the ordered pair, ball-dog, in the grid as fast as they could without making any mistakes. The number of accurately circled pairs within 60 s constituted the outcome measure. Finally, for the delayed match-to-sample task, complex visual target patterns were displayed on a computer screen. After a delay varying from zero to twelve seconds, participants were asked to identify the viewed pattern from among 4 possible alternatives. The percent of accurately identified patterns was the dependent variable. Participants were tested using parallel versions of each of these tasks during each testing occasion to limit practice effects.

2.2.1. *Water condition*

After Baseline testing, participants drank 250 ml of bottled water. Following a twenty minute delay, children were tested again on our cognitive battery (i.e., Short-term assessment). Once participants completed this assessment, a third urine sample was obtained (at approximately 10:10 A.M.). Participants were then given a 90 min break during which they were allowed to read, play quiet games, or sit with their parents or guardians in the laboratory. Exercise and other active play were not allowed to avoid water loss resulting from sweating.

At 10:30 A.M., participants consumed an additional 250 ml of water after which they consumed a standard snack involving fruit yogurt. A final 250 ml of water was given at 11:30 A.M., for an overall total of 750 ml. At 11:45 A.M., a fourth and final urine sample was obtained. At 11:50 A.M., participants were asked to complete a third and final cognitive battery (i.e., Long-term assessment), which provides the main outcome data for this report. According to the Dietary Reference Intakes for water published by the Institute of Medicine, the amount of water provided, including all fluids consumed during the study, was age appropriate for our participants.

2.2.2. *Control condition*

This experimental condition was analogous to the Water condition with the exception that no water was consumed during the experimental session (expect for that provided during breakfast). All urine samples were stored in sealed containers and analyzed at the UC Davis Medical Center.

2.3. *Statistical analyses*

As a manipulation check, preliminary analyses verified that water intake resulted in the expected changes in urine osmolality by conducting a 2 (Treatment: Water versus Control) × 4 (Time points: Awakening vs. 8:30 A.M. vs. 10:10 A.M. vs. 11:45) repeated-measure ANOVA. Our central hypothesis was that the effects of drinking water on working memory and attention would vary based on individual differences in urine osmolality change. Thus, to verify that individual differences in response to water intake existed we conducted correlational analysis between urine osmolality during the water and control sessions. We then conducted a regression analyses to verify that the changes did not simply reflect differences in urine osmolality at awakening. Response to water intake was calculated by subtracting urine osmolality at the end of the water session from urine osmolality at awakening. Change in osmolality on the control day was calculated by subtracting urine osmolality at the end of the control session from urine osmolality at awakening. Additional analyses using the change in osmolality from waking to the sample collected immediately after the short term testing were also conducted.

Then, we conducted a series of 2 (Osmolality reduction group: High Change versus Low Change) × 2 (Treatment: Water vs. Control) ANCOVA. Assignment to the high-osmolality change group or the low-osmolality change group was made based on whether the child's change in urine osmolality on the Water day was either above or below the median split of the average reduction in osmolality on that day. We used change during the water day because we were interested in assessing the effect of response to water intake on working memory and attention.

In order to account for day to day differences in children's cognitive performance, we used the baseline test as an assessment of the child's general performance on that day. Thus, for each of our outcome measures, we calculated difference scores from the baseline test to the post test on each testing day and these differences were analyzed as the dependent measures in the ANCOVAs. Mean urine osmolality at awakening across the two days was entered as a covariate to account for individual differences in hydration status.

3. Results

Previous studies have used a urine osmolality above 800 mOsm/kg to indicate dehydration (Bar-David et al., 2005). Using this value as a reference, 65% of the sample was dehydrated at awakening. At the end of the testing sessions, 35.1% of the sample remained dehydrated on the control day, while only 2 children (3.8%) did so on the water day. (These children consumed a total of 205 ml and 540 ml of water, respectively). Results did not change when these children were removed from analysis; thus, they were included in all analyses.

The first repeated-measures ANOVA verified changes in urine osmolality as a result of water intake. As expected, urine osmolality decreased during both treatment days, but this reduction was of much larger magnitude on the water day compared to the control day, and indicated by a significant Treatment × Time Point interaction, $F(3, 45) = 54.26$, $p < .001$, $\eta_p^2 = .78$ (Fig. 2).

There were no significant differences between the control and

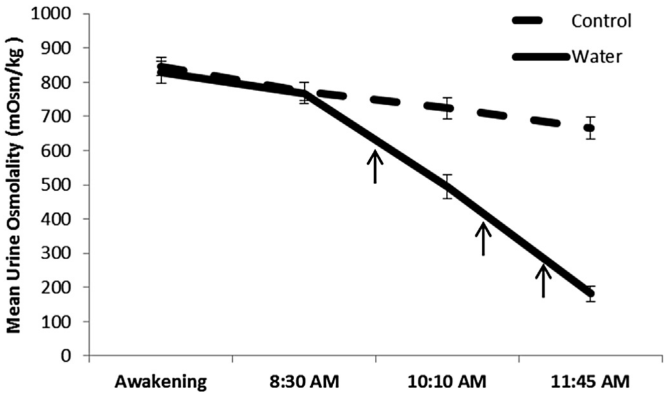

Fig. 2. Mean urine osmolality levels as a function of treatment condition and time of assessment. The arrows indicate when treatment was provided on the water day.

water days for urine osmolality prior to administration of water at either awakening ($p = .99$) or baseline time ($p = .83$). However, the differences in urine osmolality between the two testing days became significant at 10:10 A.M., after participants drank the first 250 ml of water ($p < .001$), and were even larger at 11:45 A.M., after participants consumed the full 750 ml of water ($p < .001$).

Changes in urine osmolality on both test days were positively correlated with the average osmolality at awakening across the two days (water day: $r = .66$ and control day: $r = .56$; $p < .001$ for both). Urine osmolality changes on the two testing days were also significantly correlated with each other ($r = .63$, $p < .001$). Urine osmolality at awakening and urine osmolality reduction during the control day were both significant independent predictors of urine osmolality reduction during the water day: urine osmolality at awakening ($\beta = .42$, $p < .01$), osmolality reduction during control day ($\beta = .38$, $p < .01$) (overall regression $p < .001$, adjusted $R^2 = .50$). Thus, osmolality reduction does not seem to be a simple by-product of osmolality at awakening. The median values of 393 mOsm and 737 mOsm in urine osmolality reduction during the water condition were used to define the high and low reduction groups for short term and long term change respectively. For no outcome measure was change in osmolality to the short term testing session associated with any difference in performance, thus these findings will not be discussed further. Sample characteristics of the high and low reduction groups defined for long term change are described in Tables 1 and 2.

3.1. Digit span

Descriptive statistics about performance during baseline and post phase as well as change scores between these phases are reported in Table 3a.

We found a significant interaction between treatment condition and osmolality reduction group on children's change scores at both the short-, $F(1, 49) = 4.59$, $p < .05$, $\eta_p^2 = .086$ (Fig. 3a), and long-term assessment, $F(1, 49) = 14.06$, $p < .01$, $\eta_p^2 = .23$ (Fig. 3b): Children whose urine osmolality changed less with water intake (low-change group) showed improved performance on the water day and worsened performance during the control day; in contrast, children who had more substantial declines in osmolality (high-change group) showed improved performance on the control day, but not on the water day.

Although the analysis above controlled for osmolality at awakening, thereby providing some reassurance that the observed effects hold across the full range of urine osmolality at awakening observed is the same, we repeated the same analysis restricted to the subset of the sample that was identified as dehydrated based on urine osmolality values above 800 mOsm on awakening ($N = 33$; 10 Low change, 23 High-change). A confirmation would bolster the case that low osmolality change is critical to observe the benefits of water even among those children who intuitively might be expected to benefit from substantial water consumption and related osmolality change. The same significant interaction between treatment condition and urine osmolality reduction was confirmed, $F(1, 30) = 22.13$, $p < .001$, $\eta_p^2 = .43$.

To confirm that other extraneous variables (e.g., IQ, order, and amount consumed of the food provided for breakfast or snack) did not influence our pattern of results, we ran a series of ANCOVA's using each as a covariate. We found no effect of IQ, Order, or amount consumed of the food provided at breakfast or for the snack.

3.2. Paired cancellation

Descriptive statistics are presented in Table 3b. The results of the overall ANCOVA model on paired cancellation were similar to those found with digit span. Specifically, we found a significant treatment by osmolality group interaction for both the short-, $F(1, 49) = 9.51$, $p < .01$, $\eta_p^2 = .163$ (Fig. 4a), and long-term assessments, $F(1, 49) = 4.24$, $p < .05$, $\eta_p^2 = .19$ (Fig. 4b), such that children in the low-change group benefitted more from receiving water than did those in the high-change group; the opposite was true in the control condition.

Again, this interaction was statistically significant even when the analyses were restricted to participants who started the day with urine osmolality above 800 mOsm/Kg, $F(1, 30) = 7.79$, $p < .01$, $\eta_p^2 = .21$. As well, we found no effect of IQ or amount consumed of the food provided at breakfast or for the snack. However, we did find that when order was included as a covariate, the interaction between treatment and change in osmolality no longer reached conventional levels of statistical significance at both the short-, $F(1,48) = 3.77$, $p = .06$, $\eta_p^2 = .07$, and long-term time assessments, $F(1,47) = 3.66$, $p = .06$, $\eta_p^2 = .07$, even though it closely approached it and showed the same pattern of results described earlier when session order was not examined.

3.3. Delayed match to sample

Descriptive statistics are reported in Table 3c. In contrast to the other two measures, no significant effects were found in this task at either the short term assessment or long term assessment. Though to determine whether there was a difference in performance due to delay type we repeated the analyses separately for each delay duration. We found no significant effect of treatment or osmolality change at the simultaneous, 4, or 12 s delays and only a trend toward significance at the immediate recognition delay we did note a non-significant trend, $F(1,49) = 2.875$, $p = .096$, $\eta_p^2 = .06$ at the immediate delay. We found no effect of IQ, Order, or amount consumed of the food provided at breakfast or for the snack.

4. Discussion

The goal of this study was to examine whether children's response to water intake was associated with changes in cognitive performance, namely in working memory and attention. Our results showed that drinking water impacts cognition differentially, depending on the child's underlying urine osmolality. Controlling for urine osmolality at awakening, children who responded to

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[1] High- and Low-change refers to whether the degree of osmolality change was above or below the median value of 737 mOsm respectively.

Table 1
Sample Characteristics as a function of Participant group (High-versus Low- Change)[a].

Variable	Low osmolality change (N = 26)	High osmolality change (N = 26)	p
Age in years: M (SD)	10.46 (.21)	10.50 (.22)	.91
Sex: N females (%)	12 (46%)	14 (54%)	.59
Weight in kg: M (SD)	42.03 (16.18)	38.66(10.20)	.38
Height in cm (SD)	144.09 (14.41)	143.30 (10.96)	.83
Water ingested on water day in ml: M (SD)	671.85 (116.43)	639.42 (183.06)	.45
Verbal IQ	114.12 (11.05)	117.38 (13.31)	.34
Performance IQ	113.81 (12.65)	119.69 (15.48)	.14

[a] High- and Low-change refers to whether the degree of osmolality change was above or below the median value of 737 mOsm respectively.

Table 2
Amount of provided food consumed as a function of participant group (High-versus Low- Change)[a].

	Variable	Low osmolality change (N = 26)	High osmolality change (N = 26)	p
Control Day	Percent of banana consumed (SD)	79.17 (35.1)	84.91 (27)	.52
	Percent of cereal consumed (SD)	86.53 (23.13)	95.19 (12.29)	.10
	Milk consumed in ml (SD)	146.56 (88.04)	161.44 (70.18)	.51
	Water consumed in ml (SD)	102.12 (44.86)	98.65 (42.67)	.78
	Percent of yoghurt consumed	98.08 (9.81)	100 (0)	.32
Water Day	Percent of banana consumed (SD)	75.19 (37.84)	83.91 (31.69)	.38
	Percent of cereal consumed (SD)	80.44 (24.4)	93.91 (15.19)	.02*
	Milk consumed in ml (SD)	151.90 (82.65)	149.29 (82.30)	.91
	Water consumed in ml (SD)	90.77 (51.17)	84.04 (52.52)	.64
	Percent of yoghurt consumed	98.08 (9.81)	100 (0)	.32

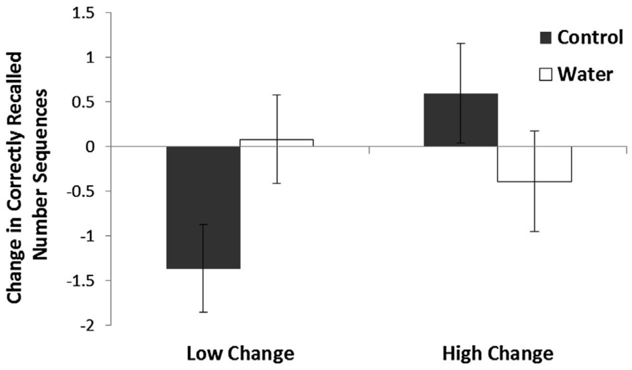
[a] High- and Low-change refers to whether the degree of osmolality change was above or below the median value of 737 mOsm respectively.

Table 3
Descriptive statistics on primary outcome measures: (a) digit span and (b) paired cancellation and by treatment condition (Water versus Control) and Urine osmolality reduction group (High versus low change)[a]. These values do not account for urine osmolality at awakening as is the case in the full analysis and resulting figures.

		Low change		High change	
		M	SD	M	SD
a) Digit span: Number of correctly recalled number sequences					
Baseline	Control	17.31	3.21	17.27	4.11
	Water	16.69	3.50	18.38	4.40
Short Term	Control	16.23	3.12	17.58	3.84
	Water	16.69	3.28	18.08	4.65
Short Term – Baseline	Control	−1.08	2.59	.31	1.72
	Water	0.00	2.30	−0.31	2.62
Long Term	Control	16.35	3.37	18.31	4.58
	Water	17.92	3.55	18.04	4.66
Long Term – Baseline	Control	−0.96	1.73	1.04	2.41
	Water	1.23	2.30	−0.35	2.15
b) Paired Cancellation: Mean number of pairs identified					
Baseline	Control	61.31	8.98	57.38	10.39
	Water	57.23	11.62	61.27	9.64
Short Term	Control	63.88	6.73	62.38	7.67
	Water	63.42	7.52	64.54	6.42
Short Term – Baseline	Control	2.58	5.02	5.00	7.32
	Water	6.19	7.13	3.27	5.55
Long Term	Control	63.96	5.91	64.00	6.14
	Water	64.12	6.90	65.08	5.46
Long Term – Baseline	Control	2.92	7.57	6.62	6.52
	Water	6.88	8.35	3.81	6.95
c) Delayed Match to sample: Percent accurately identified patterns					
Baseline	Control	79.74	15.26	80.51	14.35
	Water	83.59	11.35	77.18	18.10
Short Term	Control	82.31	14.10	78.46	13.64
	Water	81.79	16.71	78.72	16.55
Short Term – Baseline	Control	2.56	13.21	−2.05	11.59
	Water	−1.79	14.18	1.54	16.90
Long Term	Control	77.69	15.88	73.08	17.64
	Water	78.72	15.67	76.15	14.50
Long Term – Baseline	Control	−2.05	17.77	−7.44	17.00
	Water	−4.87	12.44	−1.03	13.69

[a] High- and Low-change refers to whether the degree of osmolality change was above or below the median value of 737 mOsm respectively.

a) Short-Term Assessment



b) Long-Term Assessment

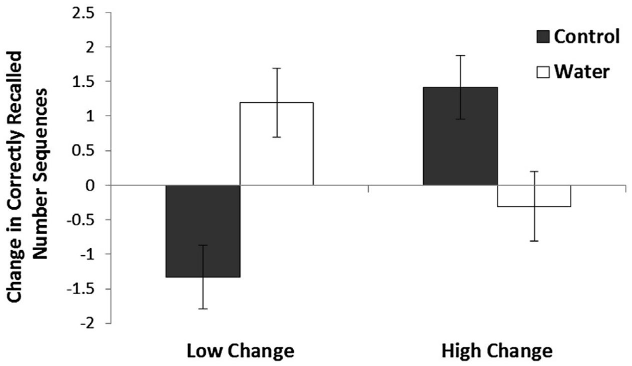
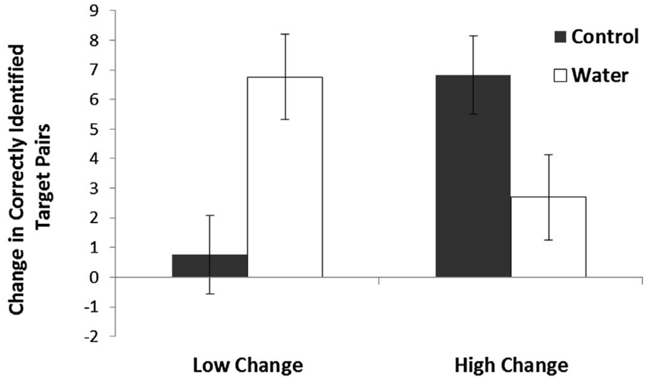


Fig. 3. Changes in Digit Span Test Scores as a function of osmolality reduction group[1] and treatment condition. Change Scores are calculated by subtracting scores obtained in the short-term assessment and in the long-term assessment respectively from performance on Baseline testing on that day. These values account for individual variability in osmolality at awakening.

a) Short-Term Assessment



b) Long-Term Assessment

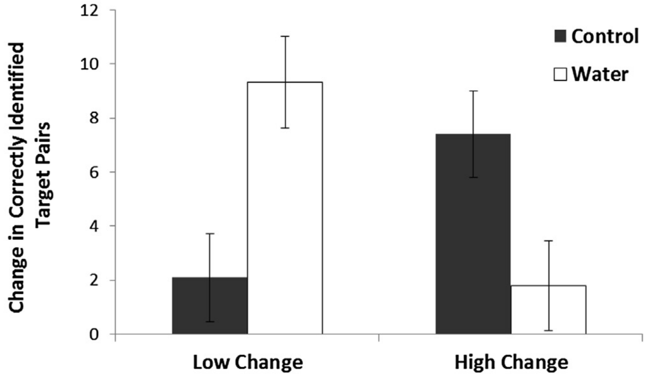


Fig. 4. Changes in paired cancellation scores as a function of osmolality reduction group[1] and treatment condition. Change Scores are calculated by subtracting scores obtained in the short-term assessment and in the long-term assessment respectively from performance on Baseline testing on that day. These values account for individual variability in osmolality at awakening.

water with smaller osmolality declines performed better (i.e., improved from baseline) in the water compared to the control condition. In contrast, children with larger urine osmolality declines performed worse in the water compared to the control condition. This pattern was similar for both the short and long term assessments and regardless of whether participants started the day with high or more moderate urine osmolality.

Retention or excretion of water and electrolytes by the kidneys is driven by anti-diuretic hormone, aldosterone and other biochemical signals reflecting circulatory volume, serum osmolality and hydration status (de Rouffignac, 1999; Bouby & Fernandes, 2003; Armstrong et al., 2010). Concentrated urine osmolality at awakening combined with a lesser decrease in urine osmolality after drinking water suggests a need for water retention, presumably reflecting underlying dehydration. Children with these urine osmolality trends improved their performance on cognitive tests when given water. Of interest, even among children who awakened with lower urine osmolality, a lesser osmolality decrease with water was associated with improved cognitive performance. This result suggests that urine osmolality on awakening alone may not be an ideal indicator of hydration status (Armstrong, Johnson, McKenzie, & Muñoz, 2013). Children who awaken with lower urine osmolality and exhibit moderate osmolality declines after water consumption may have lower urine concentrating capacity and therefore greater ongoing need for water intake. If lower urine osmolality at awakening reflected adequate hydration for all participants with osmolality in this range, we would have expected to observe similar declines in osmolality with water intake for all of these participants. Instead, water retention in some of these children suggested a continued need for hydration. Overall, therefore, our results suggest that adequate water intake resulting in moderate osmolality changes is important for optimal cognitive performance.

In contrast, children who exhibited the greatest fluctuations in urine osmolality after drinking water did not cognitively benefit from drinking additional water (and in the case of digit span, a decrease in performance was observed). The physiologic mechanism is unclear. Previous research reported that abrupt changes in hydration can result in modulation of cellular metabolism, hormone expression (de Rouffignac, 1999; D'Anci et al., 2006; Suhr, Patterson, Austin, & Heffner, 2010; Wilson & Morley, 2003), and blood pressure (Cian et al., 2000). Further, it has been proposed that abrupt physiological changes can impact cognitive ability through competition for resources for attention and awareness (Rampersaud, Pereira, Girard, Adams, & Metzl, 2005; Rogers et al., 2001). It is possible that the children who exhibited larger osmolality reduction experienced more substantial physiological changes that may have negatively impacted performance on cognitive testing.

Further, these effects were only observed when accounting for the change in osmolality across the entire testing session. That is, change in osmolality to the short term testing period had no significant association with test performance at the short term testing session (results not reported). However, there were strong associations between performance at the short term testing and the overall change in hydration across the testing day. Together, these suggest that the physiological systems responsible for the change in cognitive performance may be slow functioning and thus may not be detectable in the short term osmolality assessment, even though the effects on cognition are already tangible even in the short term. Future studies should examine these differences in timing further.

In the only other study examining the association between reduction of in urine osmolality following water intake and cognitive performance (Fadda et al., 2012), children who experienced larger osmolality decreases performed better on the same digit span task used in the current research. In that study, however, the amount of water intake was not standardized and the observed reduction in urine osmolality was substantially smaller than that reported here, with the average reduction in osmolality falling well within the low-change group in the present study. Therefore, the current results are consistent with these previous findings in suggesting that water intake that leads to moderate hydration status changes is beneficial to cognitive performance.

Of interest, changes in urine osmolality during the control day were predictive of changes in osmolality during the water day. These results may in part reflect differences in children's urine concentrating capacity, as discussed previously. These results also suggest that these fluctuations may capture something unique about hydration status: Hydration status may be not only indicated by urine osmolality level at any given time, but also osmolality change throughout the day and in response to water intake.

Overall, our study joins a nascent literature showing that response to treatment as indicated by changes in urine osmolality is a critical dimension to assess the impact of water intake. We recognize that the effect of practice on visual search tasks is well documented (Shibata, Sagi, & Watanabe, 2014) and that the paired cancellation task used in the current study was subject to significant practice effects which overshadowed the interaction between treatment and renal response. However, that we still found a trend toward significance indicates that our findings with pair cancellation, though attenuated by the effect of order, retained the same pattern of results. This finding suggests that the effect of water supplementation on visual search is robust, but that future studies would benefit greatly from the inclusion of a practice session to stabilize performance prior to testing and thus isolate the impact of water supplementation from that of practice.

We acknowledge that the delayed-match to sample did not appear to be sensitive to changes in urine osmolality. Previous research showed that the effects of water intake are subtle and not always detected across all cognitive measures (Benton & Burgess, 2009; Edmonds & Jeffes, 2009). It is not clear whether there may be some cognitive measures that are systematically more sensitive to changes in hydration status. such as the digit span which has been found to be most consistently affected by dehydration or water intake (Cian et al., 2001; Fadda et al., 2012; Owen et al., 1993; Cian et al., 2000; though see Edmonds, Crombie et al., 2013; Edmonds, Crombie, & Gardner, 2013), or if the relatively small expected effect sizes makes replication across measures and studies more challenging. Nevertheless, we point out that we adopted the most conservative approach to investigate the effects of water intake: Not only did we use a within-subject design, but we also analyzed differences scores between a baseline assessment and a post treatment assessment. Thus, it is likely that our findings are attributable to individual differences in urine osmolality reduction as a function of individual renal responses to water consumption.

Additional studies of the influence of water intake on cognitive performance in children are necessary to fully characterize this relationship. Given the methodological heterogeneity across studies, it is unclear whether the amount of water consumed, speed of consumption and time given for absorption before cognitive testing affect the response to water intake. Individual differences in food intake and history of water consumption likely influences response to water as well (Rampersaud et al., 2005; Stahl, Kroke, Bolzenius, & Manz, 2007).

Despite these limitations, our results suggest that consuming water to enhance cognitive performance may not be equally beneficial to all children and thus they should not be uniformly encouraged to consume considerable amounts of water to enhance their cognitive function. However water should be made readily available to students throughout the day in school settings (Kaushik et al., 2007) so that children can easily access it on a need basis. Furthermore, the large number of participants who started their day dehydrated in the current study as well as many others (Bar-David et al., 2005; Bonnet et al., 2012; Fadda et al., 2012; Kaushik et al., 2007; Molloy et al., 2008), illustrate the need to educate caregivers, teachers, and children alike of the importance of adequate hydration and more broadly, dietary intake. Finally, our results suggest that urine osmolality change is an important predictor of whether or not children's cognitive performance will benefit from water intake. Future research on the factors underlying larger or smaller urine osmolality declines following water consumption will likely help formulate more precise recommendations about water consumption in relation to cognitive enhancement.

Conflict of interest and funding disclosure

This work was supported by a grant from Nestec, Ltd. Gertrude Rapinett is employed by Nestec Ltd. The other authors have no potential conflict of interest to disclose.

Statement about authors' contribution

Clinton Perry collected the data, carried out the initial analyses, drafted the initial manuscript, reviewed and revised the manuscript, and approved the final manuscript as submitted. Gertrude Rapinett assisted in the conceptualization and design of the study, provided feedback on manuscript and approved the final manuscript as submitted. Nicole Glaser contributed to result interpretation and discussion, critically reviewed the manuscript, and approved the final manuscript as submitted. Simona Ghetti conceptualized and designed the study, drafted the initial manuscript and revised it upon receiving feedback, and approved the final manuscript as submitted.

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