

RESEARCH ARTICLE

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 sociodemographic characteristics, public perceptions of taste and health benefits and genetic factors influence tap water consumption within the home. We administered the survey amongst nearly 3,000 adult twins living in the UK (members of the TwinsUK cohort). Respondents consumed 2.40 ± 1.14 L/day of water from their household taps through drinking and cooking. This rate is at the high end of published values and means that 39–65% (female) and 8–39% (male) of TwinsUK participants meet international recommendations on daily intake. 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 more of the variance. 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. Rank-based and intersectional analysis (I-MAIHDA) revealed that respondents who are female and/or over the age of 45 recorded the highest intake, on average, although these demographic groups represent a higher percentage of surveyed respondents than the UK population. Focusing on older adults fills a common research gap in drinking water research, but we acknowledge our findings need to be reassessed amongst a representative population cohort before stronger inferences can be drawn around public perceptions, consumption patterns and health outcomes. Nevertheless, our study suggests there

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Data availability statement: 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/researchers/access-data-and-samples/request-access/>. All analytical R scripts used for this analysis can be found via our GitHub repository <https://github.com/RuthBowyer/TwinsUKTapWaterConsumption> commit reference 21c2baa at time of resubmission.

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are opportunities to increase overall levels of consumption to benefit public health through improving tap water taste and increasing knowledge of health benefits.

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 individuals varies widely. Daily water intake surveys have reported values ranging from just 0.55 L in Hungary [11] up to 3.60 L in the USA [12]. This is reflected in dietary guidance. The European Food Safety Authority recommends 2.00 L for women (more for pregnant or lactating women) and 2.50 L for men [13] whilst the USA National Institute of Medicine recommends higher volumes: 2.70 L and 3.70 L, respectively [14]. Total water intake refers to consumption from plain water (tap or bottle), water-based beverages and cooked food. These are recommended minimums because personal requirements will vary widely. Caloric consumption, kidney function, rates of excretion as well as levels of physical activity and environmental conditions, especially temperature and humidity, will influence an individual's water needs [15].

No firm explanation for such variance in tap water consumption has been identified to date. This may reflect tap water research having two main disciplinary foci. Dietary studies aim to estimate total intake of key nutrients. Water intake from all beverages is therefore considered, including cans and cartons [16], which probably masks effects of tap water. Moreover, sampling methods to record dietary nutrient intake prioritise consumption with food at specific times of day [17], which may underestimate total daily water intake [18]. A separate body of research explores the behaviours and perceptions that dictate beverage choice – for example, choosing a soft drink over water – rather than the amount that is consumed [19–21] or measures of water quality [22]. Studies on tap water avoidance often use consider tap and bottles water together or binarised consumption: i.e., respondents either do or do not consume tap water [23]. Overall, surprisingly few water intake surveys concurrently explore individuals' perceptions of tap water and how much those same individuals consume. Elucidating how perceptions and water quality interact has wide implications for public health, for instance via the strong associations between plain water consumption and diet quality [17,24,25].

The extensive tap water literature reports mixed socio-demographic associations. A number of studies report notable differences in daily intake between sexes, age groups or ethnicity [12,26–28], but others found no significant difference [29]. Socioeconomic factors, including education and water insecurity [30], religion and cultural considerations such as common foodstuffs and cooking practices can also influence consumption. Tani et al. [31] 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 [32]. 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 [32], possibly related to heat and humidity levels [31]. The importance of personal and environmental characteristics in determining an individual's tap water consumption relative to public intake recommendations therefore remains unclear [33].

The genetic heritability of water intake remains understudied by comparison with the larger literature on coffee, tea and alcohol consumption [34]. 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 [35]. de Castro [36] reported a higher heritability estimate for drinking water (43%) from a much smaller participant pool (<200 twin pairs). Taylor et al. [37] 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. 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 highly susceptible to dehydration [38,39] 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 [40]. The UK National Diet & Nutrition Survey focused on adults aged 19 – 64 years [41], 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. Persistent confusion on fluid intake recommendations for older adults is acknowledged to hamper hydration care [42].

Here, we report the results of 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 through three interlinked research questions. We first compare consumption patterns against existing sociodemographic data for TwinsUK participants to ascertain how personal characteristics and living circumstances (e.g., retirement) relate to intake. The mean age of participants in the TwinsUK cohort is 59 [43], so our survey should provide important insight into consumption patterns amongst older adults. Secondly, we analyse how respondents' perceptions of tap water characteristics, including its taste, colour and health benefits, modulate consumption. Third, working with twins allows us to 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.

An important feature of our study is that we intentionally surveyed only respondents' consumption from taps within their own homes. This choice relates to associated research where we calculate individual solute exposure from drinking water using chemical composition data reported by household water suppliers [44]. As a result, our calculations in this paper do not include bottled water nor water consumption from taps outside the house. This likely introduced bias based on time spent at home. For instance, respondents who regularly leave the house for work likely consume a smaller proportion of their daily water intake at home. Existing TwinsUK socioeconomic data on employment status was used to stratify by this measure. At the same time, a 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 record their tap water consumption using four mug and glass sizes, assisted by pictorial guides, unlike previous studies which often use 'glasses' as a single uniform measure.

2. Materials and methods

2.1. Ethical approval and informed 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. All participants were over the age of 18 and provided written informed consent as members of the TwinsUK cohort register. An information page on risks and benefits of the project and how personal survey data would be stored and handled was provided in written form at the start of the questionnaire. Contact details for TwinsUK and, in turn, the investigators, were provided in case respondents had procedural queries.

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 18–100 years. Monozygotic twins are identical as they develop from a single fertilised egg. Nearly 100% of their genetic material is shared. Dizygotic twins develop from two separate eggs fertilised by different sperm, and thus about ~50% of their DNA is shared. 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 [43]. The TwinsUK research team have extensive experience administering health- and nutrition-focused surveys to its cohort [45]. 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. Questionnaire design is adapted from the validated seven-day fluid diary of Johnson Evan and colleagues [46,47]. A seven-day sampling window was deemed reliable through comparison against records by diet entry specialists and D₂O levels in urine samples [47]. Individual water consumption was quantified as follows: respondents were asked to recall 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 the supporting information (S1 Text). 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 (see Supplemental Information).

Drinking or cooking vessel	Volume (L)
Cold drink (small glass)	0.20
Cold drink (large glass)	0.50
Hot drink (small mug)	0.25
Hot drink (large mug)	0.38
Small saucepan	1.00
Large saucepan	2.00

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The questionnaire was sent to 4822 potential participants from the TwinsUK cohort. These were the subset who live in the UK and for whom TwinsUK had prior consent to contact via email with research questionnaires. REDCap electronic data capture tools hosted at King's College London were used to develop, administer and extract data from the online questionnaires [48,49]. 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* [50] and *ggpubr* [51]. Daily water intake data are reported as means in the text unless otherwise stated. Consumption amounts more or less than three standard deviations from the mean were excluded from the statistical analysis due to potential misapprehension of the question or inaccurate data entry by the 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. Intersectional effects were explored using a multilevel analysis of individual heterogeneity and discriminatory accuracy (I-MAIHDA [52]). Sociodemographic characteristics of each respondent are included in a linear additive model as a unique combination of fixed effect predictors. This method predicts daily intake for each unique stratum.

To estimate heritability, we used the classical twin, or 'ACE', model via the 'mets' package v 1.3.3 [53]. 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 Home-maker were grouped into one strata ($n = 1372$). All others were classified within the 'employed' strata because TwinsUK does not currently collect data on working-from-home patterns. 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

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. A high proportion of the respondents were female (89%), 92% identified their ethnicity as white and the median age of respondents was 65 years (Table 2). These demographics are therefore overrepresented in our dataset in comparison with the UK population, but are in keeping with the full TwinsUK cohort. Moreover, focusing on older adults 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

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. Percentages are calculated based on *n* for that demographic characteristic.

Characteristic	Class	Value (% of all respondents)
Respondents (after exclusions)	<i>n</i>	2710
Age (years)	Median	65
	Range	18 – 92
Sex	F	2415 (89%)
	M	295 (11%)
Zygosity	Monozygotic	1706 (63%)
	Dizygotic	988 (37%)
Ethnicity	White	2503 (97%)
	Racially minoritised in the UK	69 (3%)
Education	Undergraduate degree or higher (<i>n</i>)	1413
Index of Multiple Deprivation	Median	7
	Range	1 – 10
Employment status	Not retired	825 (49%)
	Retired, long-term sick, unemployed or opt to care for home or family	853 (51%)

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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. Third, we binarised respondents by time likely spent inside the home (see Section 2.4 Statistical analysis).

3.2. Consumption patterns and amount

We find marked differences in how many drinks respondents consume from their household tap during a typical day (Fig 1). Sixteen twins reported drinking 12 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* = 79) reported consuming zero drinks comprising tap water.

Total daily intake of household tap water as drinks (mean ± standard deviation) is 2.31 ± 1.15 L/day but varies substantially amongst respondents (Fig 2; Table 3). 316 respondents (11%) report drinking less than 1 litre per day from their household tap. On average, respondents consume 53% in the form of hot drinks, with females consuming slightly more (median = 0.13 L/day). Respondents in the Over-65 age group consume nearly twice as much water from hot drinks (1.39 L/day) as Under 45s (0.79 L/day).

We find that females drink significantly more tap water (median = 2.28 L/day) than males (2.2 L/day) within their homes (Fig 2A; Wilcoxon test, *p* < 0.01, *|r|* = 0.1). When grouped by age (pre-defined groups and terciles; see Methods), younger respondents (under 45) drink significantly less (0.25–0.35 L/day) in the home than older adults (*p* < 0.01), with no significant differences between the middle and oldest age groups (Fig A in S2 Text). Using our stratification scenarios of where respondents spend their time (see section 2.4 Statistical analysis), 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 are non-significant (*p* > 0.1; Fig B, Fig C in S2 Text). Respondents who report their ethnicity as white appear to drink more tap water than those from ethnic groups who are racially minoritised in the UK (*p* < 0.05; Fig 2B), although with small effect size owing to the low number of respondents in the latter group (*|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

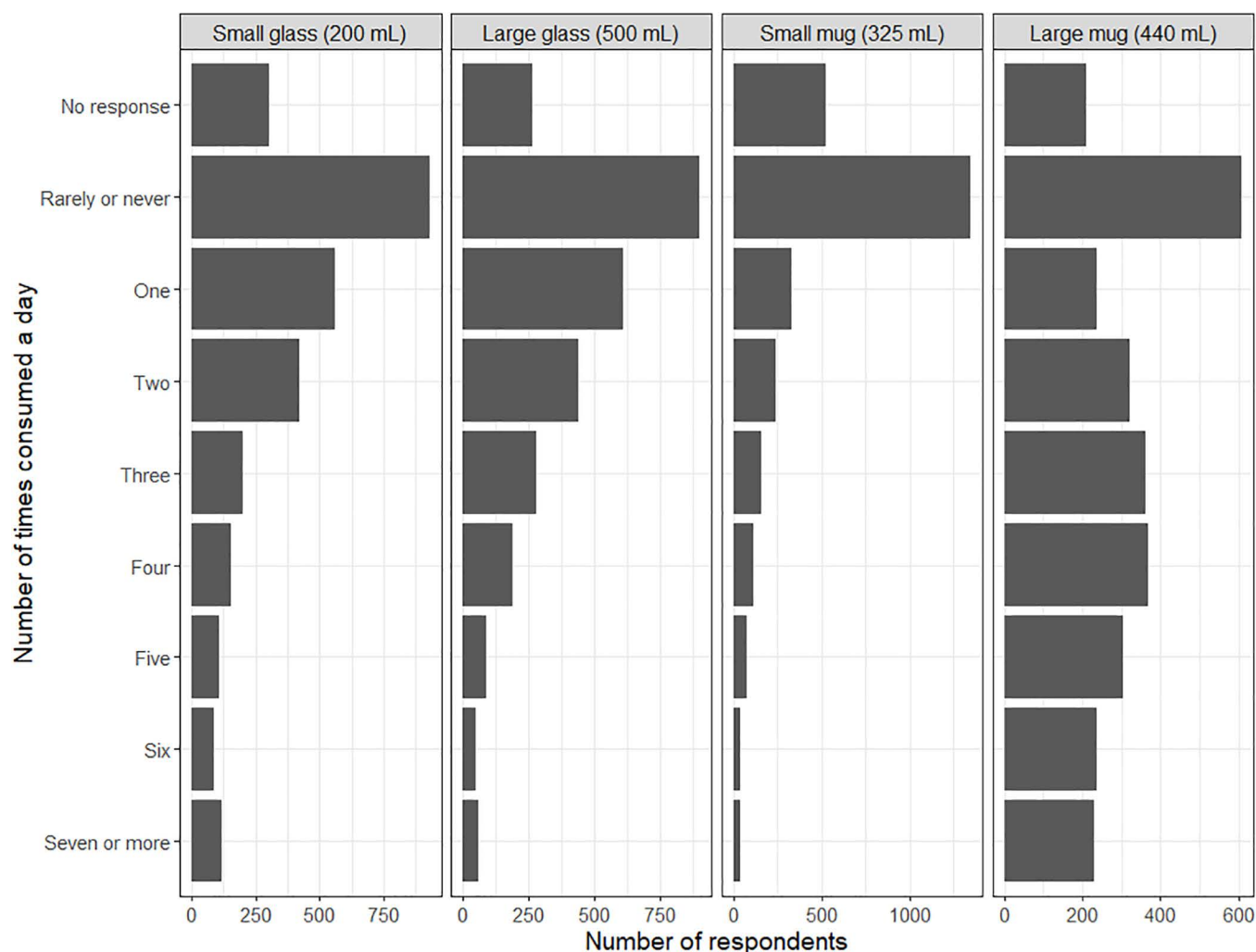


Fig 1. Number of drinks comprising tap water consumed daily. Small and large glasses are cold drinks; mugs are hot drinks. Vessel volumes were taken from existing water questionnaire and food diary methodologies and checked by measuring glasses and mugs in the authors' homes.

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area-level deprivation (Index of Multiple Deprivation) nor university degree status is a significant determinant of water consumption ($p > 0.1$). The intersectional MAIHDA analysis provides a similar summary. We defined 22 strata encompassing binarised sex, ethnicity, employment and education (as in Table 2) and age as terciles. The highest predicted intake from the fixed effects Model 1B strata (~ 2.5 L/day) are clustered around female, white respondents across different age groups and levels of education (Table 4; Fig 3). Respondents in the lowest ranked strata (mostly females from racialised minorities and males) consume nearly 0.5L/day less. Finally, we calculate average total daily water consumption from household taps through cooking to be 0.09 ± 0.08 L/day and drinking plus cooking to be 2.40 ± 1.14 L/day (Table 3; Fig E, Fig F in S2 Text).

3.3. Perceptions of UK tap water

Our dataset presents evidence that perceptions around tap water taste and its associated health benefits influence daily intake (Fig 4). Respondents who Agreed and Strongly Agreed that they like the taste of their tap water consume nearly 0.5L more

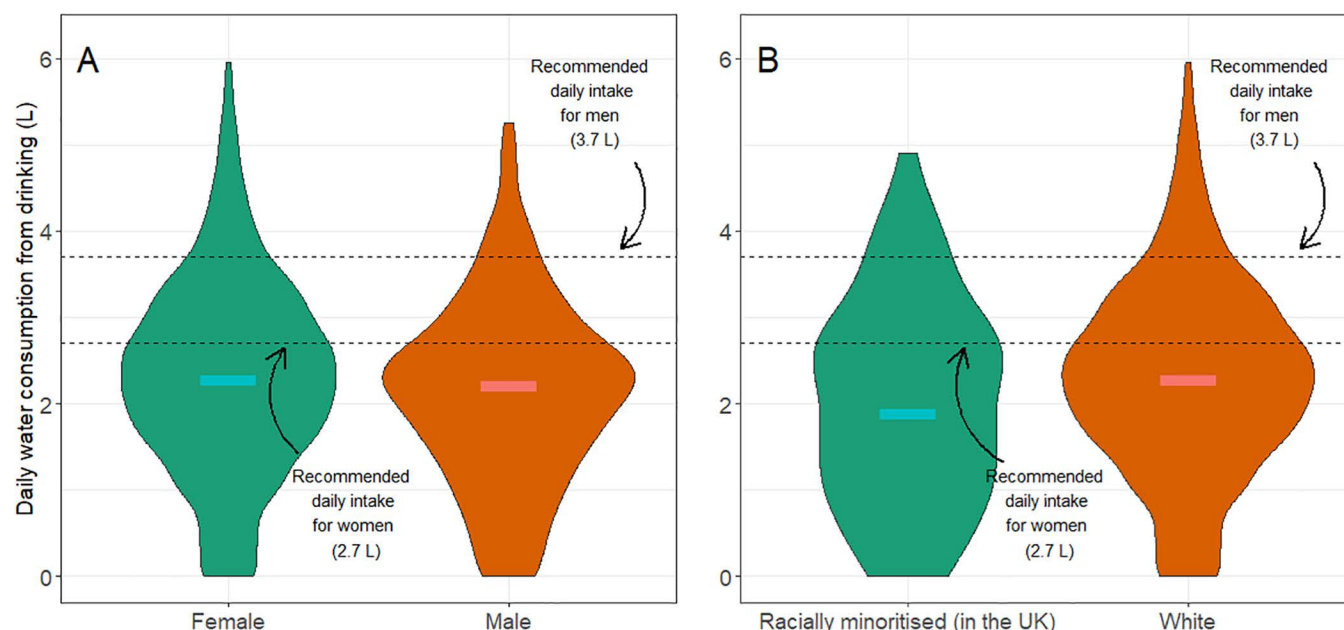


Fig 2. Distribution of daily tap water consumption through drinking. A) Daily tap water consumption through drinking stratified by sex. Dashed lines show the US National Academy recommended daily water intake. Short orange and green lines show median consumption for males (2.20 L/day) and females (2.28 L/day). B) Daily tap water consumption through drinking stratified 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). The effect sizes are small ($|r| \leq 0.1$) because a high proportion of respondents are female and report their ethnicity as white (Table 2).

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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)	2.31 $\pm$ 1.14	0.99 $\pm$ 0.91	1.22 $\pm$ 0.86	0.09 $\pm$ 0.08	2.40 $\pm$ 1.14
Median	2.25	0.80	1.13	0.1	2.38
90 th Percentile	3.75	2.20	2.38	0.2	3.85

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water per day, on average, than respondents who had a less favourable view (Fig 4A). A Kruskal-Wallis test confirms a significant difference in daily drinking consumption ($H(4) = 39.71$, $p < 0.001$). This pattern generally holds true across age groups and amongst female respondents but is less clear amongst male respondents (Fig G in S2 Text). This result is likely influenced by the over-representation of females amongst the survey respondents (Table 2). Additionally, of the respondents who reported consuming zero drinks from their household tap ($n = 79$), 47% reported not liking the taste of the water in their home compared to only 14% in the wider group of respondents. 21% of respondents felt their water is unusual in appearance at least once or twice a year (Table 5). More than 13% of all respondents considered their water to be cloudy (Table 6). 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 (Fig 5), although there is no significant difference (Kruskal-Wallis, $H(4) = 7.26$, $p > 0.1$). Almost a quarter of respondents (23%; 616 of 2710) use some form of water filter (Fig K in S2 Text). 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, more respondents report always using a filter when making hot (13.0%) and cold (12.5%) drinks compared to cooking (4.9%). Half as many respondents never use a filter for cold (2.6%) compared to hot (5.2%) drinks.

Table 4. List of the five highest and lowest ranked strata for the predicted mean daily water intake from Model 1B (I-MAIHDA analysis). Sex ($p < 0.01$), ethnicity ($p < 0.05$) and employment status ($p < 0.05$) generated significant coefficients of variance.

Rank	Stratum	n	Sex	Ethnicity	Employment status	Age	Education	Predicted mean (L/day)	95% CI
Highest five strata									
21	11223	263	F	White	Retired/not employed	≥ 71	Degree or equivalent	2.55	2.45 -2.64
20	11221	40	F	White	Retired/not employed	< 60	Degree or equivalent	2.55	2.41 -2.71
22	11222	197	F	White	Retired/not employed	60-71	Degree or equivalent	2.55	2.46 -2.64
17	11211	23	F	White	Retired/not employed	< 60	Other	2.49	2.33 -2.64
18	11212	207	F	White	Retired/not employed	≥ 71	Other	2.48	2.39 -2.58
Lowest five strata									
5	21122	24	M	White	Employed	60-71	Degree or equivalent	2.18	2.01 -2.34
4	21123	8	M	White	Employed	≥ 71	Degree or equivalent	2.18	1.98 -2.40
2	12222	9	F	Racialised minority	Retired/not employed	60-71	Degree or equivalent	2.11	1.78 -2.48
3	21111	19	M	White	Employed	< 60	Other	2.11	1.94 -2.30
1	12121	30	F	Racialised minority	Employed	< 60	Degree or equivalent	1.95	2.61 -2.31

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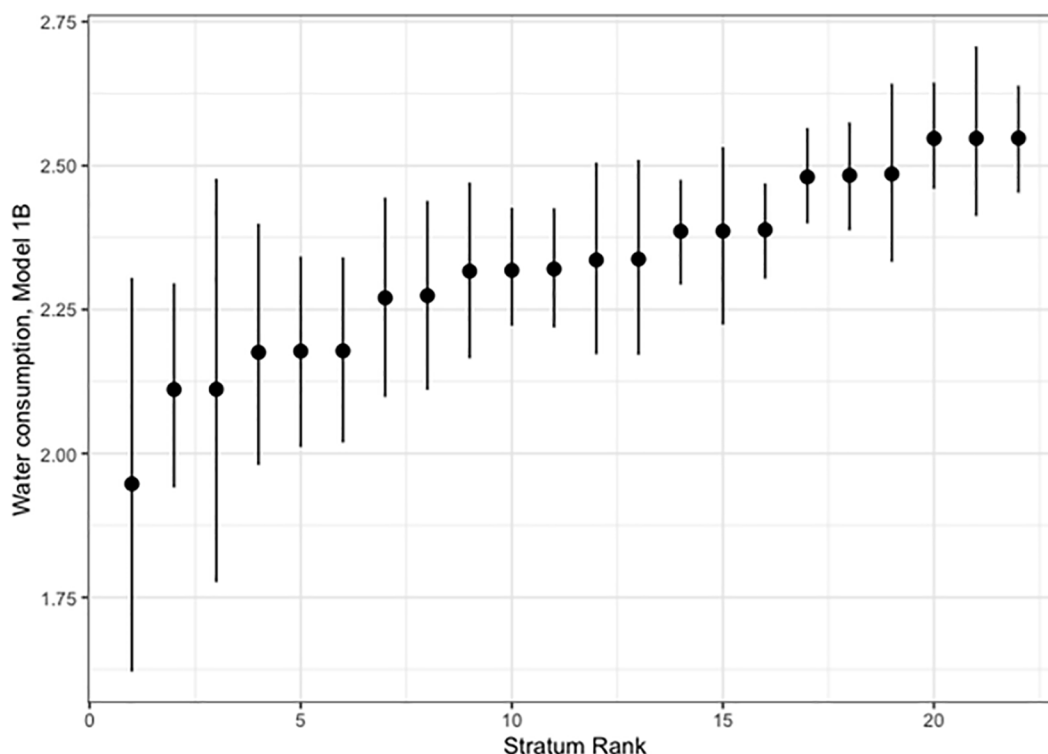


Fig 3. Predicated average daily intake (L/day) across each intersectional stratum according to the I-MAIHDA model.

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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 (Fig 4B; Kruskal-Wallis, $H(4) = 44.35$, $p < 0.001$). Strong agreement leads respondents to consume over 0.5L more per day (2.52L/day), on average, than those who strongly disagree (1.92L/day). This pattern is consistent across age and sex (Fig I, Fig J in S2 Text).

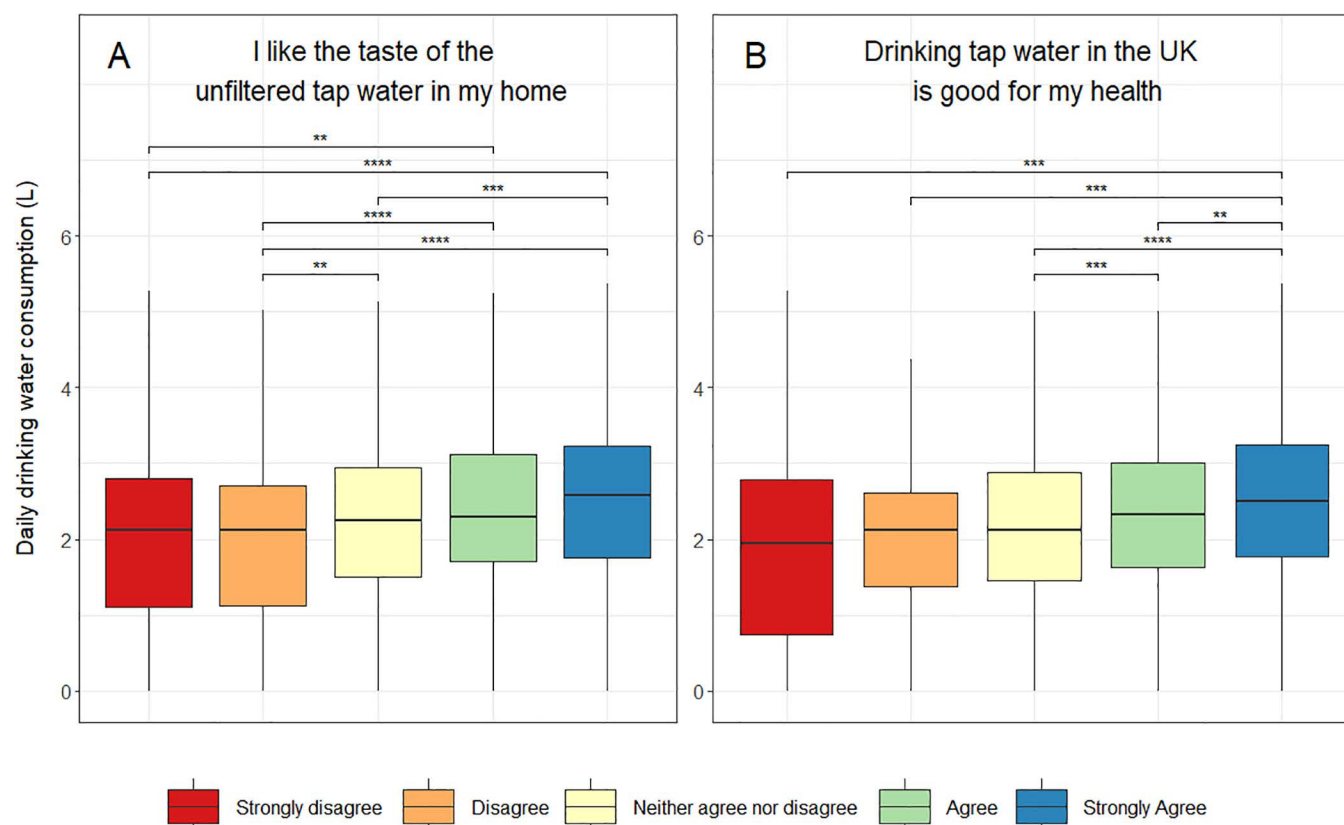


Fig 4. Perceptions of taste and health benefits influence daily drinking water consumption. A) Daily drinking water consumption (L/day) by responses to the question “To what extent do you agree with the following statement: I like the taste of the unfiltered tap water in my home”. B) Daily drinking water 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: ** $p < 0.01$; *** $p < 0.001$; **** $p < 0.0001$. Brackets for non-significant pairs are not plotted.

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Table 5. 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	2087	77.5
Once or twice a year	441	16.4
A few times a year	135	5.0
Monthly	18	0.7
Weekly	13	0.5

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3.4. Heritability of tap water consumption and discordant twin analysis

Of our respondents, 1500 individuals (750 pairs; 67.6% 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 2506 individuals (of whom 1356 individuals were complete twin pairs – 678 pairs). These pairs were used in the stratified model scenarios (Table 7). 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 23 and

Table 6. Respondents were asked which of the following best describes the visual appearance of their unfiltered tap water when they considered it to be unusual. Values were omitted for categories with fewer than ten respondents to maintain personal data protection.

Visual characteristic of the way	Number of responses	Percentage (%)
Straw-coloured or yellow	49	1.8
Brown or orange	84	3.1
Blue or green	---	---
Black, brown or tea-coloured	11	0.4
Cloudy, grey or white	371	13.7
Contains stains, slime or mould	---	---
There are visible bits in the water	54	2.0
Unsure	69	2.5

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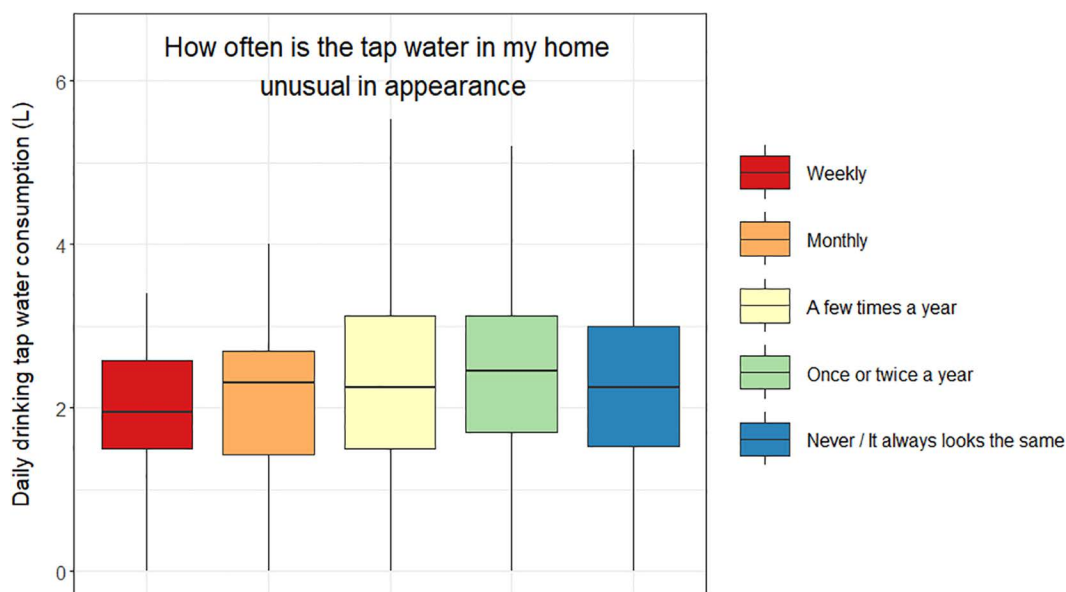


Fig 5. Responses to the question “In the last year, how often did you consider your tap water to be unusual in visual appearance” compared to daily drinking intake. Pairwise relationships are non-significant with multiple comparisons. Total consumption (drinking + cooking) boxplots are presented in Fig L in S2 Text.

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31% and was higher in individuals who reported themselves to be employed in 2021 ($h^2 = 30\text{--}31\%$). Our discordant twin analysis did not find a significant difference in the influence of health perceptions (Wilcoxon paired test, $p = 0.2$) and taste perception (Wilcoxon paired test, $p = 0.08$) on water intake. There were 101 and 162 pairs (of 750) discordant for questions regarding health perceptions and taste of tap water, respectively.

4. Discussion

4.1. Global daily water consumption patterns

Our central estimate of daily water intake from drinking ($2.29 \pm 1.15\text{L/day}$) and drinking plus cooking ($2.40 \pm 1.14\text{L/day}$) inside UK homes fits within values reported for other European countries in the order of $2.0\text{--}2.5\text{L/day}$ [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

Table 7. 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. Twin pairs of uncertain zygosity were removed from analysis ($n = 4$).**

Modelling scenario	Model of best fit (AIC)		Variance decomposition		
			Estimate	2.5%	97.5%
1. All available twin pairs ($n = 745$ pairs, 68% MZ)	AE (7284.7)	A	0.29***	0.21	0.38
		E	0.70***	0.62	0.78
2. Stratified by employment status					
Retired, sick, unemployed or opt to care for home or family group ($n = 291$ pairs, 62.5% MZ)	AE (2832.7)	A	0.23***	0.1	0.37
		E	0.76***	0.63	0.90
Employed ($n = 241$ pairs, 78.4% MZ)	AE (2392.6)	A	0.31***	0.18	0.44
		E	0.68***	0.56	0.82
3. Stratified by employment status, adjusted for age group					
Retired, sick, unemployed or opt to care for home or family	AE (2835.7)	A	0.23***	0.09	0.3
		E	0.77***	0.63	0.91
		Age group	NS		
Employed ($n = 241$ pairs, 78.4%)	AE (2395.9)	A	0.31***	0.18	0.44
		E	0.69***	0.56	0.82
		Age group	NS		

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reported purely for tap water (Table 8). Previous data for the UK were considerably lower, around 1.1 – 1.2 L/day [54,55]. 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 [54,56]. 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. [29] 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 0.56 and 0.97 L/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 1.14 L/day, of which just 0.64 L/day was from the tap. Even single studies that deployed a consistent survey instrument in multiple countries observed marked variation in consumption (e.g., [32]). The UK has seen a steady rise in water intake [54], and increases in consumption associated with our findings would continue this trend.

Our finding that hot beverages constitute 53% of daily water intake in the home matches earlier surveys in the UK [32,39,41,54]. This preference lends support to proposals to address low-intake dehydration amongst older adults, which can be a chronic ailment, by offering hot drinks more frequently [38,39]. This must, however, be considered against a potentially higher risk of oesophageal cancers [57]. Of the 13 countries surveyed by Guelinckx et al. [32], 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 [31,58]. Our estimate of 0.09 L absorbed from cooking sits close to values from Canada (0.07 L; [29]) and lower than Japan cooking (0.24 L; [31]). 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 daily intake

Female respondents in our survey consumed significantly more tap water in their homes than males (Fig 2; Table 8). Previous studies report mixed findings. Gibson et al. [54] found the same in the UK, as did Guelinckx et al. [32] for some

Table 8. 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 (L/day)	N	Sex	Methodology	Reference
UK ¹	2.20		M	7-day recall	Our data
	2.28		F		
UK ²	1.99	NR	M	National diet survey	Gibson et al. (2012)
	1.63	NR	F		
USA ³	1.31	9666		24-hour recall and phone follow-up	Rosinger et al. (2018)
USA ²	3.85	NR	M	24-hour recall	Manz & Wentz (2005)
	3.10	NR	F		
France ¹	0.83	831 ⁶		7-day diary and illustrations	Bellisle et al. (2010)
	0.80	443 ⁷			
Germany ²	1.53 ± 0.62	639	M	7-day diary and interview	
	1.21 ± 0.48	889	F		
Germany ⁴	2.26	507	M	National diet survey	Manz & Wentz (2005)
	1.88	682	F		
Canada ¹	1.44	125		24-hour recall and 1-day diary	Levallois et al. (1998)
Canada ¹	1.32	NR	M	National diet survey	
	1.39	NR	F		
Korea ¹	1.66	545	M	24-hour recall	Ji et al. (2010)
	1.33	547	F		
Korea ⁵	0.53	545	M	24-hour recall	Ji et al. (2010)
	0.43	547	F		
Japan ¹	0.56	121	M	4-day diary	Tani et al. (2015)
	0.78	121	F		
Japan ⁵	0.25	121	M	4-day diary	Tani et al. (2015)
	0.22	121	F		
13 countries	0.46 (Poland)	16,276		24-hour diary for 7 days including illustrations	Guelinckx et al. (2015)
	1.78 (Indonesia)				
12 European countries ²	1.01 (Italy)		M	Various	
	0.94 (Italy)		F		
	2.66 (Germany)		M		
	2.37 (Germany)		F		

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.

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other European countries. Conversely, Rosinger & Herrick [12] reported men consuming nearly 0.75L/day more than women in the US and Manz et al. [59] recorded intake for men in Germany to be ~0.45L/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 [59], stronger social barriers to water consumption amongst men [60] or females holding more favourable views on the health benefits of tap water [20]. Our study surveyed a high proportion of female respondents and considers only tap water consumption within the home. So, differences in the amount of time men spend in other locations compared to women could be another explanation.

Consumption across age groups reported in the literature is somewhat more consistent than between sexes. We find highest consumption amongst those aged 45–65 (Fig A in [S2 Text](#)) and this pattern is repeated in studies from the US [12], Germany [59] and Japan [31]. Conversely, Drewnowski et al. [61] 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 [62]. We recorded the highest water consumption amongst respondents who identified their ethnicity as white, which is in accord with data from the US [12,27], keeping in mind the effect size in our study is low.

Our intake values mean 65% of female respondents meet the EU Food Safety Authority recommendation of 2.0 L/day and 39% of female respondents meet the US National Academy advisory value of 2.7 L/day. This compares to 39% (EU Food Safety Authority) or 8% (US National Academy) for males. A high percentage of our respondents are female, white and older in age compared to the UK population so it will be important to reassess our findings amongst a larger cohort. Moreover, 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.

4.3. Perceptions and heritability as drivers of individual intake

Our data suggest that individuals holding favourable perceptions of the taste or health benefits of tap water consume around 0.5 L more per day (Fig 4). Understanding how cultural and physical influences shape such views [63] could explain an important portion of the variance in daily intake observed between countries and published surveys (Table 8). UK drinking water composition is regionally clustered into groundwater or surface water-dominated sources [64]. Hydro-chemistry can influence (perceptions of) taste. A previous survey showed UK residents hold negative views on taste and quality of 'hard' (Ca- and Mg-rich), groundwater-sourced drinking water [19]. Those who dislike tap water may substitute bottled water, but this is rarely a like-for-like. Although taste testers could not differentiate tap and bottled water [65], perception of flavour has been shown to be a key influence on an individual's judgement of drinking water quality [19,21]. Furthermore, under UK law, chlorine is added as a disinfectant to the public drinking supply at source. Target concentrations of 0.5 mg/L are well below World Health Organisation guidelines (5 mg/L), but water companies are permitted to add higher amounts of chlorine locally during routine maintenance or to respond to contamination concerns, and taps at households closest to their water treatment source tend to have higher chlorine levels [66]. Colloquially, people often comment negatively on the taste of their tap water when moving to a new place. How this alters drinking patterns, and the ensuing implications for nutrient intake and personal health, are understudied. Spatial and longitudinal analyses of associations between drinking water hydrochemistry, perceptions and intake is beyond the scope of our study but would be a valuable future investigation. Importantly, our observed effects of perception on intake could inform public policy around maximising hydration. A considerably lower proportion of respondents who Dislike or Strongly Dislike the taste of their tap water meet international daily intake guidelines (31% above 2.7 L; 55% above 2.0 L) versus those with a favourable view: 46% (2.7 L) and 75% (2.0 L). Differing perceptions on the health benefits of tap water have comparable effects: Disagree/Strongly Agree at 26% (2.7 L) and 54% (2 L) compared to Agree/Strongly Agree at 41% and 94%. These findings suggest strategies to boost tap water consumption should focus on promoting the health benefits of tap water [65] and exploring what modulates perceptions of its taste [67,68]. Encouraging greater tap water intake creates a range of positive opportunities, including financial [68], environmental [69] and for the social life cycle [70].

Most research into cultural factors and behaviours around drinking water has emerged from the US [71], often from the perspective of associations between perceptions of tap water safety and sociodemographics [20,21,72–74]. Differences in consumption between white respondents and those from racial minorities in the UK could reflect levels of (mis)trust of tap water [20,75], a legacy of long-standing inequalities in access to clean water [30]. We also find the strongest difference amongst Under 45s, which concurs with some studies showing lower consumption of tap water amongst younger age

groups [29,31] whilst others found the opposite trend [26,59]. Interestingly, this age effect is not significant when we stratify by employment status. This may reflect our overrepresentation of respondents reporting their ethnicity as white and/or that our questionnaire focuses on within-home consumption and working-age people typically spend less time within the home. At the same time, psychology research suggests drinking water is strongly influenced by situational habits and personal views of oneself [76]. 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 ACE heritability estimates for tap water consumption range between 19 and 31% are slightly lower than the few published values for drinking water ($h^2 = 37 - 43\%$; [35,36]). We note that these studies measured UK and US residents; obtaining more globally diverse estimates would be valuable and may help further explain observed geographical differences (Section 4.1). Our results are 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 [35]. As with many behavioural traits, a small but significant genetic influence would be expected [77]. It is reassuring that we find such an effect within our measure of tap water consumption. Our findings also point towards environmental factors having a larger influence on the trait. This in part reflects spatial effects attributable to twin discordance, which would likely be significantly different within an analysis within higher power (i.e., more twin pairs discordant for the questions on perceptions of health benefits and taste). 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. First, 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. Second, 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 also 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 1 L 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 respondents consume, on average, 2.40 ± 1.14 L/day per day from taps within their own households, with higher rates recorded by females, adults over the age of 45 and those who reported their ethnicity as white. Each of these demographic groups is overrepresented in our dataset compared to the UK population, so these are statistically significant differences but with low effect sizes. 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 average consumption of ~ 0.5 L per day. 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 39–65% of females and 8–39% of males at or above international guidelines for 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.

Supporting information

S1 Text. The tap water questionnaire we administered that underpins the study.

(DOCX)

S2 Text. Fig A. Daily tap water consumption (L/day) for drinking by pre-defined age groups (A) and by terciles of respondent ages (B). Vertical bars are median values. Fig B. Daily tap water consumption (L/day) grouped by time likely spent inside the home. One group comprises respondents who self-report as “not retired” and presumably spend more time outside the home. The other group comprises respondents who self-report as retired, long-term sick, unemployed or opt to look after home or family. Fig C. Daily tap water consumption (L/day) grouped by time likely spent inside the home and stratified by age terciles. The group denoted by blue boxplots includes survey respondents who report their employment status as Retired, Long-term Sick, Unemployed or Homemaker (i.e., opt to care for home or family). Fig D. Daily tap water consumption (L/day) for drinking for females and males across different age categories. Fig E. Daily tap water consumption (L/day) from cooking for female and male respondents. Data points are adjusted for the proportion of a dish cooked using tap water that was eaten by the respondent. Horizontal bars are the median values. Fig F. Total tap water consumption within the home from both drinking and cooking. Short orange and green lines show median consumption for males (2.25 L/day) and females (2.40 L/day). Fig G. Total daily tap water consumption (L) within the home from drinking grouped 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” and stratified by sex. Fig H. Total daily tap water consumption (L/day) within the home from drinking grouped 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” and stratified by age. Fig I. Total daily tap water consumption (L) within the home from drinking grouped by responses to the question “To what extent do you agree with the following statement: Drinking tap water in the UK is good for my health” and stratified by sex. Fig J. Total daily tap water consumption (L) within the home from drinking grouped by responses to the question “To what extent do you agree with the following statement: Drinking tap water in the UK is good for my health” and stratified by age. Fig K. Frequency of water filter usage within the home for different drink types. Fig L. Responses to the question “In the last year, how often did you consider your tap water to be unusual in visual appearance” compared to total intake (drinking plus cooking). Pairwise relationships are non-significant with multiple comparisons.

(DOCX)

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