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# Dehydration Predicts Longitudinal Decline in Cognitive Functioning and Well-Being Among Older Adults

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Adequate hydration is essential for health, with even mild forms of dehydration often having negative effects on cognition and well-being. Despite evidence of higher risk for dehydration among older adults, links between dehydration and cognitive or well-being outcomes have not been established in old age. In this study, we used longitudinal data from the Berlin Aging Study II (age range 60–89) to investigate whether trajectories of cognitive functioning (digit symbol, $N = 1{,}111$) and well-being (Diener satisfaction with life, $N = 1{,}066$; Socio-Economic Panel Study life satisfaction, $N = 1{,}067$; and Lawton morale, $N = 1{,}067$) are associated with objective dehydration (osmolarity; 33% dehydrated). Our results revealed that higher dehydration was associated with steeper decline in cognitive functioning and well-being over time, and lower well-being among those with higher body mass index. These associations were independent of sociodemographic and physical health characteristics. Our findings highlight the importance of adequate hydration for preserved cognition and well-being across old age. We discuss potential mechanisms and consider practical implications arising from our results.

*Keywords:* aging, osmolarity, perceptual speed, life satisfaction, within-person

Dehydration is a common problem in geriatric medicine, representing one of the main reasons behind emergency hospital admissions and incurring estimated health care costs of up to 5.5 billion USD per year in the United States alone (Kim, 2007). Dehydration refers to a reduction in total body water resulting from water loss or a combination of water and salt deficits (Thomas et al., 2008),



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This article reports data from the Berlin Aging Study II (BASE-II, coprincipal investigators are Lars Bertram, Ilja Demuth, Denis Gerstorf, Ulman Lindenberger, Graham Pawelec, Elisabeth Steinhagen-Thiessen, and Gert G. Wagner). BASE-II is supported by the German Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung under Grants 01UW0808, 16SV5536K, 16SV5537, 16SV5538, 16SV5837, 01GL1716A, and 01GL1716B). Another significant source of funding is the Max Planck Institute for Human Development, Berlin, Germany. Additional contributions (e.g. equipment, logistics, personnel) are made from each of the other participating sites.

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and has been consistently associated with adverse outcomes ranging from weight loss and dizziness to hospitalization and higher mortality rates (for a review, see Popkin, D'Anci, & Rosenberg, 2010). Recent studies have suggested that even mild dehydration (1–2% water loss) can impair cognition (Wittbrodt & Millard-Stafford, 2018) and lower well-being among young adults (Adan, 2012). Despite evidence of high prevalence of dehydration among community-dwelling (approximately 26% dehydrated and 40% at risk for dehydration; Stookey, 2005) and hospitalized older adults (1 in 3 hospitalized older adults; El-Sharkawy et al., 2015), the role of dehydration for cognitive health and well-being in old age has largely been ignored, with numerous reviews highlighting this paucity (Benton & Young, 2015; Pross, 2017). To address this gap, we used longitudinal data from the Berlin Aging Study II (BASE-II) to investigate how dehydration is related to within-person changes in cognitive functioning and well-being, and the role of sociodemographic and physical health characteristics.

## Dehydration in Old Age

Older adults' higher risk for dehydration has been attributed to age-related decrements in water homeostasis and psychosocial factors. For example, aging is associated with reductions in tissue and muscle mass, resulting in 15% decreased water capacity compared with young adults (Allison & Lobo, 2004). Additionally, fluid intake decreases because of dysregulations in the biomolecular systems that signal thirst and motivate water intake (Sfera, Cummings, & Osorio, 2016), and because older adults tend to take more diuretic medications or restrict their fluid consumption to prevent urinary incontinence (Anger et al., 2011). With increasing age, older adults also become more susceptible to environmental and internal factors that are relevant for hydration (e.g., higher temperatures), which can trigger more frequent dehydration episodes (Wotton, Crannitch, & Munt, 2008). As a result, dehydration could be a recurring rather than an acute problem in old age (Bennett, Thomas, & Riegel, 2004; Frangeskou, Lopez-Valcarcel, & Serra-Majem, 2015).

Whereas short bouts of dehydration can occur in all individuals across the life span because of sweating or short-term illnesses resulting in loss of total body water (Popkin et al., 2010), it is possible that older adults experience longer and more severe episodes of dehydration, which could be associated with the decrease in fluid intake typically seen in old age (Bennett et al., 2004; Sfera et al., 2016). The difficulty in addressing the neurobiological and psychosocial factors underlying lower fluid intake in old age could make dehydration management particularly challenging. It has been observed that diagnosis of dehydration even at a single time point is associated with longer hospital stays and higher likelihood of hospital readmissions among older adults (Frangeskou et al., 2015), suggesting that dehydration could lead to long-term negative consequences for older adults' health.

## Cognitive and Well-Being Outcomes of Dehydration

Research into the cognitive and well-being effects of dehydration has almost exclusively focused on young adults. A recent meta-analysis has demonstrated small but significant associations, with more severe water loss being linked to larger impairments across many domains of cognitive functioning, including attention and executive control (Wittbrodt & Millard-Stafford, 2018). Of note, some studies have not identified such links (e.g., Armstrong et al., 2012), presumably because they were not adequately powered (for a discussion, see Benton & Young, 2015). For well-being outcomes, current evidence indicates that even seemingly small changes in hydration status (1–2% water loss) can reliably decrease positive affect and increase confusion, fatigue, stress, and depression (Pross, 2017).

Evidence from older adults is surprisingly scarce. In fact, no studies have assessed the potential link between objective dehydration and well-being in aging, an important omission considering the associations of dehydration with physical health (Popkin et al., 2010) and brain functionality (Sfera et al., 2016), and their consequences for quality of life in old age. Specifically, dehydration has been associated with the presence of physical conditions and symptoms that could impact older adults' quality of life and well-being. For example, links have been found between dehydration and gastrointestinal health (Lindeman et al., 2000), cardiovascular health and hemodynamic responses (Popkin et al., 2010), as well as headaches and migraines (Shirreffs, Merson, Fraser, & Archer, 2004), all of which could plausibly contribute to a reduction in subjective well-being and quality of life among older adults.

For cognitive outcomes, research conducted with middle-aged and older adults has found dehydration to be associated with decrements in attention and memory (Suhr, Hall, Patterson, & Niinistö, 2004). These associations are typically attenuated when controlling for cardiovascular factors such as diastolic blood pressure (DBP; Suhr, Patterson, Austin, & Heffner, 2010), suggesting that cognitive decrements might be driven by dehydration-induced changes in cardiovascular functionality. Echoing criticisms of studies being inadequately powered to detect dehydration-related changes in cognition (Benton & Young, 2015), these studies also included a small number of participants (Suhr et al., 2004: $n = 28$; Suhr et al., 2010: $n = 21$) and recruited a mixed sample of both middle-aged and older adults, complicating speculations about the role of age-related differences. The hydromolecular hypothesis posits that dehydration can lead to the production of defective proteins that have been linked with neuronal damage and synaptic dysregulation in the brain (Sfera et al., 2016). Specifically, whereas adequate hydration allows proteins to become biologically active and immediately available for reactions, dehydration causes significant delays in this process that can result in slower or late chemical reactions in the brain (Sen & Voorheis, 2014). Additionally, it has been found that effective water circulation in the brain is paramount for clearing waste produced by the neurons such as beta amyloid, which, in turn, has been associated with Alzheimer's pathology (Nedergaard, 2013). Indeed, a recent study conducted with older adults has reported that higher dehydration is associated with increased risk of being diagnosed with dementia (Lauriola et al., 2018), suggesting that dehydration and severe cognitive impairment may be associated. Considering the importance of intact physiological and brain functionality for healthy aging, cognitive functioning and well-being could be closely associated with dehydration in old age.

## The Present Study

A common feature of the studies reviewed is that they are all cross-sectional, thereby precluding inferences about the longitudinal consequences of dehydration. In light of studies showing that diagnosis of dehydration even at a single time point is associated with long-term consequences for health (Bennett et al., 2004; Frangeskou et al., 2015; Popkin et al., 2010), we argue that one-time assessment of dehydration might also be associated with within-person longitudinal changes in cognition and well-being. The goal of the present study is to investigate whether dehydration assessed at a single time point could be associated with longitudinal trajectories of cognitive functioning and well-being in old age. Based on studies reporting links between hydration status and sociodemographic (e.g., sex and age; Armstrong, Johnson, McKenzie, Ellis, & Williamson, 2016; Benton, 2011) and physical health characteristics (e.g., DBP; Suhr et al., 2010), we also consider the role of sociodemographic and health variables as moderators. To that end, we applied growth models to longitudinal data from the BASE-II. Dehydration was assessed via *osmolarity*, a measure of the balance of water and other particles in the blood. Osmolarity can detect even small changes in hydration (1% change in body weight; Kavouras, 2002), it has been used in aging research (Lauriola et al., 2018; Siervo, Bunn, Prado, & Hooper, 2014), and is considered an important component of dehydration assessment protocols in laboratory settings (Armstrong, 2007). Cognitive functioning was evaluated using the Digit Symbol Substitution test (DSST; Wechsler, 1981), a perceptual speed test that is highly sensitive to age-related cognitive decline (Hoyer, Stawski, Wasylyshyn, & Verhaeghen, 2004) and loads highly on a factor of general intelligence (Tucker-Drob, Briley, Starr, & Deary, 2014). Well-being was comprehensively assessed with the Satisfaction with Life Scale (Diener, Emmons, Larsen, & Griffin, 1985), a widely used life satisfaction single item (Fujita & Diener, 2005), and Lawton's Morale Scale (Lawton, 1975).

We expected more severe dehydration to be associated with lower levels of and steeper declines in cognitive functionality and well-being over time. Additionally, based on studies suggesting that associations between dehydration and cognition are moderated by cardiovascular functionality, we expected that dehydration might interact with physical health variables to affect cognition and well-being.

# Method

To address our research questions, we used data from the BASE-II. The BASE-II has received ethical approval by the ethics committees at the Charité University Hospital and the Max Planck Institute of Human Development, Berlin. All participants provided written consent prior to taking part in the study. Data from the BASE-II study have been used in a number of publications covering a variety of research questions (see https://www.base2.mpg.de/en, for a complete list). The present report does not overlap with other BASE-II publications.

A detailed overview of the BASE-II can be found in other publications (Bertram et al., 2014; Gerstorf et al., 2016). We selectively provide information on variables relevant to our study.

## Participants and Procedure

Our sample included community-dwelling older adults aged 60 and above, recruited from the greater Berlin metropolitan area. With our focus on the nature and consequences of dehydration among older adults, the young adult sample of the BASE-II is not included in this report. Medical data used to assess osmolarity and the health background variables were collected at the Charité University Hospital (for an overview, see Buchmann et al., 2017). We only included older adults who had available data on hydration status, which resulted in the inclusion of 1,611 older adults. To assess sample selectivity, we examined potential differences between participants with available hydration data ($N = 1{,}611$) and those who did not have hydration data available ($N = 65$). Participants with hydration data had lower levels of morbidity, $M = 1.25$ ($SD = 1.30$) versus $M = 1.76$ ($SD = 1.91$), $t(1517) = -2.31$, $p = .021$, $d = .38$, but no other differences were found between the two groups (all $ps > .10$). A meta-analysis using data from 33 studies (413 participants) has found a small effect size for associations between dehydration and cognition (Hedges' $g = .21$; Wittbrodt & Millard-Stafford, 2018). Using an even larger sample size would allow us to identify even small effects that could otherwise go undetected.

Cognitive performance scores were collected at the Charité University Hospital (individual sessions) and the Max Planck Institute (group sessions). Overall, five assessment waves have been completed (Wave 1, 2010–2013: $N = 1{,}379$; Wave 2, 2012–2013: $N = 1{,}333$; Wave 3, 2012–2013 [weeks following Wave 2]: $N = 1{,}362$; Wave 4, 2016: $N = 251$; and Wave 5, 2017: $N = 82$). Well-being data were collected with take-home questionnaires using an online interface or a paper-and-pencil format. Restrictions in funding for data collection did not allow us to include all well-being measures at each assessment wave. As a result, well-being data were collected either at two assessment waves (Satisfaction with Life Scale in Wave 1, 2012–2013, $N = 1{,}409$; and Wave 2, 2016: $N = 250$), four waves (well-being, morale in Wave 1, 2012–2013: $N = 1{,}408$; Wave 2, 2014: $N = 1{,}254$; Wave 3, 2016: $N = 250$; and Wave 4, 2017–2018: $N = 1{,}138$), or eight waves (life satisfaction, single item in Wave 1, 2008: $N = 98$; Wave 2, 2009: $N = 952$; Wave 3, 2010: $N = 84$; Wave 4, 2012: $N = 1{,}063$; Wave 5, 2012–2013: $N = 1{,}382$; Wave 6, 2014: $N = 1{,}261$; Wave 7, 2016: $N = 247$; and Wave 8, 2017–2018: $N = 1{,}148$).

We also assessed sample attrition effects by comparing participants who provided a single data point to those who completed two or more assessments on the digit symbol (1 data point: $N = 172$; 2 or more: $N = 1{,}397$), and on the well-being Morale Scale (1 data point: $N = 109$; 2 or more: $N = 1{,}388$). For the digit symbol, participants who provided more data were younger, $M = 70.62$ ($SD = 3.85$) versus $M = 72.93$ ($SD = 4.09$), $t(1408) = -3.14$, $p = .002$, $d = .60$, and reported higher levels of well-being on the Satisfaction with Life Scale, $M = 3.67$ ($SD = 0.70$) versus $M = 3.06$ ($SD = 0.79$), $t(1406) = 4.52$, $p < .001$, $d = .87$, the life satisfaction single item, $M = 7.64$ ($SD = 1.60$) versus $M = 6.63$ ($SD = 2.27$), $t(1379) = 3.21$, $p = .001$, $d = .63$, and the Morale Scale, $M = 4.08$ ($SD = 0.82$) versus $M = 3.40$ ($SD = 0.89$), $t(1405) = 4.29$, $p < .001$, $d = .83$. No other differences were found (all $ps > .11$). For well-being, participants who provided more data points were younger at the largest assessment time point, $M = 70.59$ ($SD = 3.81$) versus $M = 72.27$ ($SD = 4.19$), $t(1441) = -3.73$, $p < .001$, $d = .44$, performed better on the cognitive test, $M = 44.92$ ($SD = 9.20$) versus $M = 40.64$ ($SD = 10.11$), $t(1382) = 3.82$, $p < .001$, $d = .46$, and reported higher levels of well-being on the Satisfaction with Life Scale, $M = 3.67$

(*SD* = 0.70) versus $M = 3.44$ (*SD* = 0.68), $t(1439) = 2.82$, $p = .005$, $d = .33$, and the life satisfaction single item, $M = 7.64$ (*SD* = 1.61) versus $M = 7.17$ (*SD* = 1.80), $t(1410) = 2.44$, $p = .015$, $d = .29$. No other significant differences were identified (all *p*s > .11).

## Measures

**Cognition.** Cognitive functioning was assessed with the DSST of the Wechsler Adult Intelligence Scale (Wechsler, 1981). Participants were presented with a coding key consisting of nine unique digit-symbol pairs and a test section with numbers and empty boxes. After a brief practice, participants were asked to fill the boxes with the appropriate symbol for each number, as fast and accurately as possible within 90 s. Performance on the digit symbol was scored as the number of correctly completed symbols (total completed minus the errors).

**Well-being.** Well-being was assessed with three separate scales, measuring cognitive-evaluative components of well-being. First, we used the Satisfaction with Life Scale (Diener et al., 1985). Participants were provided with five statements (e.g., "I am satisfied with my life." Cronbach's alpha = .84) and gave their responses on a 5-point scale ranging from 1 (*strongly disagree*) to 5 (*strongly agree*). Second, we used participants' ratings on the life satisfaction single item "How satisfied are you with your life, all things considered?" provided on a scale ranging from 0 (*completely unsatisfied*) to 10 (*completely satisfied*). This item is widely used in psychological research (Fujita & Diener, 2005). Finally, we used three items measuring life dissatisfaction (e.g., "I take things hard"; Cronbach's alpha = .74) selected from the Philadelphia Geriatric Center Morale Scale (Lawton, 1975). Participants gave their ratings on a scale ranging from 1 (*strongly disagree*) to 5 (*strongly agree*). Items were reverse-coded such that higher scores indicate higher well-being. For consistency and direct comparison across well-being scales, scores were *T* standardized ($M = 50$, $SD = 10$).

**Dehydration.** Participants' osmolarity was used as an objective index of dehydration. Although plasma osmolality measured with an osmometer has been found to be the most accurate method of diagnosing dehydration in laboratory settings (e.g., Cheuvront, Ely, Kenefick, & Sawka, 2010), we did not have data on plasma osmolality available. Therefore, we calculated osmolarity levels using blood parameters collected during the medical assessment and entering them in the osmolarity equation validated in Siervo et al. (2014): $1.86 \times (\text{sodium} + \text{potassium}) + 1.15 \times \text{glucose} + \text{urea} + 14$ (all values in mmol/L). This formula is used as an indirect measure of plasma osmolality and has been proven to have good sensitivity and specificity, as well as good diagnostic accuracy in older adults, irrespective of hydration status or diabetes diagnosis (Siervo et al., 2014). Higher osmolarity indicates higher levels of dehydration, with values over 296 mmol/L interpreted as indicative of being dehydrated at the time of the medical assessment (Siervo et al., 2014). Osmolarity was assessed once (assessment period 2010–2013).[1]

**Individual difference correlates.** We examined the role of sociodemographic and physical health characteristics as moderators. Age was calculated as participants' date of birth subtracted from the date of each assessment, in years (rounded to two decimals). Sex was coded 0 for men and 1 for women. Education was measured as the number of years that participants had spent in formal education. Morbidity was assessed by self-report, with select diagnoses (e.g., diabetes) being further verified by medical examination at the Charité University Hospital. Diseases were classified based on the Charlson index (Charlson, Pompei, Ales, & MacKenzie, 1987) and the overall morbidity score was calculated as the weighted sum of these conditions (disease severity ranging from 1 to 3). We used four measures of physical functioning. First, participants' grip strength was assessed with a hand dynamometer (Smedley, Stoelting Company, Wood Dale, Illinois). Participants were asked to exert force on a dynamometer three times with each hand, and the scores were averaged across both hands and all trials. Second, the body mass index (BMI) was calculated as weight/height$^2$ (kg/m$^2$). We also used participants' resting heart rate and DBP as measures of cardiovascular functionality, measured with participants in a sitting position. Heart rate (beats per minute) was measured along with blood pressure (mmHg) using an electronic sphygmomanometer (Boso, Jungingen, Germany) placed on each arm, and an average value was obtained.

## Statistical Analyses

To examine our research questions, we estimated growth models using multiyear longitudinal data on the digit symbol test and well-being. The model was specified as

$$\text{cognition}_{ti}/\text{well-being}_{ti} = \beta_{0i} + \beta_{2i}(\text{time-in-study}_{ti}) + \beta_{4i}(\text{time-in-study}^2_{ti}) + e_{ti},$$

where person *i*'s cognition/well-being at occasion *t*, $\text{cognition}_{ti}/\text{well-being}_{ti}$, is a function of an individual-specific intercept parameter, $\beta_{0i}$, individual-specific linear and quadratic slope parameters, $\beta_{2i}$ and $\beta_{4i}$, and residual error, $e_{ti}$. The quadratic effects were only included if they were significantly different from zero. Following standard multilevel/growth modeling procedures (Ram & Grimm, 2015), individual-specific intercepts, $\beta_{0i}$, and slopes, $\beta_{2i}$ and $\beta_{4i}$, were modeled as a function of osmolarity and the correlates. To facilitate model parsimony and convergence, interaction terms with osmolarity were tested but not included in the final model when not significant, always retaining the lower-order interactions when necessary. Interaction effects of the correlates with the quadratic change terms were included if they were significantly different from zero. The digit symbol was used as a separate predictor for well-being trajectories, and vice versa. The final model took the following form (example based on the digit symbol)

$$\begin{aligned}\beta_{0i} = \gamma_{00} &+ \gamma_{01}(\text{age}_i) + \gamma_{02}(\text{women}_i) + \gamma_{03}(\text{education}_i)\\ &+ \gamma_{04}(\text{osmolarity}_i) + \gamma_{06}(\text{morbidity}_i) + \gamma_{07}(\text{grip}_i)\\ &+ \gamma_{08}(\text{BMI}_i) + \gamma_{09}(\text{heart rate}_i) + \gamma_{10}(\text{DBP}_i)\\ &+ \gamma_{011}(\text{well-being}_i) + \gamma_{012}(\text{morbidity}_i \times \text{education}_i)\end{aligned}$$

[1] Dehydration can be either hypotonic, hypertonic, or isotonic, depending on whether it is attributed to loss of salt, water, or both, respectively (Hooper, Bunn, Jimoh, & Fairweather-Tait, 2014). Because we used an osmolarity and not a tonicity equation, we use the general terms "not dehydrated" and "dehydrated" to characterize participants below and above the threshold of 296 mmol/L, as in Siervo et al. (2014).

$$+ \gamma_{013}(\text{grip}_i \times \text{well-being}_i)$$
$$+ \gamma_{014}(\text{well-being}_i \times \text{women}_i) + u_{0i},$$
$$\beta_{2i} = \gamma_{20} + \gamma_{21}(\text{age}_i) + \gamma_{22}(\text{women}_i) + \gamma_{23}(\text{education}_i)$$
$$+ \gamma_{24}(\text{osmolarity}_i) + \gamma_{26}(\text{morbidity}_i) + \gamma_{27}(\text{grip}_i)$$
$$+ \gamma_{28}(\text{BMI}_i) + \gamma_{29}(\text{heart rate}_i) + \gamma_{30}(\text{DBP}_i)$$
$$+ \gamma_{31}(\text{well-being}_i) + u_{2i},$$
$$\beta_{4i} = \gamma_{40} + \gamma_{41}(\text{BMI}_i) + u_{4i},$$

where the γs are sample-level associations, and $u_{0i}$, $u_{2i}$, and $u_{4i}$ are residual unexplained individual differences that are assumed to be multivariate normally distributed, correlated with each other, and uncorrelated with the residual errors. For all outcomes, time in study was centered at the time point where most data were collected (i.e., 2010–2013 wave for the digit symbol and 2012–2013 wave for all well-being measures). Age was centered at 70 years, and all other predictors were grand-mean centered so that the regression parameters for these variables indicate the average trajectory and the extent of differences associated with a particular variable, rather than for a particular group.

Models were fit to the data using SAS PROC MIXED (Littell, Miliken, Stoup, & Wolfinger, 2006), with incomplete observations treated as missing at random (Little & Rubin, 1987). The predictors and correlates (age, sex, education, cognition, and physical health) represent attrition-informative variables and so helped to accommodate longitudinal selectivity for the outcome variables (i.e., missingness may have been related to these variables; McArdle, 1994).

## Results

### Correlates of Dehydration

Table 1 reports descriptive statistics and the intercorrelations for the variables used in the present report. Of the 1,047 participants with available data on all variables of interest during the largest assessment wave, 345 (33%) had an osmolarity value >296 mmol/L and were thus characterized as experiencing dehydration. Higher osmolarity was associated with older age, $r = .13$, $p < .001$, more morbidities, $r = .08$, $p = .008$, and higher BMI, $r = .15$, $p < .001$.

### Dehydration and Trajectories of Cognitive Functioning

Results of growth models examining associations between osmolarity and trajectories of cognitive functioning are presented in Table 2. Performance on the digit symbol test declined over time ($\gamma_{20} = -0.53$, $p < .001$), also showing some convex curvature ($\gamma_{40} = 0.10$, $p = .025$). Older age ($\gamma_{01} = -0.35$, $p < .001$), being a man ($\gamma_{02} = 5.43$, $p < .001$), fewer years of education ($\gamma_{03} = 0.44$, $p < .001$), lower grip strength ($\gamma_{07} = 0.14$, $p = .009$), and lower well-being ($\gamma_{011} = 1.39$, $p < .001$) were each associated with lower levels of cognitive functioning. Significant interactions were identified between grip strength and well-being ($\gamma_{013} = -0.19$, $p = .006$), and sex and well-being ($\gamma_{014} = -3.15$, $p = .006$), indicating that higher well-being was associated with better cognitive functioning among those with lower grip strength and among men, respectively. An

Table 1
*Descriptive Statistics and Intercorrelations of Study Measures at Largest Assessment Time Point (2012–2013 Assessment) for Participants With Available Data on All Variables of Interest*

| | | | Intercorrelations | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Variable | *M* | *SD* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| Dehydration | | | | | | | | | | | | | | | |
| 1. Osmolarity (268.44–315.29 mmol/L) | 293.78 | 5.33 | 1 | | | | | | | | | | | | |
| Well-being | | | | | | | | | | | | | | | |
| 2. Satisfaction with Life Scale, Diener (1.60–5) | 3.67 | 0.70 | .01 | 1 | | | | | | | | | | | |
| 3. Life satisfaction, single item (1–10) | 7.66 | 1.59 | −.01 | .67** | 1 | | | | | | | | | | |
| 4. Well-being, morale (1–5) | 4.08 | 0.85 | −.01 | .46** | .43** | 1 | | | | | | | | | |
| Sociodemographic | | | | | | | | | | | | | | | |
| 5. Age (60.78–88.47) | 70.67 | 3.82 | .13** | −.01 | .001 | −.02 | 1 | | | | | | | | |
| 6. Women (0, 1) | 0.52 | 0.50 | −.04 | −.06 | −.04 | −.11** | .01 | 1 | | | | | | | |
| 7. Education (7–18) | 14.15 | 2.88 | −.05 | −.04 | .01 | .05 | −.06 | −.17** | 1 | | | | | | |
| Physical and cognitive health | | | | | | | | | | | | | | | |
| 8. Morbidity (0–10) | 1.26 | 1.32 | .08** | −.09** | −.11** | −.11** | −.003 | −.05 | .001 | 1 | | | | | |
| 9. Grip strength (7.50–54.58) | 30.00 | 8.61 | .03 | .14** | .09** | .14** | −.09** | −.80** | .12** | −.03 | 1 | | | | |
| 10. BMI (17.71–47.68) | 26.86 | 4.14 | .15** | −.01 | −.03 | .02 | −.02 | −.09** | −.08** | .17** | .10** | 1 | | | |
| 11. Heart rate (37–129 bpm) | 69.28 | 11.38 | −.04 | .03 | −.03 | −.03 | −.05 | .05 | −.06* | .04 | −.04 | .13** | 1 | | |
| 12. DBP (47–196 mmHg) | 83.18 | 11.05 | .05 | .02 | −.001 | .07* | −.08* | −.09** | .04 | −.07* | .12** | .05 | .23** | 1 | |
| 13. Digit symbol (12–90) | 44.95 | 9.08 | −.05 | .07* | .08* | .10** | −.13** | .11** | .08** | −.10** | −.05 | −.05 | −.03 | .002 | 1 |

*Note.* $N = 1{,}047$. Range of values for each variable in parentheses. *M* = mean; *SD* = standard deviation; BMI = body mass index; DBP = diastolic blood pressure.
* $p < .05$. ** $p < .01$.

Table 2
*Growth Curve Models of the Digit Symbol Substitution Test Over Time*

| Parameters | Estimates | *SE* |
|---|---|---|
| Fixed effects estimates | | |
| Intercept$_{\gamma 00}$ | 49.48*** | 0.31 |
| Time$_{\gamma 20}$ | −0.53*** | 0.11 |
| Time$^2_{\gamma 40}$ | 0.10* | 0.04 |
| Age$_{\gamma 01}$ | −0.35*** | 0.08 |
| Women$_{\gamma 02}$ | 5.43*** | 0.96 |
| Education$_{\gamma 03}$ | 0.44*** | 0.10 |
| **Osmolarity$_{\gamma 04}$** | **0.08** | **0.05** |
| **Osmolarity$^2_{\gamma 05}$** | — | — |
| Morbidity$_{\gamma 06}$ | −0.39 | 0.22 |
| Grip$_{\gamma 07}$ | 0.14** | 0.06 |
| BMI$_{\gamma 08}$ | −0.04 | 0.07 |
| Heart rate$_{\gamma 09}$ | −0.01 | 0.03 |
| DBP$_{\gamma 010}$ | −0.002 | 0.03 |
| Well-being$_{\gamma 011}$ | 1.39*** | 0.34 |
| Age × Time$_{\gamma 21}$ | −0.05 | 0.03 |
| Women × Time$_{\gamma 22}$ | 0.56 | 0.31 |
| Education × Time$_{\gamma 23}$ | 0.01 | 0.03 |
| **Osmolarity × Time$_{\gamma 24}$** | **−0.06*** ** | **0.02** |
| Morbidity × Time$_{\gamma 26}$ | −0.05 | 0.08 |
| Grip × Time$_{\gamma 27}$ | 0.04* | 0.02 |
| BMI × Time$_{\gamma 28}$ | 0.04 | 0.03 |
| BMI × Time$^2_{\gamma 41}$ | −0.03* | 0.01 |
| Heart Rate × Time$_{\gamma 29}$ | 0.01 | 0.01 |
| DBP × Time$_{\gamma 30}$ | −0.02** | 0.01 |
| Well-being × Time$_{\gamma 31}$ | 0.12 | 0.11 |
| Morbidity × Education$_{\gamma 012}$ | 0.15* | 0.07 |
| Grip × Well-being$_{\gamma 013}$ | −0.19** | 0.07 |
| Well-being × Women$_{\gamma 014}$ | −3.15** | 1.15 |
| Random effects estimates | | |
| Variance intercept | 74.04*** | 3.67 |
| Variance time | 0.60** | 0.23 |
| Covariance intercept, time | 5.11*** | 0.82 |
| Residual variance | 32.20*** | 1.06 |

*Note*. Unstandardized estimates and *SE*s are presented. Results are based on 1,111 participants who provided a total of 3,358 observations. Digit Symbol Substitution test scores were *T* standardized. Age was centered at 70 years. BMI = body mass index; DBP = diastolic blood pressure; Grip = grip strength. Model parameters for osmolarity as our focus variable highlighted in bold. Dashes indicate that the parameter was not significant and was not included in the model.
* $p < .05$. ** $p < .01$. *** $p < .001$.

interaction between morbidity and education was also found ($\gamma_{012} = 0.15$, $p = .034$), indicating that more morbidities predicted lower cognitive functioning among those with fewer years of education. Furthermore, higher BMI was associated with accelerated cognitive decline over time ($\gamma_{41} = -0.03$, $p = .027$).

Osmolarity was not associated with levels of cognitive functioning, but an osmolarity by time interaction was identified ($\gamma_{24} = -0.06$, $p < .001$). Results of follow-up analyses contrasting people above and below the established dehydration threshold (296 mmol/L) are graphically presented in Figure 1. Those above the dehydration threshold experienced steeper decline in cognitive functioning over time.

## Dehydration and Trajectories of Well-Being

Results of growth models examining associations between osmolarity and trajectories of well-being are presented in Table 3. Well-being appeared to be stable across our measures, with only the satisfaction with life scale showing evidence of decline over time (Satisfaction with Life Scale, $\gamma_{20} = -0.72$, $p < .001$). Older age was associated with higher life satisfaction on the single item ($\gamma_{01} = 0.21$, $p = .002$), while being a woman was associated with higher levels of well-being in two of the three measures (Satisfaction with Life Scale, $\gamma_{02} = 2.80$, $p = .006$; and life satisfaction, single item, $\gamma_{02} = 2.20$, $p = .007$). An interaction between age and sex was found across all measures (Satisfaction with Life Scale, $\gamma_{04} = -0.34$, $p = .030$; single item, $\gamma_{04} = -0.30$, $p = .017$; and Morale Scale, $\gamma_{04} = -0.28$, $p = .026$), indicating that older age was associated with lower well-being among women. Higher morbidity, lower grip strength, and lower cognitive performance each predicted lower well-being consistently across our measures (e.g., grip strength: Satisfaction with Life Scale, $\gamma_{08} = 0.30$, $p < .001$; single item, $\gamma_{08} = 0.20$, $p < .001$; Morale Scale, $\gamma_{08} = 0.16$, $p < .001$). Finally, an interaction between sex and BMI was found across all three scales (Satisfaction with Life Scale, $\gamma_{020} = 0.40$, $p = .007$; single item, $\gamma_{020} = 0.26$, $p = .034$; Morale Scale, $\gamma_{020} = 0.37$, $p = .003$), indicating that higher BMI was associated with lower well-being among men, but not women.

Higher osmolarity was associated with accelerated decline in well-being over time, as measured by the morale scale (Morale Scale, $\gamma_{26} = -0.03$, $p = .022$). We also found several interaction effects between osmolarity and physical health characteristics. More consistently, an osmolarity by BMI interaction was found for two of the three scales (Satisfaction with Life Scale, $\gamma_{014} = -0.05$, $p < .001$; life satisfaction single item, $\gamma_{014} = -0.02$, $p = .035$), indicating that higher BMI was associated with lower well-being among dehydrated older adults (Figure 2). Analysis of the Morale Scale showed that osmolarity was additionally associated with accelerated decline in well-being among participants younger than 70 years old ($\gamma_{016} = 0.003$, $p = .037$), those with lower BMI ($\gamma_{017} = 0.002$, $p = .047$), and participants with high DBP ($\gamma_{018} = -0.001$, $p = .010$). These effects were independent of sociodemographic, physical, and cognitive health characteristics.[2]

## Discussion

Although associations between dehydration and physical health in old age are well established, the question of whether and how dehydration shapes within-person change in cognition and well-being among older adults remains unexplored. Using longitudinal data from the BASE-II, our study is the first to demonstrate that dehydration is associated with longitudinal trajectories of lower cognitive functioning and well-being in older adults, highlighting the long-term effects of dehydration. We also found evidence for a moderating role of physical health, showing that dehydration relates to lower well-being among those with high BMI.

The predictive effects of dehydration observed in this report were found above and beyond other physical health characteristics such as cardiovascular factors that are known to attenuate such

[2] In follow-up analyses, we accounted for the time lag between dehydration assessment and the assessment of each outcome, and the time of year that dehydration was assessed (summer months vs. other seasons). Results were substantively identical to those reported in the main text.

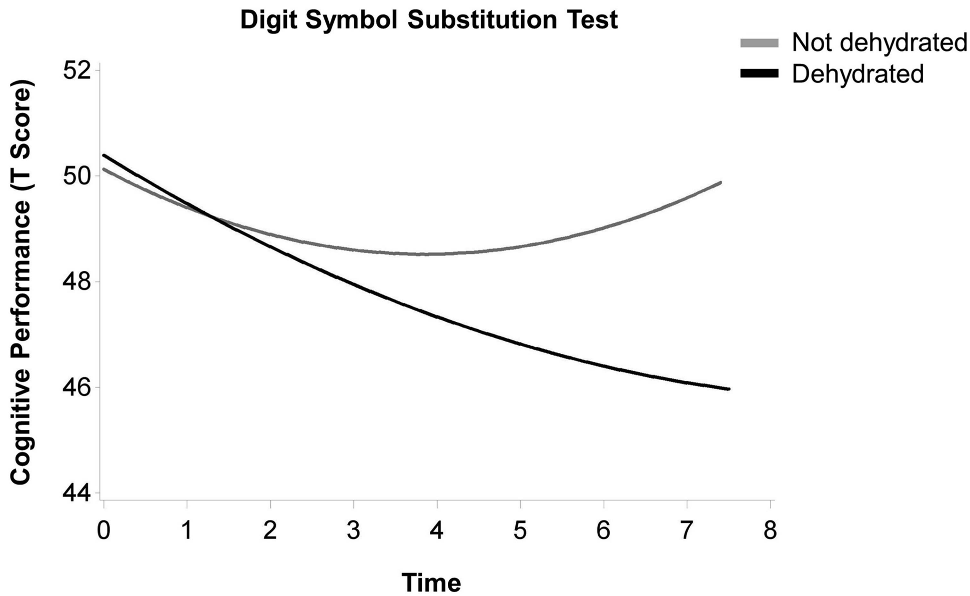


*Figure 1.* Illustrating trajectories of cognitive change over time by osmolarity, exemplified as differences in hydration status (not dehydrated vs. dehydrated). Participants were split into the hydration groups based on guidelines suggesting that values larger than 296 mmol/L can be characterized as experiencing dehydration at the time of assessment (Siervo et al., 2014). It can be seen that those above the dehydration threshold show steeper cognitive decline than their nondehydrated peers.

associations (e.g., DBP; Suhr et al., 2010). It has been suggested that dehydration may lead to the creation of defective proteins, which, in turn, affect cognitive functionality through impairments in information processing or via damaging neurons and synaptic connections (Sfera et al., 2016). In line with this notion, mild dehydration has been found to predict lower levels of cognitive functioning (Wittbrodt & Millard-Stafford, 2018) and well-being among young adults (for reviews, see Adan, 2012; Benton, 2011; Benton & Young, 2015). Additionally, recent studies have found that even transient decreases in hydration are associated with structural alterations in brain areas supporting cognition (Wittbrodt, Sawka, Mizelle, Wheaton, & Millard-Stafford, 2018). Considering the high prevalence of dehydration among both clinical populations (37% dehydrated; El-Sharkawy et al., 2015) and community-dwelling older adults (approximately 26% dehydrated and 40% at risk; Stookey, 2005), also mirrored in our sample (33% dehydrated), it is possible that dehydration-related decrements in brain functionality may affect even larger population segments among older adults. Neuroimaging studies examining associations of dehydration with the structural and functional integrity of key brain areas supporting cognition and well-being would be highly informative in understanding the neurobiological correlates of dehydration in old age.

We also identified interactions of dehydration with physical health variables, suggesting that dehydration constitutes a risk factor particularly for those with a less favorable physical health profile (i.e., higher BMI and DBP), a pattern that is consistent with evidence showing strong associations between dehydration and health outcomes (Popkin et al., 2010). Similar to previous research (Lauriola et al., 2018), dehydration was also associated with lower well-being among older adults below the age of 70 rather than their older counterparts. We speculate that dehydration in those below age 70 might go unrecognized compared with older adults who visit the hospital more regularly and have their hydration status routinely checked. In fact, it has been suggested that dehydration might go unnoticed in about 74% of dehydrated older adults visiting the emergency room (Bennett et al., 2004), highlighting the extent of the problem and its potential implications for quality of life.

To test the robustness of the phenomenon, we made use of three well-being indicators and obtained both consistent and diverging results. Whereas the two life satisfaction measures indicated that dehydration was consistently associated with lower well-being for those with a higher BMI, analysis of morale showed that dehydration is associated with steeper well-being decline among those with lower (as opposed to higher) BMI. We can only speculate about possible reasons. Although all measures tap into cognitive-evaluative aspects of well-being, differences exist in the number and valence of items included and the life domains covered (e.g., Morale Scale involving only negatively worded items that tap into lonely dissatisfaction; Lawton, 1975), as well as the number of waves available for each well-being measure that can directly impact the measures' power to detect dehydration-related changes in well-being. These differences should be explored in more detail in the future.

Considering that dehydration could be a recurring rather than an acute problem in old age (Bennett et al., 2004; Weinberg, Pals, McGlinchey-Berroth, & Minaker, 1994) and can have long-term implications for older adults' health (Frangeskou et al., 2015; Popkin et al., 2010), rapid diagnosis and treatment of fluid imbalances could minimize the economic burden associated with dehydration in old age (e.g., costs of hospitalization; Kim, 2007).

Table 3
*Growth Curve Models of Well-Being Measures Over Time*

| Parameters | Satisfaction with life (Diener) | | Life satisfaction (single item) | | Well-being (morale) | |
|---|---|---|---|---|---|---|
| | Estimate | *SE* | Estimate | *SE* | Estimate | *SE* |
| Fixed effects estimates | | | | | | |
| Intercept$_{\gamma 00}$ | 50.30*** | 0.30 | 50.09*** | 0.24 | 50.42*** | 0.34 |
| Time$_{\gamma 20}$ | −0.72*** | 0.21 | −0.01 | 0.05 | −0.04 | 0.12 |
| Time$^2_{\gamma 40}$ | — | — | — | — | −0.04 | 0.07 |
| Age$_{\gamma 01}$ | 0.03 | 0.08 | 0.14* | 0.06 | −0.14 | 0.08 |
| Women$_{\gamma 02}$ | 2.80** | 1.01 | 2.20** | 0.81 | 0.31 | 0.83 |
| Education$_{\gamma 03}$ | −0.14 | 0.10 | −0.11 | 0.08 | 0.02 | 0.08 |
| Age × Time$_{\gamma 21}$ | −0.01 | 0.06 | −0.01 | 0.01 | −0.03 | 0.03 |
| Women × Time$_{\gamma 22}$ | 0.12 | 0.68 | −0.09 | 0.16 | 0.70* | 0.33 |
| Education × Time$_{\gamma 23}$ | 0.11 | 0.07 | −0.01 | 0.02 | −0.03 | 0.03 |
| Age × Women$_{\gamma 04}$ | −0.34* | 0.15 | −0.30* | 0.12 | −0.28* | 0.13 |
| **Osmolarity$_{\gamma 05}$** | **–0.02** | **0.06** | **–0.03** | **0.05** | **0.05** | **0.06** |
| **Osmolarity$^2_{\gamma 06}$** | — | — | — | — | **–0.01** | **0.01** |
| Morbidity $_{\gamma 07}$ | −0.51* | 0.23 | −0.63*** | 0.18 | −0.70*** | 0.19 |
| Grip$_{\gamma 08}$ | 0.30*** | 0.06 | 0.20*** | 0.05 | 0.16*** | 0.05 |
| BMI$_{\gamma 09}$ | −0.09 | 0.08 | −0.04 | 0.06 | −0.10 | 0.07 |
| Heart rate$_{\gamma 010}$ | 0.05 | 0.03 | 0.01 | 0.02 | 0.02 | 0.02 |
| DBP$_{\gamma 011}$ | −0.01 | 0.03 | 0.004 | 0.02 | 0.05* | 0.03 |
| Digit symbol$_{\gamma 012}$ | 0.08* | 0.03 | 0.09*** | 0.03 | 0.09*** | 0.03 |
| **Osmolarity × Time$_{\gamma 25}$** | **–0.07** | **0.04** | **0.01** | **0.01** | **0.03** | **0.02** |
| **Osmolarity$^2$ × Time$_{\gamma 26}$** | — | — | — | — | **–0.03*** | **0.01** |
| Morbidity × Time$_{\gamma 27}$ | 0.05 | 0.19 | 0.05 | 0.03 | −0.02 | 0.07 |
| Grip × Time$_{\gamma 28}$ | 0.04 | 0.04 | −0.01 | 0.01 | 0.02 | 0.02 |
| BMI × Time$_{\gamma 29}$ | 0.01 | 0.06 | −0.01 | 0.01 | −0.01 | 0.02 |
| Heart Rate × Time$_{\gamma 30}$ | 0.03 | 0.02 | −0.0004 | 0.004 | 0.02 | 0.01 |
| DBP × Time$_{\gamma 31}$ | −0.01 | 0.02 | −0.01 | 0.004 | −0.01 | 0.01 |
| Digit Symbol × Time$_{\gamma 32}$ | 0.03 | 0.02 | 0.001 | 0.01 | −0.01 | 0.01 |
| **Osmolarity × Age$_{\gamma 013}$** | — | — | — | — | **0.01** | **0.01** |
| **Osmolarity × BMI$_{\gamma 014}$** | **–0.05***** | **0.01** | **–0.02*** | **0.01** | **–0.002** | **0.01** |
| **Osmolarity × DBP$_{\gamma 015}$** | — | — | — | — | **0.01** | **0.01** |
| **Osmolarity$^2$ × Age$_{\gamma 016}$** | — | — | — | — | **0.003*** | **0.001** |
| **Osmolarity$^2$ × BMI$_{\gamma 017}$** | — | — | — | — | **0.002*** | **0.001** |
| **Osmolarity$^2$ × DBP$_{\gamma 018}$** | — | — | — | — | **–0.001*** | **0.0005** |
| Morbidity × Digit Symbol$_{\gamma 019}$ | — | — | — | — | 0.03** | 0.01 |
| BMI × Women$_{\gamma 020}$ | 0.40** | 0.15 | 0.26* | 0.12 | 0.37** | 0.12 |
| Heart Rate × Women$_{\gamma 021}$ | — | — | 0.09* | 0.04 | — | — |
| Random effects estimates | | | | | | |
| Variance intercept | 72.94*** | 6.20 | 46.82*** | 2.51 | 43.97*** | 2.65 |
| Variance time | 1.01 | 2.15 | 0.37*** | 0.09 | 3.34*** | 0.45 |
| Covariance intercept, time | 2.88 | 2.75 | 0.21 | 0.33 | −3.18*** | 0.72 |
| Residual variance | 18.34** | 6.21 | 43.99*** | 1.18 | 42.57*** | 1.82 |

*Note*. Unstandardized estimates presented. $N$ = 1,066 who provided 1,260 observations (Satisfaction with Life Scale; Diener scale), and $N$ = 1067 who provided 4,733 (life satisfaction, single item), and 3,115 observations (well-being, morale), respectively. Scores $T$ standardized. Age centered at 70 years. BMI = body mass index; DBP = diastolic blood pressure; Grip = grip strength. Model parameters for osmolarity as our focus variable highlighted in bold. Dashes indicate that the parameter was not significant and was not included in the model.
* $p < .05$. ** $p < .01$. *** $p < .001$.

Additionally, in light of our findings showing significant associations between dehydration and longitudinal decline in cognitive functioning and well-being, it is possible that the effective management of dehydration and dehydration-related decrements could have beneficial effects on older adults' health, cognition, and overall quality of life.

## Limitations

We note several limitations of our study. First, our study design did not allow us to track changes in dehydration to examine the reverse ordering of how lowered cognition or well-being precede dehydration (e.g., people forgetting to drink). It would also be intriguing to investigate how dysregulations in biological mechanisms that contribute to higher dehydration in aging (e.g., biomolecular systems that signal thirst) might be uniquely associated with cognition and well-being (e.g., free-radical-induced energetic and neural decline in senescence (FRIENDS) model: Raz & Daugherty, 2018). Similarly, in-depth investigations into the pathways through which dehydration is posited to influence cognition and well-being could be highly advantageous in pinpointing the mechanisms that underlie dehydration-related decrements in cog-

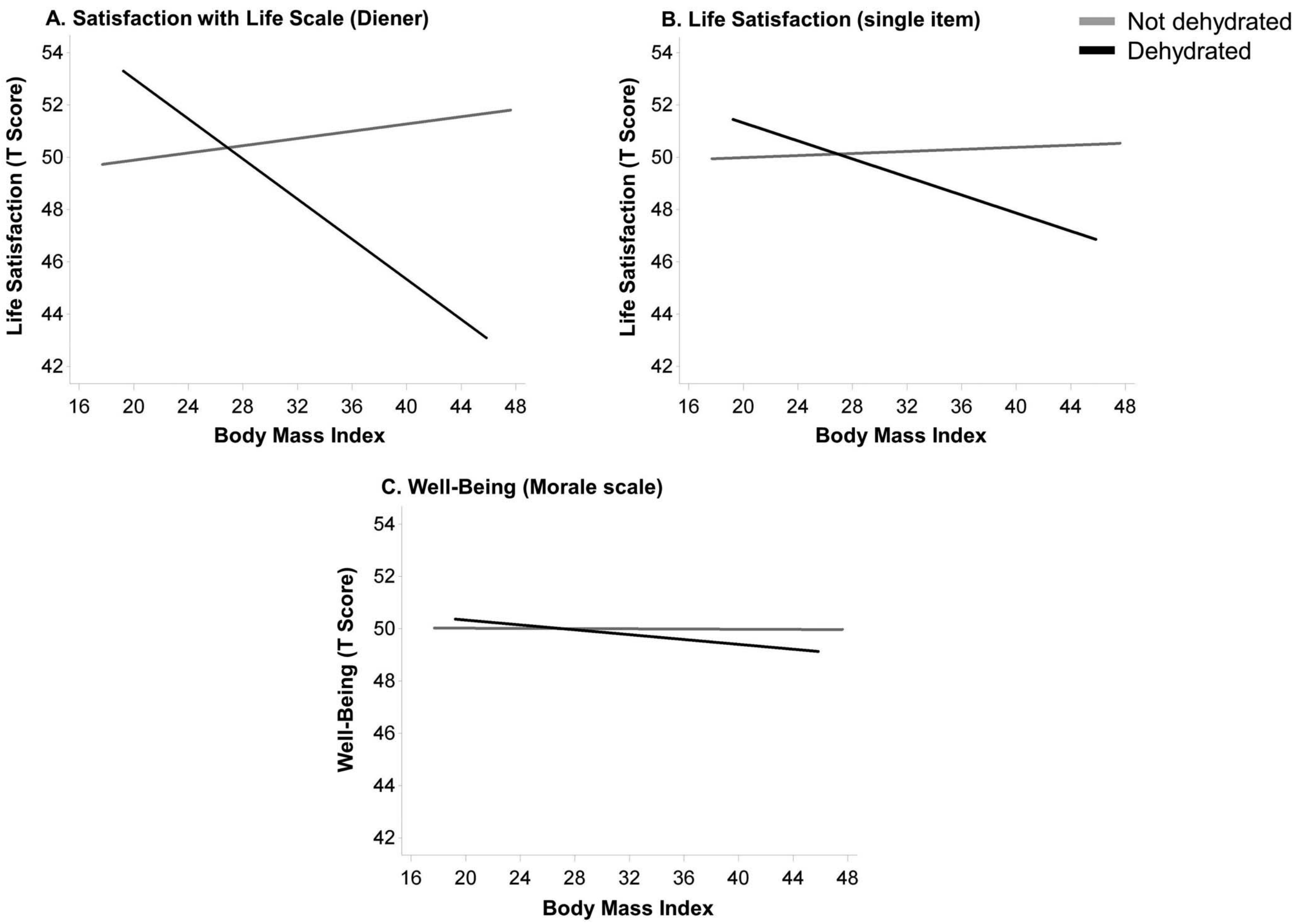


*Figure 2.* Illustrating interaction effects between osmolarity (exemplified as differences in hydration status between not dehydrated vs. dehydrated older adults) and physical health (body mass index [BMI]) on levels of (A) Satisfaction with Life (Diener scale), (B) life satisfaction (single item), and (C) well-being (Morale Scale). Higher BMI is associated with lower levels of life satisfaction among older adults who were dehydrated, but not among those who had normal levels of hydration. No associations were found for the well-being (morale) scale.

nitive functioning and well-being (e.g., hydromolecular hypothesis; Sfera et al., 2016).

Importantly, because only one dehydration assessment time point was available, we do not have information on how hydration levels fluctuate throughout the day and the within-person changes in hydration status over time. Although the literature suggests that older adults' hydration status tends to remain stable over time (e.g., Weinberg et al., 1994) and that being dehydrated on one occasion can lead to long-term negative consequences for health (Frangeskou et al., 2015), it is important for future studies to assess hydration indices at multiple time points to get a clearer picture of how changes in life circumstances across late adulthood contribute to hydration status. Having multiple assessments of hydration status would allow researchers to further explore the acute versus chronic nature of fluid imbalances in old age and how the amount of fluctuation in hydration levels could be associated with levels of and changes in cognitive functioning and well-being. At the same time, it would also be important to assess how changes in eating habits, habitual fluid intake, and prescription of diuretic medications could contribute to the longitudinal trajectories of hydration status among older adults.

Additionally, although osmolarity is a highly accurate dehydration assessment tool with good diagnostic capacity in laboratory settings (Kavouras, 2002), research suggests that it should be used alongside other measures to ensure even higher accuracy (e.g., total body water; Armstrong, 2007). Studies have also suggested that low fluid intake and dehydration could be partially attributed to conditions such as noncontrolled diabetes (Stookey, Pieper, & Cohen, 2005). Rerunning our analyses after excluding participants with a history of diabetes did not substantially affect the results reported, with only exception being the Morale Scale where interactions of dehydration with other variables of interest disappeared. It should be noted that we assessed dehydration using an osmolarity equation that has good diagnostic capacity in older adults with and without diabetes, irrespective of hydration status (Siervo et al., 2014). In addition, because we controlled for morbidities in our analyses (including diabetes), we decided to not exclude participants with a history of diabetes. Nevertheless, future studies should further investigate the associations between diabetes and dehydration more closely.

For our outcomes, we used the digit symbol as a proxy for cognitive functioning in old age. Although this test has been found to be highly sensitive to age-related cognitive decline (Hoyer et al., 2004), it primarily measures perceptual speed. Future studies should explore further aspects of cognitive functioning that have also been shown to be sensitive to dehydration (e.g., attention; Suhr et al., 2004). This would provide additional insights into which aspects of cognitive functioning are most sensitive to dehydration (Armstrong et al., 2012; Wittbrodt & Millard-Stafford, 2018). For our well-being measures, different questionnaire administration methods have been used across different waves, including paper-and-pencil and online interface formats. Future studies should examine how different methodologies could affect completion rates and the quality of data obtained.

Finally, our sample consisted primarily of healthy older adults in their 60s and 70s, so our results may not generalize to less healthy older adults or those in very old age. Because we found dehydration to be particularly detrimental among those with higher BMI and DBP, we would expect dehydration to be associated with even larger cognitive and well-being decrements among less healthy older adults. Furthermore, it would be interesting to assess how dehydration might be associated with cognitive and well-being outcomes in middle-aged and young adults with suboptimal health profiles (e.g., metabolic syndrome). It is possible that vulnerable members of these age groups could be similarly sensitive to the negative consequences of dehydration. Additionally, because our sample consisted of older adults residing in the greater Berlin metropolitan area, we do not currently know whether our results would also generalize to older adults from geographical locations with different climate that could uniquely contribute to older adults' hydration status (e.g., countries in hotter climates).

## Conclusions

To our knowledge, our study is the first to examine the role of dehydration for longitudinal trajectories of cognitive functioning and well-being in old age. We found that dehydration is intertwined with longitudinal decrements in performance-based cognition and subjective ratings of well-being, as well as lower well-being among those with suboptimal physical health profiles. Considering that many countries over recent years have begun to experience severe heat waves over extended periods, it is possible that dehydration symptoms might worsen among older adults, leading to more pronounced decrements in quality of life and higher rates of hospitalization and mortality (Liss, Wu, Chui, & Naumova, 2017).

Early detection and interventions to manage dehydration could have important implications not only for older adults' health, but also for cognitive functioning, well-being, and overall quality of life. For example, it has been found that a combination of different approaches could be beneficial for combating dehydration in older adults, including easy access to and availability of different types of beverages, educating staff in residential care homes (Bunn, Jimoh, Wilsher, & Hooper, 2015), as well as using visual prompts such as high-contrast fluid containers (e.g., bright-colored cups; Dunne, Neargarder, Cipolloni, & Cronin-Golomb, 2004) and stickers or badges (e.g., "hydration stickers"; Bhatti, Ash, Gokani, & Singh, 2017) to motivate higher fluid intake among older adults.

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