

Tap water consumption amongst a cohort of UK twins is linked to perceptions of taste and health benefits

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Abstract:	Drinking sufficient clean water is essential for human health. Surveys that estimate daily water intake report striking differences between individuals and countries, but the factors determining such variance remain unclear. Here we report results from the first survey that, to our knowledge, evaluates concurrently how public perceptions (of taste and health benefits) and genetic factors influence tap water intake within the home. We administered the survey amongst nearly 3,000 adult twins living in the UK (members of the TwinsUK cohort). Respondents consumed 2.38 ± 1.16 L/day of water from their household taps through drinking and cooking. This rate is at the high end of published values, and implies that the majority of TwinsUK participants meet recommended international guidelines, although there was substantial heterogeneity. We also found that variability in tap water consumption is moderately explained by genetic factors (heritability (h^2) = 19 – 31%, $p < 0.0001$), but environmental and stochastic factors explain variance more. Indeed, respondents who like the taste of their tap water or consider it to have positive health benefits consume significantly more (~ 0.5 L/day; $p < 0.001$) than individuals with negative perceptions. Respondents who are female, in older age groups or report their ethnicity as white recorded highest intake, on average. Our study suggests there are opportunities to increase overall levels of consumption to benefit public health through improving tap water taste and increasing knowledge of health benefits. Further studies could investigate whether differences in tap water consumption are causally associated with health differences between groups.
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Competing Interests On behalf of all authors, disclose any competing interests that could be perceived to bias this work. This statement will be typeset if the manuscript is accepted for publication. Please review the instructions link below and PLOS Water's competing interests policy to determine what information must be disclosed at submission.	The authors have declared that no competing interests exist.
Data Availability Before publication, Authors are required to make fully available and without restriction all data underlying their findings. Please see our PLOS Data Policy page for detailed information on this policy. A Data Availability Statement, detailing where the data can be accessed, is required at first submission. Insert your Data Availability Statement in the box below. Please see the data reporting section of our submission guidelines for instructions on what you need to include in your Data	Data and software availability Our study makes use of personal health behaviour data and demographic characteristics for individuals. Therefore, under UK data governance laws and the data governance protocols by which ethical approval for this study was granted, our questionnaire and demographic data is only available following reasonable request to the TwinsUK Data Access Committee. Information on data access and how to apply is available at https://twinsuk.ac.uk/resources-for-researchers/data-samples/. All analytical R scripts used for this analysis can be found via our GitHub repository https://github.com/RuthBowyer/TwinsUKTapWaterConsumption commit reference 11e9a19 at time of submission.

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1 Tap water consumption amongst a cohort of UK twins is linked to perceptions of taste
2 and health benefits

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Abstract

Drinking sufficient clean water is essential for human health. Surveys that estimate daily water intake report striking differences between individuals and countries, but the factors determining such variance remain unclear. Here we report results from the first survey that, to our knowledge, evaluates concurrently how public perceptions (of taste and health benefits) and genetic factors influence tap water intake within the home. We administered the survey amongst nearly 3,000 adult twins living in the UK (members of the TwinsUK cohort). Respondents consumed 2.38 ± 1.16 L/day of water from their household taps through drinking and cooking. This rate is at the high end of published values, and implies that the majority of TwinsUK participants meet recommended international guidelines, although there was substantial heterogeneity. We also found that variability in tap water consumption is moderately explained by genetic factors (heritability (h^2) = 19 – 31%, $p < 0.0001$), but environmental and stochastic factors explain variance more. Indeed, respondents who like the taste of their tap water or consider it to have positive health benefits consume significantly more (~ 0.5 L/day; $p < 0.001$) than individuals with negative perceptions. Respondents who are female, in older age groups or report their ethnicity as white recorded highest intake, on average. Our study suggests there are opportunities to increase overall levels of consumption to benefit public health through improving tap water taste and increasing knowledge of health benefits. Further studies could investigate whether differences in tap water consumption are causally associated with health differences between groups.

1 Introduction

Access to clean drinking water is important for hydration, food preparation and cleaning, and as a source of soluble minerals essential for human health. For example, drinking water provides up to 20% of required dietary intake of calcium (Ca) and magnesium (Mg) [1]. Many studies have sought to identify impacts of drinking water composition on human health outcomes [2–5]. These produce inconsistent results. A systematic review with meta-analysis by Gianfredi et al. [6], for example, found that water hardness could be protective against cardiovascular disease, but noted strong spatial heterogeneity effects. The size of the study regions appears to influence whether or not a significant effect is found, as do differences in study design [7]. Several systematic reviews of nitrate and nitrite concentrations in drinking water have identified evidence of an association to stomach and colorectal cancers [8–10], but links to other forms of cancers are inconclusive.

One likely confounder of water-health research is that the volume of water consumed by different individuals varies widely. Daily water intake surveys have reported values ranging from just 550 mL in Hungary [11] up to 3600 mL in the USA [12]. This is reflected in dietary guidance. The European Food Safety Authority recommended 2000 mL for women (more for pregnant or lactating women) and 2500 mL for men [13]. The USA National Institute of Medicine recommended higher amounts: 2700 mL and 3700 mL, respectively [14]. Total water intake refers to consumption from plain water (tap or bottle), water-based beverages and cooked food. These are reported as recommended minimums because an individual's personal requirement will vary widely [15], being dependent on caloric consumption, kidney function, rates of excretion as well as levels of physical activity and environmental conditions, especially temperature and humidity.

No firm explanation for such variance in tap water consumption has been identified. Some studies report notable differences in daily intake between sexes and age groups [12,16], but others found no significant difference [17]. Sociocultural factors, such as common foodstuffs and cooking practices, have also been proposed to influence consumption. Tani et al. [18] concluded that high consumption levels of water-rich rice means Japanese adults obtain half of their daily water intake from food, compared to 30% or less in Europe [19]. A 7-day survey of 16,000 adults from 13 countries found that the source of daily fluid intake – natural water, hot beverages, sugary drinks – varies substantially between sub-continental regions [19]. This could relate to heat and humidity levels [18].

Surprisingly few water intake surveys concurrently explore individuals' perceptions of tap water and how much those same individuals consume. To what extent consumption is influenced by public health recommendations or wider sociocultural norms therefore remains unclear, but may go some way in explaining reported differences in daily consumption between countries [20]. Dedicated investigation is evidently merited. Furthermore, research into the behaviours and perceptions that dictate beverage choices tend to focus on drink type – for example, choosing a soft drink over tap water – rather than the amount that is consumed [21–23] or measures of water quality [24]. Another common limitation amongst published water intake surveys is the under-representation of older adults. They tend to spend the most time inside their homes, are more susceptible to dehydration and more commonly experience chronic conditions linked to nutrient intake, such as sarcopenia, of which water consumption for both hydration and dissolved nutrients are a crucial element [25]. The UK National Diet & Nutrition Survey focused on adults aged 19 – 64 years [26], for example, whilst the average age for respondents of the Oxford WebQ

Questionnaire is 43. This could be because it uses a streamlined web-only interface, which may limit engagement from older adults.

The genetic heritability of water intake also remains understudied by comparison with the much larger literature on coffee, tea and alcohol consumption [27]. A recent food frequency questionnaire within TwinsUK ($n = 1858$) calculated the heritability to be 37% for the cumulative intake of water from all dietary sources [28]. de Castro [29] reported a higher heritability estimate for drinking water (43%) from a much smaller participant pool (<200 twin pairs). Taylor et al. [30] identified a negative association between the genetic risk score of coffee relative to water consumption. Their findings are based on a simple tally of glasses of water drunk per day, thereby assuming each glass had uniform volume.

Here, we report results from the first water intake questionnaire that, to our knowledge, tallies tap water consumption within the home and respondents' perceptions of taste and health benefits for a large cohort of twins, thereby enabling heritability to be assessed. The recall questionnaire was administered amongst nearly 3,000 adult twins from the TwinsUK registry, a deeply phenotyped population cohort in the UK. This study design enables us to address several key gaps in the drinking water literature. First, our questionnaire collated respondents' perceptions of tap water characteristics that may modulate consumption patterns, including its taste, colour and health benefits. When combined with existing sociodemographic data on TwinsUK participants, we can explore the extent to which personal choices or lived circumstances relate to tap water intake. Working with twins also means we can perform a dedicated assessment of the role of genetic variation (heritability) within tap water consumption. Heritability analysis is a common method

within twin research to evaluate the relative importance of environmental and genetic influences in explaining variation in a given trait – in this case, the amount of water consumed by an individual. Third, the mean age of participants in the TwinsUK cohort is 59 [31], so our survey should provide important data on consumption patterns amongst older adults. A fourth strength of our approach is the use of multiple sampling volumes to maximise the granularity – and, in principle, the accuracy – of intake estimates. We asked respondents to tally tap water consumption using four mug and glass sizes, assisted by pictorial guides, whereas previous studies often tally ‘glasses’ as a single measure.

An important feature of our study is that we intentionally surveyed only respondents’ consumption from taps within their own homes. This choice reflects a related research aim, which is to calculate individual solute exposure from drinking water using chemical composition data reported by household water suppliers. As a result, our calculations do not include bottled water nor water consumption from taps outside the house. This likely introduced bias based on time spent at home. Respondents who, for example, regularly travel to a workplace likely ingest a smaller proportion of their daily water intake within the home. Existing TwinsUK data on employment status was used to stratify by this measure.

2 Materials and Methods

2.1 Ethical approval and consent

This study was carried out under TwinsUK BioBank ethics, approved by North West – Liverpool Central Research Ethics Committee (REC reference 19/NW/0187), IRAS ID 258513. This approval supersedes earlier approvals granted to TwinsUK by the St Thomas’ Hospital Research

Ethics Committee, later London – Westminster Research Ethics Committee (REC reference EC04/015), which have now been subsumed within the TwinsUK BioBank.

2.2 The TwinsUK cohort

The Department of Twin Research and Genetic Epidemiology at St. Thomas' Hospital, King's College London (KCL), hosts TwinsUK, the UK's largest adult twin registry. The adult participants consist of 14,575 monozygotic (MZ) and dizygotic (DZ) twins aged between 18 to 100 years. Since 1992, active twins have participated in both questionnaire and clinical visits, where multiple samples and physical measures were obtained, resulting in extensive health and multiomics data [31]. The TwinsUK research team have extensive experience administering health- and nutrition-focused surveys to its cohort [32]. Our study is the first to directly explore water consumption patterns.

2.3 Drinking water questionnaire design and administration

Data were collected using an online questionnaire administered through REDCap (Research Electronic Data Capture) that asked respondents about their drinking water consumption vessels and volumes, their perceptions of the tap water quality in their own home (taste, visual appearance) as well as their views on the health benefits of drinking tap water. The recruitment period ran from 5 October – 24 October 2022. All participants were over the age of 18 and provided informed consent as members of the TwinsUK cohort register. Specific information on data handling was provided in written form on the questionnaire. Questionnaire design is adapted from the validated fluid diary of Johnson and colleagues [33,34]. Individual water consumption was quantified as follows: respondents were asked to reflect on the previous seven days and tally how many portions of water of pre-set volumes from their household tap they consumed for drinking and cooking in

a typical day (Table 1). Hot and cold drinks were tallied separately. A version of the questionnaire is available to download in Supporting Information. Perceptions on health, taste and visual appearance were surveyed using Likert-scale questions.

Table 1. Pre-set volumes for six drinking and cooking vessels used in the survey. Respondents were provided with illustrations to maximise reporting accuracy.

Drinking or cooking vessel	Volume (mL)
Cold drink (small glass)	200
Cold drink (large glass)	500
Hot drink (small mug)	250
Hot drink (large mug)	375
Small saucepan	1000
Large saucepan	2000

The questionnaire was sent to 4822 potential participants from the TwinsUK cohort. These were the subset for whom we had prior consent to contact for emailed questionnaires and lived in the UK. REDCap electronic data capture tools hosted at King's College London were used to develop, administer and extract data from the online questionnaires [35,36]. We linked each respondent's completed survey to their demographic and socioeconomic characteristics held within the TwinsUK repository.

2.4 Statistical analysis

Data analysis was performed in RStudio version 2023.12.1 and R 4.3.2. Graphs were generated using *ggplot2* [37] and *ggpubr* [38]. Daily water intake data are reported as means in the text unless

otherwise stated. Consumption larger or smaller than three standard deviations from the mean were excluded on the basis of misapprehension of the question or inaccurate data entry by that respondent. Water consumption amounts were strongly non-normal (Shapiro-Wilk, $p < 0.0001$) so associations between water intake and demographic (age, sex, ethnicity) and socioeconomic (employment status, education, IMD) characteristics were assessed by Kruskal-Wallis and pairwise Wilcoxon signed-rank tests. We also applied paired Wilcoxon signed-rank tests to test for differences in consumption rate between twin pairs discordant by more than one category within the Likert-scale questions on perceptions of health and taste, to assess the extent these influenced consumption rates within-family.

To estimate heritability, we used the classical twin, or ‘ACE’, model via the ‘mets’ package v 1.3.3 [39]. The ACE model allows us to disaggregate the variance associated with the trait – tap water intake – into its estimated additive genetic (A), shared environmental (C) and unique environment/error (E) contributions. Outputted estimates of heritability range from 0 (no genetic influence) to 1 (the trait is wholly influenced by genetics). We fit a univariate model for our estimate of tap water consumption, as deciles, within three scenarios: 1) deciles of our whole population; 2) stratified by employment status; and 3) as a multivariate model, stratified by employment status, and with age group as a covariate. We fit “ACE”, “AE”, “CE”, “E” and report the results for the model with the lowest Akaike Information Criterion (AIC) in each instance. We used these stratification scenarios to accommodate differences in how much time respondents are likely to spend within and outside their home, which is the focal location of our study. Questionnaire respondents for whom TwinsUK holds up-to-date data on employment status ($n = 2662$) and are classified as Retired, Long-term Sick, Unemployed or Homemaker were grouped

into one strata ($n = 1372$). All others were classified within the ‘employed’ strata. We further assessed differences in tap water consumption by age group within-strata via pairwise comparisons using Wilcoxon rank sum test. All analytical R scripts used for this analysis can be found via our GitHub repository <https://github.com/RuthBowyer/TwinsUKTapWaterConsumption> commit reference 11e9a19 at time of submission (and see Data Availability Statement).

3 Results, or a descriptive heading about the results

3.1 The twins survey respondents

The questionnaire was completed by 2881 twins. The high response rate of 59% is typical of health questionnaires administered amongst the research-engaged TwinsUK cohort. The median age of respondents was 65 years (**Table 2**), so our dataset is over-represented by older adults. This is in keeping with the TwinsUK cohort demographic and could yield important insight into consumption patterns amongst a group that is historically less well studied by water intake surveys. To account for the predominance of older adults, we stratified by age in three ways. First, by common groupings that reflect general healthiness with ageing: <45, 45-65 and 65+ years. Second, by terciles, which split the dataset into <57, 57-70 and 70+ years. Last, we binarised respondents by time likely spent inside the home (see 2.4 Statistical analysis). Most respondents were female (89%) and 92% identified their ethnicity as white.

3.2 Consumption patterns and amount

We find marked differences in how many drinks respondents consume from their household tap during a typical day (**Figure 1**). Thirteen twins reported drinking 14 or more glasses of tap water

per day. Nearly 40% of respondents drink three or four hot drinks (mugs) containing tap water during a typical day. Whilst the mode for each individual classification of glass or mug is “Rarely or never”, only a small number of respondents ($n = 83$) reported consuming zero drinks comprising tap water.

Total daily intake of household tap water as drinks has a mean ($\pm$ standard deviation) of 2.29 ± 1.15 L/day but varies substantially amongst respondents (**Figure 2; Table 3**). 329 respondents (11%) report drinking less than 1 litre per day from their household tap. On average, respondents consume 55% in the form of hot drinks, with females consuming slightly (106 mL/day) more. Respondents in the Over 65 group consume nearly twice as much water from hot drinks (1.39 L/day) as Under 45s (0.79 L/day).

Table 2. Summary description of the survey respondents. Rows that do not add up to the total number of survey respondents reflect instances where a particular item of personal data is not held by TwinsUK.

Characteristic	Class	Value
Respondents (after exclusions)	<i>n</i>	2710
Age (years)	Median	65
	Range	18 - 92
Sex	F	2415
	M	295
Zygosity	Monozygotic	1706
	Dizygotic	988

Ethnicity	White	2503
	Racially minoritised in the UK	69
Education	Undergraduate degree or higher (<i>n</i>)	1413
Index of Multiple Deprivation	Median	7
	Range	1 – 10
Employment status	Not retired	825
	Retired, long-term sick, unemployed or opt to care for home or family	853

FIGURE 1 HERE

Fig 1. Number of drinks comprising tap water consumed daily. Small and large glasses are cold drinks; mugs are hot drinks. Vessel volumes were taken from existing water questionnaire and food diary methodologies and checked by measuring glasses and mugs in the authors' homes.

Table 3. Summary statistics for daily tap water consumption (in L/day) inside the home.

	All drinks	Cold drinks	Hot drinks	Cooking	Total
Mean ($\pm$ SD)	2.29 $\pm$ 1.15	1.03 $\pm$ 0.91	1.26 $\pm$ 0.84	0.10 $\pm$ 0.09	2.38 $\pm$ 1.16
Median	2.25	0.90	1.25	0.1	2.35
90 th Percentile	3.75	2.30	2.38	0.2	3.83

We find that females drink significantly more tap water (2.33 L/day) than males (2.12 L/day) within their homes (**Figure 2A**; Wilcoxon test, $p < 0.01$). When grouped by age (pre-defined groups and terciles; see Methods), younger respondents drink significantly less than older adults in the home ($p < 0.01$), with no significant differences between the middle and oldest groups (Supporting Information). Following stratification by employment status (see Methods), respondents who likely spend more time inside the home report higher rates of consumption ($p < 0.001$), although differences between age groups within each strata became non-significant ($p > 0.1$; Supporting Information). Respondents who report their ethnicity as white tend to drink more tap water (**Figure 2B**). We found a significant difference in daily drinking intake between respondents who identify as white and those from ethnic groups who are racially minoritised in the UK, although with weak effect size owing to sample sizes ($p < 0.05$, $|r| = 0.1$). Differences across all ethnic groups (Asian or Asian-British, Black or Black-British, Mixed Ethnic Group or Other Ethnic Group, White) are not significant. Neither area-level deprivation (Index of Multiple Deprivation) nor university degree status is a significant determinant of water consumption ($p > 0.1$). Finally, we calculate average total daily water consumption from drinking and cooking from household taps to be 2.38 ± 1.16 L/day (Supporting Information).

FIGURE 2 HERE

Fig 2. A) Distribution of daily tap water consumption through drinking for females and males. Dashed lines show the US National Academy recommended daily water intake. Short orange and green lines show median consumption for males (2.20 L/day) and females (2.28 L/day). **B)** Daily tap water consumption through drinking for respondents subdivided by reported ethnicity. Short

range and green lines show median consumption for white (2.28 L/day) and racially minoritised respondents (1.88 L/day).

3.3 Perceptions of UK tap water

There is evidence in our dataset that perceptions around tap water quality and its associated health benefits influence daily consumption (**Figure 3**). Respondents who Agreed and Strongly Agreed that they like the taste of their tap water consume nearly half a litre more water per day, on average, than respondents who had a less favourable view (**Figure 3A**). A Kruskal-Wallis tests confirms significance differences in daily consumption ($H(4) = 39.71$, $p < 0.001$). This pattern generally holds true across age groups and amongst female respondents but is less clear – and indeed veers towards the opposite trend – amongst male respondents (Supporting Information). This result is likely influenced by the under-representation of males amongst the survey respondents (**Table 2**). Additionally, of the respondents who reporting consuming zero drinks from their household tap ($n = 83$), 47% reported not liking the taste of the water in their home compared to only 14% in the wider group of respondents. Almost a quarter of respondents (22%; 640 of 2881) use some form of water filter (Supporting Information). The questionnaire did not ask respondents to state why they use a water filter, but associations with health, taste and visual appearance are reasonable inferences. Interestingly, when respondents prefer to use filtered water at home varies. More report always using a filter when making cold (13%) and hot (12%) drinks compared to cooking (5%). Half as many respondents never use a filter for cold (2.5%) compared to hot (5.2%) drinks.

We also find that respondents who consider drinking tap water in the UK to be good for their health consume significantly more in the home (**Figure 3B**; Kruskal-Wallis, $H(4) = 44.35$, $p < 0.001$). Strong agreement leads respondents to consume over half a litre more per day (2.52 L/day),

on average, than those who strongly disagree (1.92 L/day). This pattern is consistent across age and sex (Supporting Information).

21% of respondents felt their water is unusual in appearance at least once or twice a year (**Table 4**). More than 13% of all respondents consider their water to be cloudy (**Table 5**). Other forms of discolouration include 2% reporting “visible bits in their water” and nearly 5% considering their water to be brown, orange or yellow in colour. Drinking and total consumption is lowest for respondents who consider their water to be unusual in appearance at least weekly (**Figure 4**), although there is no significant difference (Kruskal-Wallis, $H(4) = 7.26$, $p > 0.1$).

FIGURE 3 HERE

Fig 3. A) Daily drinking water consumption (L/day) by responses to the question “To what extent do you agree with the following statement: I like the taste of the unfiltered tap water in my home”. **B)** Daily drinking water consumption (L/day) by responses to the questions “To what extent do you agree with the following statement: “Drinking tap water in the UK is good for my health”. Significance stars for pairwise Wilcoxon rank sum tests: ** $p \leq 0.01$; *** $p \leq 0.001$; **** $p \leq 0.0001$. Brackets for non-significant pairs are not plotted.

Table 4. Responses to the question “In the last year, how often have you considered the visual appearance of your unfiltered tap water in your home to be unusual?”

How often	Number of responses	Percentage (%)
Never / it always looks the same	2188	77.5
Once or twice a year	455	16.4
A few times a year	142	5.0
Monthly	20	0.7
Weekly	13	0.5

Table 5. Respondents were asked which of the following best describe the visual appearance of their unfiltered tap water when they considered to be unusual. Values were omitted where response rates were below ten.

Visual characteristic of the way	Number of responses	Percentage (%)
Straw-coloured or yellow	51	1.8
Brown or orange	90	3.1
Blue or green	---	---
Black, brown or tea-coloured	12	0.4
Cloudy, grey or white	379	13.2
Contains stains, slime or mould	---	---
There are visible bits in the water	56	1.9
Unsure	75	2.6

FIGURE 4 HERE

Fig 4. Responses to the question “In the last year, how often did you consider your tap water to be unusual in visual appearance” compared to A) drinking consumption and B) total (drinking + cooking) consumption. The only significant ($p < 0.05$) pairwise relationship is “Once or twice a year” versus “Never / it always like the same”.

3.4 Heritability of tap water consumption and discordant twin analysis

Of our respondents, 1670 individuals (835 pairs; 68.1% mono-zygotic) were complete twin pairs – i.e., both co-twins returned the questionnaire. TwinsUK holds data on the 2021 employment status for a subset of 553 pairs (1106 individuals). These pairs were used in the stratified model scenarios (**Table 6**). The AE model was the best fitting (lowest AIC) in all scenarios, with both the additive genetic (A) and unique environment (E) significantly contributing to the variance of tap water consumption (**Table 6**). Heritability (h^2) ranged between 19 and 31% and was higher in individuals who reported themselves to be employed in 2021 ($h^2 = 30$ -31%). Our discordant twin analysis did not find a significant difference (Wilcoxon paired tests, $p = 0.2$) in the influence of health perceptions on water intake. There were 107 and 178 pairs (of 840) discordant for questions regarding health perceptions and taste of tap water, respectively.

Table 6. Results of twin model analysis of the heritability of daily tap water consumption. All estimates were significant at $p < 0.0001$ (***). Age was not significant when included in stratified models.

Modelling scenario	Model of best fit	Variance decomposition		
	(AIC)	Estimate	2.5%	97.5%

1. All available twin pairs	AE (7632.994)	A	0.29***	0.21	0.37
(n = 805 pairs, 65% MZ)		E	0.71***	0.63	0.79
2. Stratified by employment status					
Retired, sick, AE (3004.46)		A	0.19***	0.05	0.33
unemployed or opt to care for home or family		E	0.80***	0.67	0.94
(n = 306 pairs, 62.4% MZ)					
Employed AE (2455.804)					
(n = 247 pairs, 78.5% MZ)		A	0.31***	0.18	0.43
		E	0.69***	0.57	0.82
3. Stratified by employment status, adjusted for age group					
Retired, sick, AE (3006.623)		A	0.19***	0.05	0.33
unemployed or opt to care for home or family		E	0.8***	0.67	0.94
		Age group	NS		

Employed	AE (2459.041)	A	0.30***	0.17	0.43
		E	0.70***	0.57	0.82
		Age			
			NS		
		group			

4 Discussion

4.1 Comparison of reported daily intake

Our central estimate of daily water intake from drinking (2.29 ± 1.15 L/day) and drinking plus cooking (2.38 ± 1.16 L/day) inside UK homes fits within values reported for other European countries in the order of 2.0 – 2.5 L/day [11]. Many datasets combine water with other beverages including milk, juice, soft drinks or alcohol, however. Our estimate therefore seems at the high end of values reported purely for tap water (Table 7). Previous data for the UK were considerably lower, around 1.1 – 1.2 L/day [20,40]. This could mean our respondents provided overestimates of daily consumption. Doubly-labelled studies, on the other hand, suggest consumption tends to be underestimated by 10 – 25% in self-reported dietary surveys [20,41]. Indeed, our use of multiple cup and mug volumes rather than tallies of singular water-based beverages, plus the provision of visual representations of different drinking vessels, should improve accuracy. Levallois et al. [17] recommended pairing a 24-hour recall survey with a 24-hour diary, but we are most interested in longer-term habits in perceptions. Published studies do show striking variance between countries. Some report very low total fluid intake, including 559 and 974 mL/day in Hungary and Italy [11]. Rosinger & Herrick [12] report much higher values for men in the US aged 20-59 (3.62 L/day). At the same time, an earlier iteration of the same national survey reported 1138 mL/day, of which

just 644 mL/day was from the tap. Even single studies that deployed a consistent survey instrument in multiple countries observed marked variation in consumption (e.g., [19]). The UK has seen a steady rise in water intake [20], and increases in consumption associated with our findings would continue this trend. Our ACE heritability estimates for tap water consumption range between 19 and 31% (Table 6). These are slightly lower than the few published values for drinking water ($h^2 = 37 - 43\%$; [28,29]). We note that these studies measured UK and US residents; obtaining demographically diverse estimates would be valuable and may help further explain observed geographical differences.

Our intake values mean a high percentage of adults in the UK consume at least their recommended daily water intake from tap water in their home. Specifically, 72% of female respondents meet the US National Academy advisory value of 2700 mL/day or 86% based on the EU Food Safety Authority guideline of 2000 mL/day. This compares to 41% (US National Academy) or 71% (EU Food Safety Authority) amongst men. It will be important to verify our findings amongst other demographics because a higher percentage of our respondents are female, white and older in age compared to the UK population. Importantly, these singular thresholds do not provide a full picture as the body's daily water requirements varies between individuals and indeed for the same individual at different times depending on body characteristics, exercise patterns or dietary intake.

Our finding that hot beverages constitute 55% of daily water intake in the home matches earlier surveys in the UK [19,20,26]. Of the 13 countries surveyed by Guelinckx et al. [19], four (Argentina, Japan, Poland, UK) consume more water from hot beverages compared to cold. There are likely to be various factors at play. Cultural habits are probably important but difficult to parse, and our questionnaire did not set out to investigate their role. There is mixed evidence that seasonal temperatures and humidity have an influence on the consumption of hot relative to cold drinks

[18,42]. Our estimate of 95 mL absorbed from cooking sits close to values from Canada (65 mL; [17]) and lower than Japan cooking (235 mL; [18]). This could reflect the high rice consumption in Japanese diets, but there are few surveys from countries with similar diets to conduct a broader comparison.

4.2 Demographic differences in intake

Female respondents in our survey consumed significantly more tap water in their homes than males (Figures 2, 4). The wider literature is mixed. Gibson et al. [20] found the same in the UK, as did Guelinckx et al. [19] for some other European countries. Conversely, Rosinger & Herrick [12] reported men consuming nearly 0.75 L/day more than women in the US and Manz et al. [43] recorded intake for men in Germany to be ~450 mL/day higher based on a large survey of 24,632 people from 11,141 households. Elmadfa & Meyer [11] concluded men consume more, on average, than women across Europe. This could reflect physiological differences between males and females such as hormonal effects on sweating rates [43], stronger social barriers to water consumption amongst men [44] or females holding more favourable views on the health benefits of tap water [22]. Our study considers only tap water consumption within the home. So, differences in the amount of time men spend outside compared to women could be another explanation.

Consumption across age groups is somewhat more consistent than between sexes. We find highest consumption amongst those aged 45-65 (Supplementary Information 2) and this pattern is repeated in studies from the US [12], Germany [43] and Japan [18]. Conversely, Drewnowski et al. [45] found significantly lower consumption with age from an earlier NHANES study. In our study, it seems logical that older adults drink more inside the home, which is where they spend upwards of

90% of their time [46]. We recorded the highest water consumption amongst respondents who identified their ethnicity as white, which is in accord with data from the US [12,47].

Table 7. Daily tap water consumption in different countries from previous surveys. Only values for tap water are reported wherever possible (see footnotes). Considerable variance is evident between countries and within countries across different studies. There is also a paucity of data from lower income countries. To simplify the formatting, we stratified the table by sex (where reported) rather than age because many different age ranges are used across the publications.

	Total (mL)	<i>N</i>	Sex	Methodology	Reference
UK ¹	2200		M		Our data
	2275		F		
UK ²	1985	NR	M	National diet survey	Gibson et al. (2012)
	1631	NR	F		
USA ³	1313	9666		24-hour recall and phone follow-up	Rosinger et al. (2018)
USA ²	3848	NR	M	24-hour recall	Manz & Wentz (2005)
	3101	NR	F		
France ¹	831	831 ⁶		7-day diary and illustrations	Bellisle et al. (2010)
	798	443 ⁷			
Germany	1526 ± 620	639	M	7-day diary and	
²	1214 ± 484	889	F	interview	

Germany	2259	507	M	National diet	Manz & Wentz (2005)
⁴	1875	682	F	survey	
Canada ¹	1436	125		24-hour recall and 1-day diary	Levallois et al. (1998)
Canada ¹	1321	NR	M	National diet	
	1389	NR	F	survey	
Korea ¹	1657	545	M	24-hour recall	Ji et al. (2010)
	1330	547	F		
Korea ⁵	530	545	M	24-hour recall	Ji et al. (2010)
	425	547	F		
Japan ¹	560	121	M	4-day diary	Tani et al. (2015)
	781	121	F		
Japan ⁵	251	121	M	4-day diary	Tani et al. (2015)
	220	121	F		
13	460 (Poland)	16,27		24-hour diary for	Guelinckx et al. (2015)
countries	1780	6		7 days including	
	(Indonesia)			illustrations	
12	1014 (Italy)		M		
Europea	941 (Italy)		F		
n	2659		M	Various	
countries	(Germany)		F		
²	2366				
	(Germany)				

¹Tap water including hot beverages ²All beverages ³Tap water only ⁴All fluids plus food moisture
⁵Water added during cooking NR = Not reported ⁶Sex not reported. This value is therefore for 20-
54 age group. ⁷Sex not reported. This value is therefore for ≥55 age group.

4.3 Perceptions and heritability as drivers of individual intake

Our finding that daily water intake is significantly influenced by perceptions of tap water quality and taste is an important contribution to the literature. Most research into behaviours around drinking water has emerged from the US [48], often from the perspective of associations between perceptions of tap water safety and sociodemographics [22,23,49–51]. Differences in consumption between white respondents and those from racial minorities in the UK could reflect levels of (mis)trust of tap water [22,52], a legacy of long-standing inequalities in access to clean water [53]. We also find the strongest effect amongst Under 45s, which concurs with some studies showing lower consumption of tap water amongst younger age groups [17,18] whilst others found the opposite trend [16,43]. Interestingly, this age effect is not significant when we stratify by employment status. This may simply reflect our questionnaire focusing on within-home consumption and the working-age people being more likely to spend less time within the home. Psychology research suggests drinking water is strongly influenced by situational habits and personal views of oneself [54]. Merging data on water consumption patterns with perceptions and behaviours around drinking across sociodemographic groups is likely to be a fruitful area of future research.

Our data suggests that having a favourable view of the taste or health benefits of tap water is associated with consuming around half a litre more per day (Figure 3). This could explain an

important portion of the variance observed between countries and published surveys. Those who dislike tap water may substitute this for bottled water, but this is rarely a like-for-like. Although taste testers could not differentiate tap and bottled water [55], perception of flavour has been shown to be a key influence on an individual's judgement of drinking water quality [21,23]. Colloquially, people often comment negatively on the taste of their tap water when moving to a new place. How this influences drinking patterns, and the resulting implications for nutrient intake and personal health, are understudied. There are evident opportunities to deploy longitudinal analyses to explore these effects.

Our heritability estimates, when considering the result of the whole cohort, is suggestive of a moderate heritability of tap water consumption. This mirrors similar studies undertaken within the TwinsUK cohort on the heritability of different aspects of dietary intake [28]. As with many behavioural traits, a small but significant genetic influence would be expected [56]. It is reassuring that we find such an effect within our measure of tap water consumption. Our findings also point towards environmental factors have a larger influence on the trait, in part reflecting the spatial differences attributable to twin discordance. Interestingly, our stratified results suggested that the trait was less heritable in retired individuals, which could reflect the increasing heterogeneity of environmental factors influencing water consumption.

4.4 Limitations

There are a number of limitations to our study. We surveyed only water intake that came from taps within the respondent's home so our approach intentionally overlooks, for example, milk, soft drinks and alcoholic beverages. Similarly, we considered intake from food only where tap water would have been manually added, such as pasta, rice or stews. Humans consume many foodstuffs

that naturally contain moisture such as fruits and vegetables. Secondly, our respondents were predominantly older adults, female and white, so our findings of high daily water intake may not be generalisable to the UK population. Whilst the focus on consumption within the home does skew the overall picture of total water intake, it does mean we have likely gained a more representative picture of consumption amongst those groups who spend the most time at home. The TwinsUK programme is actively seeking to diversify its cohort so re-running the survey in the future would be useful. We had to make assumptions about food portion size as a proportion of saucepan volume. Our rationale was that a portion of pasta is 75 – 100g, which is roughly 10% the size of a 1L saucepan. Whilst portion size may differ between respondents, we do not believe this will materially affect our results because between-respondents differences in intake from drinking are considerably larger than cooking in our dataset.

5 Conclusions

We have executed, to our knowledge, the first survey that quantifies daily tap water consumption in parallel with collating respondents' perceptions of the water they drink amongst a cohort of 3000 adult twins living in the UK. Our results reveal that holding a favourable view on the health benefits, taste and visual appearance of one's tap water is significantly associated with higher consumption (~ 0.5 L/day). Our respondents consume, on average, 2.38 ± 1.16 L/day per day from taps within their own households, with higher rates recorded by females, older adults and those who reported their ethnicity as white. The mean intake sits at the high end of published values, which likely reflects respondent demographics, frequent consumption of hot drinks and our survey method of tallying cups and mugs of multiple measurement volumes. Our higher values place 72-86% (females) and 41-71% (males) at or above international guidelines on daily water intake. A twin model analysis indicates that the trait of tap water consumption is moderately heritable ($h^2 =$

19 – 31%), meaning genetic factors have a notable influence but environmental or stochastic have greater effects. Older adults and those who report their ethnicity as white are over-represented amongst our respondents, so repeat surveys across the wider UK population and international twins cohorts would be useful. Our study demonstrates the importance of simultaneously measuring consumption and collating individuals' perceptions of drinking tap water. Similar studies are now needed to better understand consumption patterns in national and global populations and as a basis for developing policies to increase overall consumption to bring public health benefits.

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Supporting Information

The supporting information document contains the tap water questionnaire we administered that underpins the study. It also contains ten figures (S1 – S10) that provide useful contextual analysis to the main findings of the study.

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Figure 1

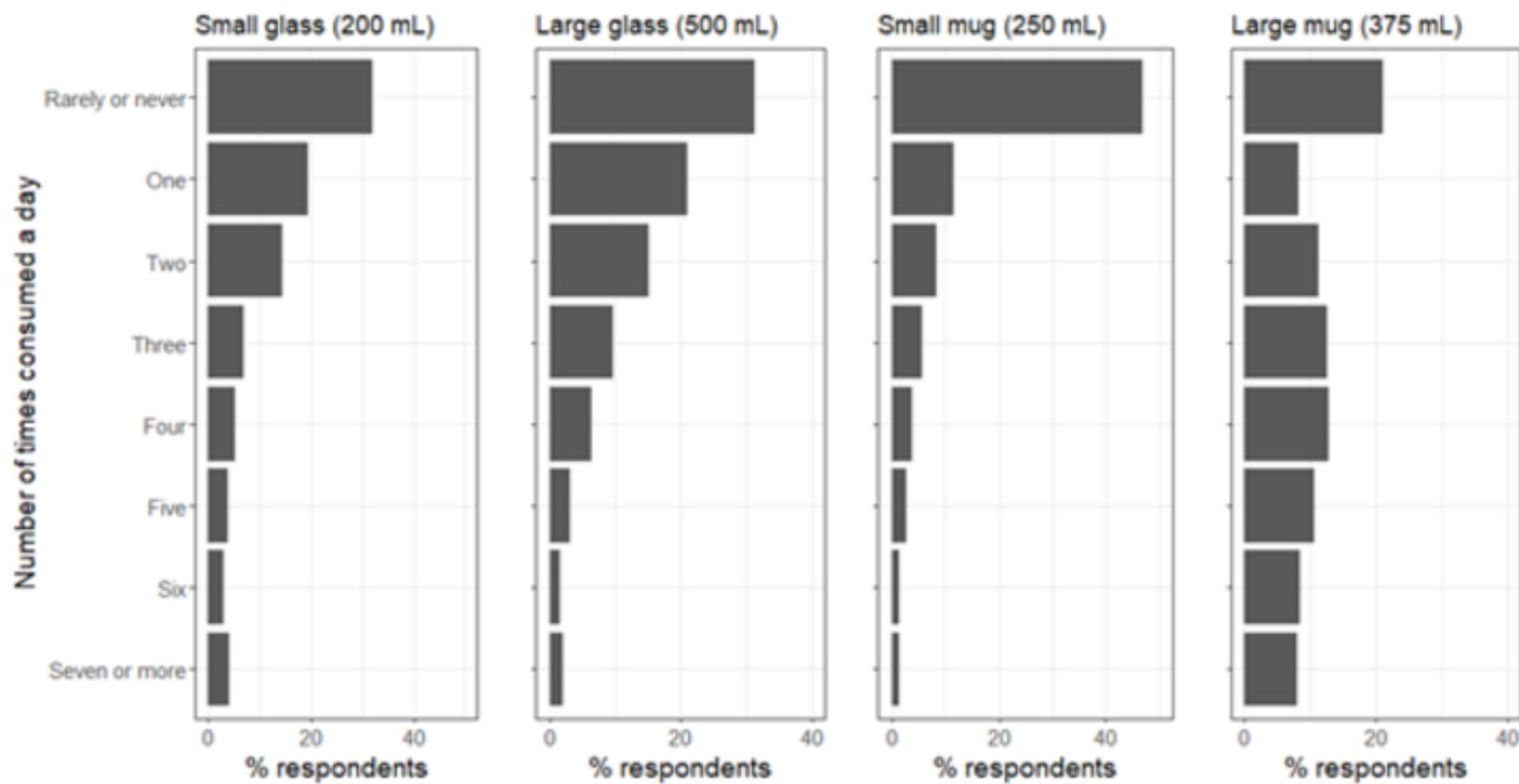


Figure 2

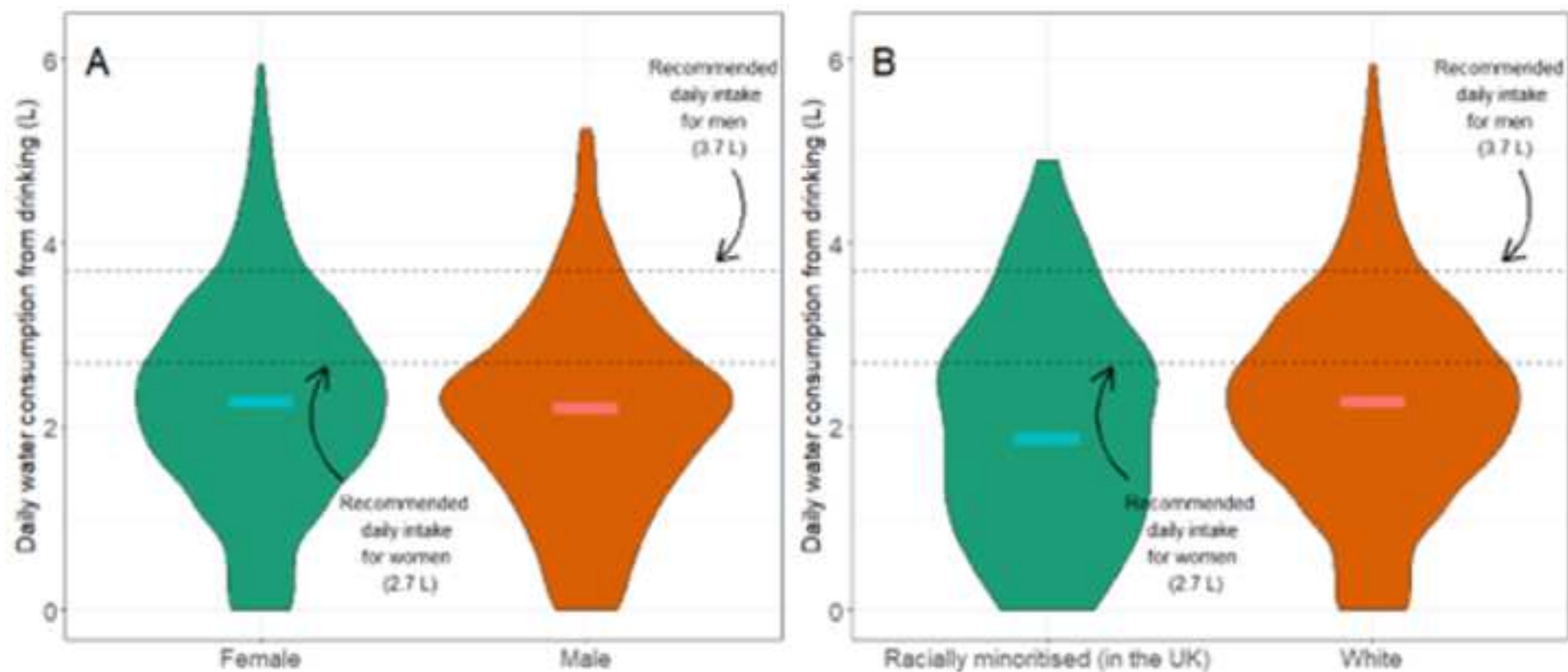


Figure 3

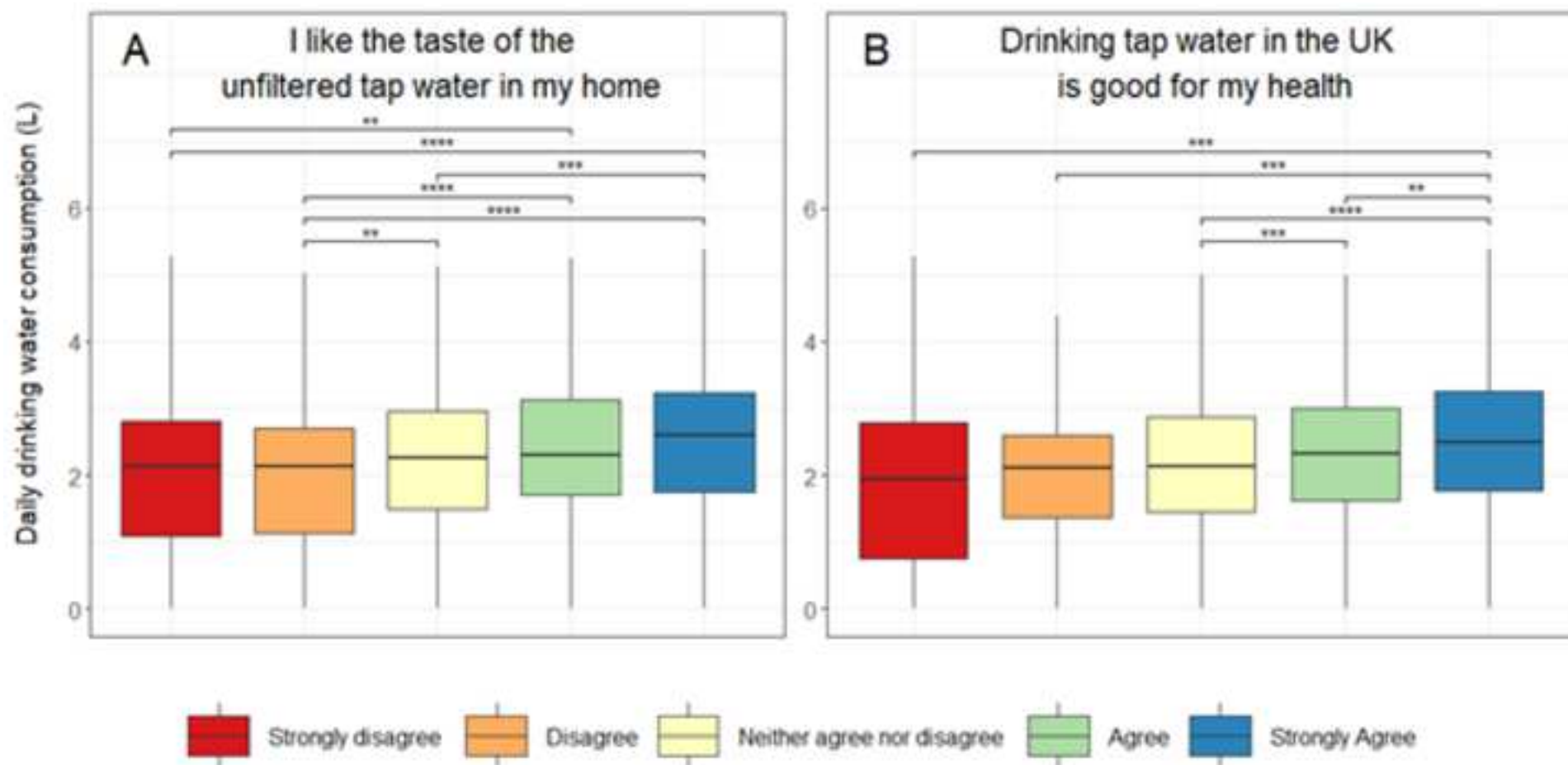
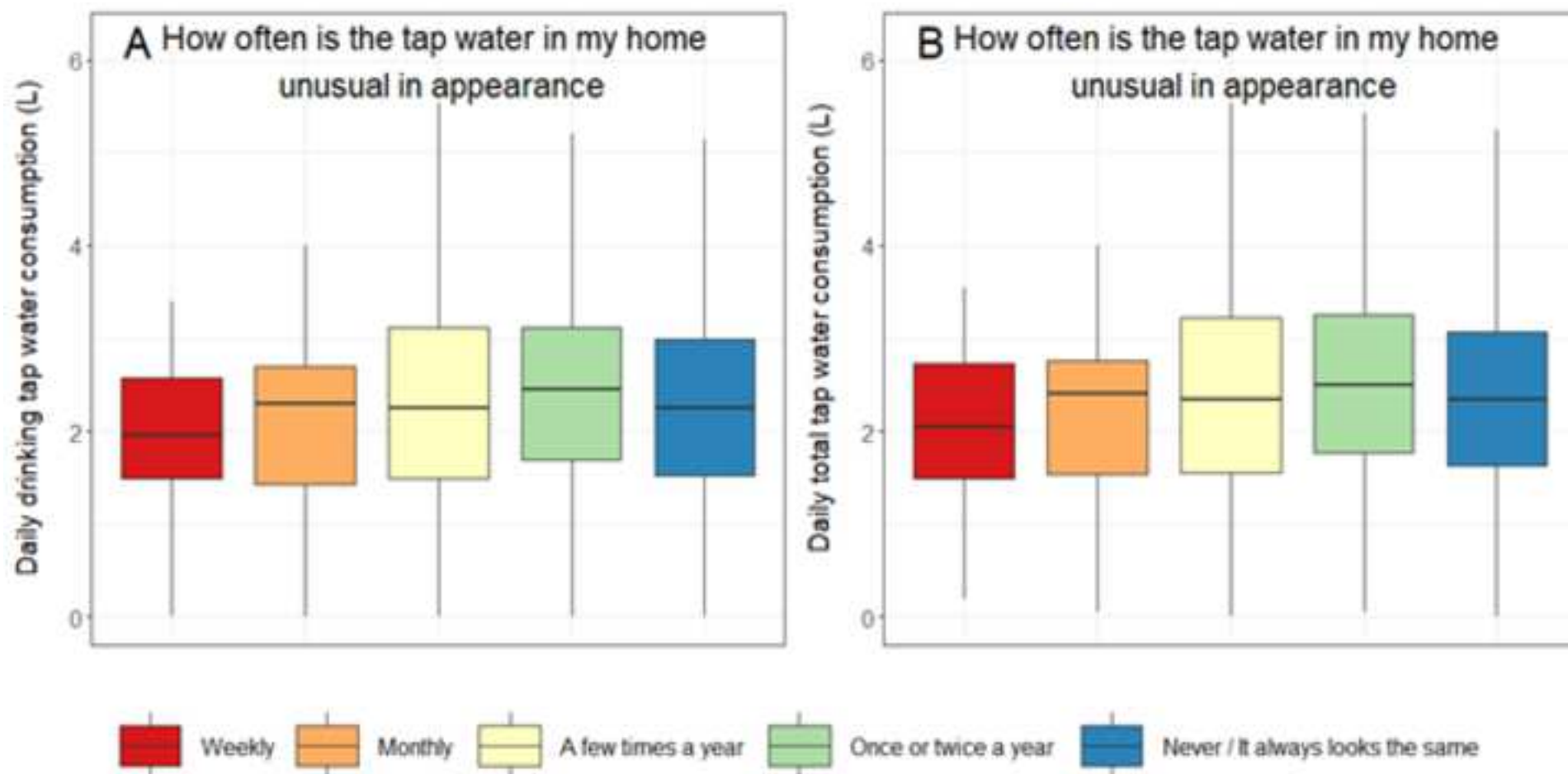
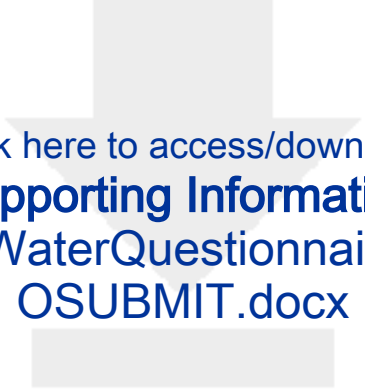


Figure 4





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Supporting Information

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