Consequences of Elevated Fluoride Exposure for Cognitive Development

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Abstract

By leveraging variation generated by geogenic factors, we identify the causal effects of elevated fluoride in household-level drinking water on the cognitive and physical development of children. Across 275 villages in 7 districts of Rajasthan, India, we consistently find that childhood fluoride exposure below the World Health Organization's permissible drinking water threshold of 1.5 mg/L is associated with improved performance on cognitive tests, but when levels exceed that standard, it leads to a 16% deficit in general intelligence. In addition, elevated exposure impedes both a child's accumulation of human capital, resulting in lower math and language proficiency test scores, as well as their physical well-being, through worse dental health and increased physical limitations. We conclude that elevated fluoride in a developing country setting leads to a self-reinforcing cycle of poverty – exposure impairs the cognition and health of children, leading to adverse inter-generational consequences, depressing economic mobility, and perpetuating inequality.

JEL codes: I12, I13, I14, I15, Q52, Q58

Keywords: Fluoride in drinking water, Cognition,, Poverty, Inequality

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1 Introduction

The use of fluoride is believed to be the most effective way to prevent tooth decay. The goal of preventing dental caries and their associated risks, such as chronic infection, weakened immune system, and less nutrient absorption, has led to the nearly universal use of fluoride in dental products and has motivated many countries around the globe to fluoridate their water.[1] Despite this general acceptance of fluoride as a positive public health instrument, there remains a debate about the safety of this naturally occurring mineral. For example, the medical literature, mainly using animal studies, maintains that exposure to a high level of fluoride adversely affects physical health and is strongly associated with poorer cognitive development (Mullenix et al., 1995; Blaylock et al., 2004), yet skeletal fluorosis and cognitive impairment at fluoride exposure levels of up to 4 mg/L are not identified as significant risks by the EPA or any other major health authority.

Prior attempts to study fluoride exposure in humans have been inconclusive with reports of positive, negative, and no health impact across several countries. However, several of these studies, especially those focusing on populations exposed to very high levels of fluoride, are based on small samples and use methodologies which, at best, can only provide correlational relationships. In its review of the existing evidence, the Center for Disease Control (CDC) highlights the need for transparent and detailed research on this issue.

More rigorous attempts to causally identify these relationships are limited to three papers (Roberts, 2024; Aggeborn and Öhman, 2021b; Glied and Neidell, 2010). Two of these papers, Aggeborn and Öhman (2021b) and Glied and Neidell (2010), examine the direct impact of fluoride ingestion in the developed country settings of Sweden and the United States, in which only low levels and minimal variation in the focal mineral are present. Both of these studies find that fluoride exposure does not generate deficits in cognition and leads to higher returns in the labor market.

A third paper, Roberts (2024), took the alternative approach of studying the reduced form effect of early-life exposure to county water fluoridation programs in the United States from the 1950s to the 1990s. While Roberts (2024) is unable to explicitly measure or identify the level of fluoride exposure as the mechanism, in stark contrast to Aggeborn and Öhman (2021b) and Glied and Neidell (2010), his findings indicate that these programs led to worse later life physical and economic well-being. Thus, there remains little consensus, even in developed country settings, on the impact of early life exposure to fluoride in the drinking

[1]However, the use and proper amount of water fluoridation has come into question in recent years. For example, Roberts (2024) provides evidence that early-life exposure to community water fluoridation is associated with worse adult outcomes and in 2015 the U.S. Public Health Service lowered the advised level of fluoride in drinking water to .7 mg/L.

water.

Moreover, none of the current literature on this topic in economics may be generalizable to the 2.5 billion people who rely on lightly or unregulated groundwater as their main source for satisfying their drinking needs. For example, the World Health Organization (WHO) has set the permissible limit of fluoride in drinking water at 1.5 mg/L, but the current literature in economics on this topic has only studied regions and individuals in which the vast majority are exposed to fluoride levels below this threshold.[2]

Our study aims to fill this important scientific gap. Broadening our understanding of exposure to higher dosages of flouride is critical if, at those levels, as the medical literature suggests, it acts as a neurotoxin. Previous studies have shown that contamination of drinking water with neurotoxins can affect the cognition and health of children, leading to adverse effects on human capital accumulation, productivity, earnings, and criminality (Chen et al., 2008; Xiang et al., 2003; Kundu et al., 2015; Lu et al., 2000; Green et al., 2019; Karimzade et al., 2014; McLeod and Kaiser, 2004; Cunha and Heckman, 2008; Cunha et al., 2010; Heckman et al., 2006; Borghans et al., 2011). This implies that elevated fluoride exposure may have a lasting, intergenerational negative impact on economic growth. In addition, if economic wellbeing affects a family's ability to mitigate exposure or adapt to environmental risks, these costs will be inequitably distributed, exacerbating pre-existing economic and social disparities and generating a self-reinforcing cycle of poverty.

To carry out our study, we collected primary data from Rajasthan, a state in India that is dependent on groundwater to meet drinking water needs and has the confluence of local geogenic factors (variation in the concentration of fluoride-bearing rocks in the underlying rock bed, pH and conductivity) that generate natural household-level variation in flouride exposure.[3] Our data span 275 villages in 7 districts, where we collected water quality samples from 815 households. The samples were then laboratory tested for 5 contaminants and the presence of biological pathogens. We also administered a household survey to collect information on economic, social, and demographic characteristics, as well as, to conduct an array of cognitive and psychological assessments of mothers and children. Critical for this study, a team of trained psychologists administered the colored progressive matrices test (CPM), a widely accepted and culturally agnostic measure of cognition for children.

For causal identification, our study, as in Aggeborn and Öhman (2021b), relies on the quasi-random variation in naturally occurring fluoride generated by local geological char-

[2]'Fluorine and fluorides, Environmental Health Criteria 36, IPCS International Programme on Chemical Safety, WHO, 1984.

[3]The source of fluoride in the drinking water in Rajasthan is the result of the mineral's natural prevalence in the rock strata that leaches into groundwater. Our sample villages come from a mix of strata of fluoride-bearing rocks.

acteristics. Specifically, the spatial variation of fluoride in drinking water is created by the geographical and geochemical conditions of the groundwater aquifers. In high fluoride-bearing geological strata, groundwater properties -i.e., pH and conductivity- determine how much fluoride is present in water. For example, a high pH leads to more leaching of fluoride in water, however, pH has no direct effects on brain functioning. This type of geogenic variation forms the basis of our strategy.

We start our analysis by conducting an exercise designed to complement the findings of Aggeborn and Öhman (2021b) by exploring the impact of childhood exposure to low levels of fluoride (<1.5 mg/L) on cognition in a developing country context.[4] When restricting the sample to only those households with fluoride exposure less than 1.5 mg/L our estimates corroborate the previous economics literature in developed countries and conclude that fluoride exposure at or below the WHO permissible limit has no adverse impact on a child's cognitive development, and if anything, has a positive association. Specifically, we find that exposure to a one standard deviation increase in fluoride below 1.5 mg/L leads to a 10% increase in IQ score relative to the mean, driven by improvements in memory, attention, and the ability to plan. These gains also translate into statistically significantly higher proficiency test scores in Math and English.

In our developing country setting, though, an exploration focused only on low levels of exposure captures less than 50% of the overall sample. Unlike Sweden or the United States, a large proportion of the population of India relies on water that contains fluoride levels that exceed the WHO-permitted safe limit. Moreover, while fluoride ingestion at low levels benefits teeth, this benefit diminishes significantly as fluoride levels rise. In fact, dental pitting is observed at fluoride concentration levels of approximately 1.5 mg/L, and the medical literature indicates detrimental effects on health after this limit is exceeded.[5,6]

Thus, to examine whether fluoride at higher levels of exposure adversely affects IQ in children, we explore this relationship throughout our full sample and document what happens to the outcomes of children living in areas with fluoride levels above 1.5 mg/L. We find that childhood exposure to fluoride levels above the WHO-permissible limit is associated with a statistically and economically significant 16% deficit in general intelligence ranking

[4]According to their figures, individuals exposed to water containing less than 1.5mg/L make up more than 99.5% of the sample in Aggeborn and Öhman (2021b) (See Figure 1, pp 472 of their paper).

[5]See "Fluoride in Drinking Water: A Scientific Review of EPA's Standards" published by the National Academy of Sciences Engineering and Medicine for details. The book can be read online at https://www.nap.edu/catalog/11571/fluoride-in-drinking-water-a-scientific-review-of-epas-standards. Chapter 7 is dedicated to documenting evidence on neurobehavioral effects.

[6]Green et al. (2019) find an association between maternal fluoride exposure and IQ among children in Canada. See a comprehensive list of all studies related to this at https://uva.theopenscholar.com/files/ground-water/files/fluorideiq_studies_list_0.pdf

as measured by CPM.

In addition, children exposed to these elevated levels of fluoride exhibit other adverse consequences such as increased tooth pitting, a reduced ability to complete physically demanding daily activities, and worsened standardized test scores (Math, English, and Hindi). Given the established and consistent relationship across various economic contexts between IQ, standardized test scores, and labor market returns (de Hoyos et al., 2021; Gensowski et al., 2011; Rose, 2006), our findings strongly suggest that elevated fluoride exposure during childhood has long-term and persistent consequences for the individual's welfare and, ultimately, economic growth.

Importantly, and as expected from the quasi-random nature of fluoride variation, there is no evidence that this relationship is the result of confounding differences between children with more or less fluoride exposure as we find that fluoride exposure is unrelated to a host of observed individual and household characteristics. Yet, there are two predominant remaining threats to the causal identification of our empirical strategy.

The first is that other minerals and water characteristics correlated with the presence of fluoride have an unexpected or undocumented relationship with our outcomes of interest, which we are falsely attributing to elevated fluoride exposure. However, other potential contaminants such as lead, mercury, and arsenic rarely exceed their respective safe permissible limits in our sample and are not correlated with the observed level of fluoride.

The second is that there are unobserved characteristics of our respondents and their families that vary across fluoride exposure levels and are correlated with cognition and physical health, but are not captured by our observed individual and household characteristics. We support our causal claim with a wide array of falsification, sensitivity, and placebo tests. For example, our estimates are robust to various specifications and estimation choices. In addition, we show balance in a large number of characteristics at the household and village level, which provides strong evidence against endogenous sorting.[7] We further address this issue by showing that there is no selective migration or differences in overall mortality, infant mortality, probability of survival, or fertility in areas with high and low fluoride.

Our findings inform the debate on whether fluoride is a neurotoxin.[8] While we detect positive effects of fluoride exposure on cognition below the WHO-permissible limit of 1.5 mg/L, we show that when the fluoride level exceeds this guideline, it severely harms children's cognition, human capital, and health. Hence, if a fluoridation policy were to be pursued because of its benefits for dental health, continual measures should be taken to ensure that the

[7]Household and village level characteristics include measures of wealth, income, demographics, geography, and access to health care.

[8]See Aoun et al. (2018) for a detailed discussion and review.

levels do not exceed 1.5 mg/L.[9] In developed countries, surveillance of a child's development by healthcare providers can signal a risk or concern. However, in developing countries, children are not routinely screened for neuro-toxic exposure.[10] Thus, our work suggests that policies that prioritize early detection will help reduce the distributional impact of environmental exposure.

Our study advances the literature examining the consequences of fluoride exposure in several key ways. First, we corroborate earlier findings that fluoride exposure below the WHO threshold is not harmful to cognition and may, in fact, be beneficial (e.g., Malin and Till, 2015; Aggeborn and Öhman, 2021b). Unlike prior work that treats IQ as a single metric, we disaggregate it and show that low-level fluoride exposure is positively associated with specific cognitive domains—namely, memory, attention, and executive function. Second, we provide novel evidence on mechanisms. While previous studies have primarily attributed fluoride's benefits to improved dental health, we show that enhanced manual dexterity also plays an important role. By integrating results from cognitive assessments and the Purdue Pegboard test, we uncover a new channel through which fluoride exposure, at safe levels, may support child development. These insights highlight specific domains of cognitive and physical development that have received limited attention in the economic literature on fluoride exposure. Finally, by clarifying both the risks of overexposure and the nuanced benefits of safe exposure, our findings provide timely, policy-relevant evidence to inform debates on fluoride regulation and public health strategies in both developed and developing country contexts.

Our study also speaks to the broader literature on environmental neurotoxins and child development. Prior research has established causal links between exposure to lead (Aizer et al., 2018; Aizer and Currie, 2017), arsenic (Pitt et al., 2015), radiation (Almond et al., 2009), and iodine deficiency (Field et al., 2009; Feyrer et al., 2017) and adverse developmental outcomes. We extend this literature by providing one of the few rigorous causal estimates of the effects of elevated fluoride exposure on both cognitive development and physical health. In doing so, we highlight fluoride as an important, yet underexamined, environmental risk factor in the global landscape of neurotoxic exposure.

The rest of the paper is organized as follows. Section 2 provides background information. Section 3 describes the data, and Section 4 documents our empirical strategy. In Section 5, we report the main results on the effect of fluoride exposure on different non-cognitive and cognitive outcomes of children. Section 6 discusses adaptive behaviors that

[9] Since people ingest fluoride from many sources, including diet, and also use fluoridated toothpaste, the optimal fluoridation guidelines may need to be considered.

[10] None of the children in our sample have ever been screened.

households may take to mitigate the detrimental effect of elevated fluoride exposure. In Section 7, we conduct a number of robustness tests and in Section 8, we provide concluding remarks.

2 Background

2.1 Naturally occurring Global Issue

Fluorine commonly occurs in the Earth's crust. As fluorides, they are naturally found in several minerals such as fluorspar, cryolite, and fluorapatite. In areas rich in fluoride-containing minerals, groundwater commonly comprises approximately 10 mg/L fluoride. Naturally occurring concentrations of staggering proportions have been found in India, China, Central Africa, and South America and occur regionally in most parts of the world. Based on data from 16 states, the US Environment Protection Agency (EPA) estimated that around 1.5-3.3 million people in the US are served by public water supplies that contain fluoride concentrations greater than 2.0 mg/L and 118-301 thousand people receive water with a fluoride concentration greater than 4 mg/L (EPA, 2010).[11] In India, 17 states and around 62 million people are chronically exposed to excessive fluoride levels in drinking water, and few resources are currently dedicated to reducing this exposure.

In Rajasthan, where our study site is situated, the high concentration of fluoride is geogenic in nature (Singh and Mukherjee, 2015; Agrawal et al., 1997; Handa, 1975) as high pH and salt due to evaporation coupled with an arid climate result in conducive conditions for the heavy leaching of fluoride into the groundwater.[12] Moreover, the characteristics of the bedrock, the alkaline hydrogeological environment, and geochemical processes in Rajasthan produce substantial local variation in fluoride.[13]

2.2 Biology and WHO limit

The World Health Organization's review of evidence on the health consequences of fluoride exposure has informed their guidance that the permissible limit in drinking water should be set at 1.5 mg/L (WHO). The guidelines were established in 1984 and reaffirmed in 1993. They

[11] In 2017, based on data from 30 states in the US, the CDC puts the number of people exposed to fluoride over 1.5 mg/L at 1.4 million (Data available from CDC my Water's Fluoride portal).

[12] When Alkaline waters (characterized by high pH) come in contact with fluoride mineral-bearing rocks, the probability of leaching increases.

[13] Occurrence of $F-$ in the groundwater of Rajasthan is extensively documented (Hussain et al., 2012; Madhavan and Subramanian, 2002). The types of fluoride-containing rocks in this region include schist (1703 mg per kg), gneiss (1563 mg per kg), granite (1043 mg per kg), silexite (982 mg per kg), conglomerate (963 mg per kg), and sandstone (903 mg per kg).

have concluded that fluoride exposure is associated with dental, non-skeletal, and skeletal fluorosis at higher levels. Later, WHO (2002) concluded that there is clear evidence from India and China that skeletal fluorosis and an increased risk of bone fractures are associated with higher fluoride intake.[14]

Most of our understanding of the health consequences of exposure to fluoride is derived from theory-based hypotheses, correlational studies, and animal experiments. This is also true with respect to fluoride's relationship with cognition. Specifically, four designs have been used to shed light on the biological pathways by which fluoride can affect the brain and the nervous system.

The first type of study analyzes laboratory assessment of fluoride dose-response in mice, rats, and rabbits. They find that chronic exposure in the range of 1.2 to 3 mg/L alters reaction time and visuospatial abilities (Westendorf, 1975). A second set of studies focused on human subjects and used small sample experimentation where the subjects underwent exposure, withdrawal, and re-exposure. The conclusions of these studies included reports of mental and physiological changes after exposure to fluoride (Waldbott et al., 1978). A third study design relies on comparing medical assessments of aborted fetuses whose mothers are exposed to high levels of fluoride with those whose mothers are not exposed.[15] These embryonic comparisons indicate differential developmental pathways for children exposed in utero. The magnitude of damage is large and consistent across these studies. Lastly, various empirical studies document the correlational relationship between fluoride and cognition and present mixed evidence. However, confidence in the validity of the results of these studies is limited due to the use of small, unrepresentative samples and low quality data (US Public Health Service, 2015). As a result, the National Research Council recommends more research in this area (Doull et al., 2006).[16]

The most credible attempt in this literature to establish the causal effects of ingestion of fluoride through drinking water on cognition comes from Aggeborn and Öhman (2021b). Their empirical evaluation uses data from a cognitive assessment of military enlistees in

[14] This conclusion was supported by the United States National Research Council in 2006 (Doull et al., 2006) and an EPA report which states that exposure to concentrations of fluoride in drinking water greater than 4 mg/L appears to be positively associated with an increased relative risk of bone fractures (EPA, 2010).

[15] Fluoride crosses over the placenta and is associated with developmental problems (Shen and Taves, 1974). Li et al. (2008) compared 44 neonates and mothers from 6 villages with fluoride levels of 1.7 to 6 mg/L in water to 47 neonates from 4 villages in the same county in China with fluoride levels of 0.5 to 1 mg/L. Their results indicate that in-utero exposure to elevated fluoride can adversely affect neonates' neuro-behavioral development.

[16] The comprehensive list of these studies is documented at https://uva.theopenscholar.com/files/groundwater/files/fluorideiq_studies_list.pdf. See Tang et al. (2008) and Choi et al. (2012) for reviews of studies in China. For other countries, see (Rocha-Amador et al., 2007); (Broadbent et al., 2015) ; (Malin and Till, 2015); (Perrott, 2017); (Barberio et al., 2017)

Sweden and pairs it with fluoride variation in municipal tap water. The mean fluoride level in their sample is 0.353 mg/L, with a standard deviation of 0.325 mg/L. In their setting, where fluoride exposure exceeds 1.5 mg/L for less than .5% of the population, they do not find a detrimental effect on cognitive outcomes. In fact, they estimate a positive effect on labor market outcomes, which they attribute to better dental health.

Aggeborn and Öhman (2021b) helped to set a higher standard of rigor within this area of study and provided a reliable estimate of the relationship between cognition and low levels of fluoride exposure. Unfortunately, many regions in the developing world and some parts of the developed world do not have access to water with the fluoride concentration levels found in Sweden. Given the guidance that fluoride levels above 1.5 mg/L may have adverse consequences and the fact that many developing countries lack institutional structures, political will and/ or regional infrastructure to regulate, monitor or mitigate exposure, we continue to have a large gap in our understanding of the relationship between elevated fluoride exposure and cognition.

3 Data

3.1 Sampling and In-Person Survey

To conduct this study, we collected primary data from 7 districts of Rajasthan, India. We administered an in-depth household survey that included instruments focused on cognition, health, household finances, and time use, among others. Appendix A provides details of our sampling strategy. Overall, we used data from 815 households spanning 275 villages.[17,18,19]

A rich survey was also conducted focusing on the children in the household. Specifically, the focal female respondent answered questions about the sampled child's health conditions, health care needs, and nutrition.

[17] In India, a *village* is the smallest recognized rural settlement unit with defined boundaries. In the administrative hierarchy it sits at the bottom: State/Union Territories → District → Sub-district → Gram Panchayat → Village; the Gram Panchayat is the lowest elected body and may govern one or several villages. On an average, our simple village has 272 households and an average population of around 1388.

[18] We interviewed 822 households but could not correctly identify 7 of them.

[19] Our original plan was to cover 300 villages in 8 districts, but a sudden change in taxation policy escalated our costs, and we could not reach the last district. We discuss the sampling and the repercussions of this truncation in Appendix A2. A detailed discussion on sampling is available on the project webpage (https://uva.theopenscholar.com/ground-water/sampling).

3.2 Health

3.2.1 Dental Condition

Physical observations were made to examine children's teeth for dental problems such as pitting, staining, or opaque surfaces indicative of dental fluorosis.

3.2.2 General Health Condition- Activities of Daily Life

Our surveys also asked about the physical ability of an individual to perform activities of daily life (ADLs). These functioning measures are based on the individuals' self-rated capacity to engage in specific activities and assess illness symptoms.[20] The ADLs surveyed include walking for one kilometer, carrying 10 kg for 250 meters, drawing a bucket from a well, climbing a ladder for two meters, and the ability to bathe oneself. Difficulty in performing ADLs is associated with severe chronic morbidity (Ralph et al., 2013).

3.3 Psychometric Testing

We use two tests to measure intelligence: one to measure generalized intelligence, which also helps us to compare our results with the literature, and the other to measure specific types of IQ abilities such as executive function, processing speed, attention, and visual discrimination.

3.3.1 CPM

General IQ in children was measured using the Hindi Edition of the Raven's Colored Progressive Matrices (CPM). In these assessments participants must identify the missing component in a series of figural patterns in increasingly difficult sets. For the CPM, norms exist to translate the score to a standard distribution by matching the raw score and age of the child to the norms table.[21] After this step, scores are scaled across age groups to compare children's performance even if they are at different developmental stages. In the case of the CPM, the tables also provide a percentile rank. For extremely high or low scores, a normed score is not available in the CPM norms table, whereas percentiles were available for every child in our data. We discuss the implications of missing data in the robustness section (Section 7).

[20] The physical functioning measures have been used extensively for reliability and validity. Economists have used these measures in developing and developed country settings to study health (Bound, 1991; Strauss and Thomas, 1995).

[21] Our cognitive team collected the age of the child based on administrative records. We used this certificate age for norming.

3.3.2 MISIC

Malin's Intelligence Scale for Indian Children (MISIC) is adopted for Indian children from the American test Wechsler WAIS. MISIC has norms for Hindi-speaking Indian children between the ages of 6 and 15 years. Our sample children are native speakers of Hindi. While MISIC has 11 sub-scales, we chose 3 sub-scales to test: Coding, Digit Span, and Mazes. In Appendix A1, we explain in detail why these were chosen and their validity for Indian children. Digit span tests attention and memory. The digits are given in non-logical order, and the participants are asked to recite the digits in either the same or the reverse order. Mazes test the planning ability of executive function and coding tests processing speed and visual discrimination. Participants are given a worksheet and asked to use a key to either mark pictures with a corresponding symbol or write the symbol for a corresponding numeral. We use normed scores on these sub-scales as outcomes.

3.4 Perdue Pegboard

Perdue Pegboard measures manual dexterity, speed, and fine motor coordination. Children work with a rectangular board with two sets of 25 holes running vertically down the board and four cups at the top. Each cup holds small metal pegs; children must remove and place as many pegs as quickly as possible in 30 seconds. The number of pegs inserted using specific hands in 30 seconds is tested. This takes 5-10 minutes to administer. The number of pins inserted is separately tallied for trials using first the left hand, then the right hand, and finally with both hands, and the sum of all three is recorded. The time taken to complete a complicated coordination task in which the children use washers, pins, and collars and assemble them is also measured, and the test is called assembly. Data Appendix A1 provides additional details about this test.

3.5 Proficiency Testing

In addition to cognitive batteries, we also administered proficiency tests to the children to measure accumulated human capital.[22] The tests have three components: Mathematics, English, and Hindi (the commonly spoken local language in the area). Each of the tests uses a four-point scale. For mathematics, the skills are: (a) can recognize numbers between 0 to 9, (b) can recognize numbers between 0 to 99, (c) can subtract two-digit numbers, and (d) can divide a three-digit number with a single-digit number. Both the English test and the Hindi test measure the following skills: (a) can recognize a letter, (b) can read a word,

[22] These have been designed by Pratham, an NGO pioneering education initiatives in India. Other large-scale surveys, such as the India Human Development Survey, also use these.

(c) can read a paragraph, and (d) can read a story fluently. Each test score ranges from a minimum of zero (the child has no skill) to a maximum of four (child possesses all four skills). On average, the respondents in our analytical sample had an average score of 1.3, 1.7, and 2.3 in English, Math, and Hindi, respectively.

3.6 Water and Village Characteristics Data

We complemented our survey data by collecting a village schedule that provides information on the infrastructure facilities and geographic characteristics of the village and by taking water samples for each household. The Birla Institute of Technology and Science in Rajasthan tested water samples for parameters such as pH, conductivity, turbidity, dissolved oxygen, and other contaminants such as lead, arsenic, nitrates, iodine, mercury, and E. coli.

3.7 Summary Statistics

A total of 815 households were surveyed but the psychological batteries were only administered to 509 children as our costs increased unexpectedly during the midst of data collection following the passage of the Goods and Services Tax Law in India.[23] Therefore, in our main analysis, we use the sample for which psychological tests could be administered. However, for outcomes with data available for all children, we performed additional robustness checks using the full sample. These analyses show that our results remain consistent across both sets of children.

The summary statistics of our outcome variables are described in Table 1. The CPM normed percentile score average is 28.24, and the standard deviation is 23.46. The mean of the MISIC normed score is 91.76. 59 % of the children in our sample experience difficulty in performing at least one activity of daily living, and 45 % have dental problems of some type, including pitting, staining, or opaque surfaces.

The demographic data of the child and the mothers for this sample are shown in Table 2.[24] We generate a set of binary variables classifying households into each distinct category of caste (general caste, scheduled caste, scheduled tribe, and other backward caste), religion (Hindu, Muslim and Jain), and sex (male, female). 48% of the children are female. Only 29% of the mothers are educated, whereas 74% of the fathers have received formal education. About 23% of the total monthly expenditure of the household is on the sample child, including food, schooling, nutrition, and healthcare.[25] The children in our sample are

[23]We discuss the implications of this sampling decision in Section 7.

[24]The corresponding summary statistics for the full sample is presented in Appendix Table A1.

[25]The share of household expenditure on the sample child is the sum of all expenditures reportedly consumed by the sample child, divided by total household expenses.

around 8.41 years old and most of them are Hindu.

The average fluoride in our sample is 1.75 mg/L, and the maximum value is 4.70. In Figure 1, we demonstrate the distribution of fluoride in our sample and display the WHO-permissible limit. An important implication of this figure is that unlike in the developed country settings previously used to study this relationship in the economics literature, a large proportion of the population in our sample, as in much of the developing world, uses drinking water containing fluoride above the WHO permissible limit of 1.5 mg/L.

4 Estimation Strategy and Identification

4.1 Empirical Model

Fluoride varies naturally in the underlying rock beds that form the aquifers and the geochemical properties of water interact with the rock materials to create high or low fluoride concentrations. The confluence of high pH and salinity of water with underlying rocks bearing fluoride is the most conducive setting to generate leaching of high fluoride levels into groundwater. Our identification strategy rests on the idea that this fluoride producing process is quasi-random, and thus the variation we exploit is not correlated with other bias-inducing regional, temporal, or household characteristics. The use of this naturally occurring variation mirrors the strategy employed by Aggeborn and Öhman (2021b) and is represented in the following empirical model:

$$Y_{ih} = \gamma_0 + \tau F_h + \delta X_{ih} + u_{ih} \tag{1}$$

where Y_{ih} is the outcome of interest for child i living in household h and F_h is a linear measure of fluoride (mg/L) detected in the water. X_{ih} represents a set of controls that includes attributes of water such as dissolved oxygen, pH, conductivity, turbidity, lead, arsenic, mercury and nitrates, as well as individual and household characteristics such as gender, an index of household assets, the level of education of the mother and father, the share of expenditure on the child, and religion and caste fixed effects. We also control for the individual's age directly in the regressions when the outcome of interest is not already a value normed by the respondent's age.[26] u_{ih} represents the error term and is estimated by clustering standard errors at the village level.

However, unlike in Aggeborn and Öhman (2021b), the environment we study has a

[26]The IQ outcomes are normed, indicating that the measure has already been adjusted to account for the child's age by referencing a table of age-specific norms for the cognitive assessment. In these cases, we do not control for the child's age; however, for all other outcomes, we control for the child's age.

great deal of variation in fluoride levels, which is representative of the reality that exists for people living in regions without strictly regulated water sources. Most relevantly, over 50% of our sample is exposed to water containing more fluoride than the WHO-admissible limit of 1.5 mg/L, which has been associated with clinical manifestations of bodily impairments. Hence, in addition to a simple linear relationship for fluoride intensity, we also estimate a model that purposefully explores impacts at levels above the recommended exposure level. Our model that incorporates the WHO permissible limit of 1.5 mg/L is:

$$Y_{ih} = \gamma_0 + \tau D_h + \delta X_{ih} + u_{ih} \tag{2}$$

where D_h is an indicator variable that takes the value 1 if the fluoride value of household water is greater than 1.5 mg/L and 0 otherwise. Vector X_{ih} includes, as before, water quality characteristics: dissolved oxygen, pH, conductivity, and turbidity; and Demographic controls: asset index, the share of household expenditure on the sampled child, mother's education, father's education, religion, caste, and sex. Our asset index measure is a count of all assets owned by the household.[27]

4.2 Identification Concerns

4.2.1 Other Contaminants

The empirical strategies proposed in models 1 and 2 face two primary challenges to causal identification. The first potential concern is that other minerals or contaminants, which could also have an undocumented or unforeseen connection to our outcomes of interest, could be correlated with fluoride. We show that this is not a first-order concern in our specific case for three reasons.

First, we find that there is no, or negligible, presence of other contaminants in this region's drinking water. In Appendix Table A2, we document the levels of fluoride, lead, nitrates, mercury, arsenic, and E-coli in our sample.[28] We report the safety thresholds recommended by the World Health Organization (WHO), the mean value and the standard deviation. While 45 percent of our sample has fluoride above the WHO-permissible limit, none of the households have lead and mercury exceeding the permissible limit. Arsenic levels exceed the permissible limit in 5% of sampled households, nitrate levels are above the allowable threshold in 19% of households, and only 5% of the households have any E-coli in their water.

[27] We discuss the balance of these characteristics in a later section.

[28] E-coli measures bacterial contamination of water.

Second, using an array of specifications, we show that these contaminants are not correlated with fluoride. To this end, our first test explores whether the levels of different water contaminants are balanced on either side of the WHO-permissible level of fluoride. Panels (a) to (e) of Figure 2 show that lead, mercury, nitrates, arsenic and E-coli do not vary with the level of fluoride nor do they change across the threshold of 1.5 mg/L. Thus, we conclude that the presence of these toxins is not correlated with fluoride, and if anything, the toxins are slightly lower at higher levels of fluoride.

In our second test, we additionally examine the correlation between fluoride and other water contaminants using two alternative measures of fluoride exposure: the standardized continuous fluoride level and a binary indicator for fluoride concentrations exceeding 1.5 mg/L. In Appendix Table A3, we show the estimates for the continuous measure in Panel A and the indicator specification in Panel B. The first four columns examine each contaminant one-by-one and the last column regresses fluoride on all these contaminants. Reassuringly, neither measure of fluoride is significantly correlated with any of the other contaminants.

Our additional test explores potential for non-linear relationships. In Appendix Table A4, we regress fluoride indicator bins (in 1 mg/L intervals) on the continuous measures of other contaminants to test whether the relationship between fluoride and other contaminants changes across different fluoride concentrations. This approach helps identify potential nonlinear patterns that might be masked in simple correlations. Consistent with the earlier findings, we observe no systematic relationship between fluoride and other contaminants across the distribution. The only exception is nitrates, which exhibit a negative association with fluoride at the highest concentration bin, indicating that, if anything, nitrate levels tend to be lower in areas with very high fluoride concentrations.

Lastly, we construct an index of these contaminants for each observation. This *toxins index* is a projection of variables that are potential toxins in drinking water (lead, mercury, arsenic, Nitrates, and E. coli.) on the normed CPM percentile outcome.[29] Similar to our examination of each toxin separately, Panel (f) of Figure 2 shows that the toxin index is balanced on either side of 1.5 mg/l, flat across fluoride's support in our data, and if anything, is correlated with slightly better CPM outcomes at higher levels of fluoride. In robustness tests discussed later, we also show that the results are unchanged when including this index as a control variable.

The third reason that bolsters our confidence in our results is that we control for these in our specifications (separate column in all tables) and find that the results are unaltered.

[29] *Toxin Index* in Appendix A2: Covariate Indices documents the construction of this index.

4.2.2 Endogenous Sorting

The second potential concern for identification would be the presence of endogenous sorting of households with respect to fluoride levels in the drinking water. For example, if households with more resources could move away from areas with elevated fluoride in the drinking water this would generate an overestimate of our hypothesized relationship.

We provide a few pieces of evidence that suggest this type of composition contamination is not occurring. First, we investigate and conclude that migration behavior and fertility choices were orthogonal to fluoride levels (Appendix Tables A5 and A6). In addition, we find that infant mortality did not vary across different fluoride exposure groups (Appendix Table A7). Lastly, we show that there is balance in our observed individual and village characteristics across household fluoride values (details provided in Section 7.1).

5 Results

5.1 When Fluoride is safe as per WHO guidelines (below 1.5 mg/L)

As a complement to Aggeborn and Öhman (2021b)'s findings in a developed country context, we first examine the effects of childhood exposure to fluoride on cognition in Rajasthan, India for a subsample where fluoride levels are lower than the WHO-permissible threshold for drinking water.[30] Column 1 of Table 3 provides the estimates of equation 1 when using the CPM percentile rank as the outcome of interest.

This table's results corroborate the conclusions of Aggeborn and Öhman (2021b) for a very different setting. Specifically, we show that when childhood fluoride exposure is restricted to levels below 1.5 mg/L, even in a developing country context, there is no evidence of worsening cognitive performance. Moreover, the coefficients for normed CPM are positive and non-trivial in size, despite being imprecisely estimated, and the estimates for the MISIC intelligence test are statistically significant and indicate that a 1 standard deviation increase in fluoride exposure below 1.5 mg/L leads to a 10% higher score. These results suggest that when fluoride exposure is below 1.5 mg/L, it has a beneficial impact on cognition.

We next extend the assessment of the effects of low levels of fluoride exposure on psychometric tests by distinguishing which areas of cognitive function drive the positive association. When exploring the components of that result in Table 4, the gains seem to be driven by economically meaningful and statistically significant improvements in the ability

[30] The summary statistics for this sample is reported in Appendix Table A8.

to plan (represented by a 15 percent improvement in mazes) and memory/attention (as indicated by a 7.3 percent improvement in Digit Span).

We follow up these findings with an investigation of whether the IQ gains these children receive from low-level fluoride in their drinking water also lead to improvements in their human capital. To do this, we test the relationship between fluoride exposure below the WHO permissible level and proficiency test scores.[31] Table 5 reports the effect of low level fluoride exposure on math, English and Hindi proficiency scores. We find that Math scores increase with fluoride levels below the WHO permissible standard and that the effect is substantial (43 percent of the mean math score) and statistically significant. A similar positive relationship exists between fluoride exposure within the permissible level and English and Hindi language proficiency, although the latter is not statistically significant.[32]

We next examine how low levels of fluoride exposure affect dental health, measured by the presence of pitting, staining, or opaque surfaces on a child's teeth. As seen in columns (1) to (3) of Appendix Table A10, somewhat unexpectedly, we find a positive, though statistically insignificant, association between higher fluoride concentrations and the incidence of dental surface irregularities. A closer inspection, however, reveals a nonlinear relationship: fluoride appears to be beneficial for dental health at lower concentrations (below 1 mg/L) but becomes detrimental as concentrations rise beyond this level (Appendix Figure A.1). These results are incongruent with finding of previous literature which finds a positive relation between fluoride and teeth health. One reason to be cautious in comparing these results to other studies is the differences in the measures of dental health. We look at pitting, staining, and such visible markers, whereas other papers have used loss of teeth due to tooth decay or gum disease (Glied and Neidell, 2010), or preventive care measures (e.g., examinations and risk evaluations) and treatment-related procedures (e.g., general treatment, dental repair, and root canals) (Aggeborn and Öhman, 2021a) as the measure.

Lastly, given the complementary relationship between dental health and nutrient absorption, we investigate whether below-threshold fluoride exposure affects broader health outcomes. To this end we use two outcome variables. First, we see the effect of fluoride on the probability that a child faces difficulty in performing one or more activities of daily living (ADLs) (columns (4) to (6) of Appendix Table A10). We observe a negative relationship between fluoride levels below 1.5 mg/L and the likelihood of experiencing difficulty in at

[31] English proficiency has been shown to be a skill that is very important for success in the labor market in developing countries (Munshi and Rosenzweig, 2006; Shastry, 2012), and math aptitude is highly correlated with selection into college majors and occupations with high returns (Joensen and Nielsen, 2009; Hanushek and Woessmann, 2008).

[32] We also run these regression when not confining the analysis to the sample for which psychometric tests were administered, and found qualitatively similar results for Math and English proficiency (Appendix Table A9).

least one ADL, but this result is imprecisely estimated and statistically insignificant.

Second, we explore the impact of low levels of fluoride exposure on dexterity and motor coordination, as fluoride also matters for bone and muscle health in children. We show that there is a significant improvement in dexterity and motor coordination when completing the Purdue Pegboard assessment. Table 6 provides these results. Panel A reports estimates when using the right hand, Panel B when using the left, and Panel C when both are used. Panel D, which is the sum of these, indicates that a one SD increase in fluoride in this sample increases dexterity that requires simple coordination by 2.97, a 10.7 percent increase compared to the mean value. In Panel E, we find that the dexterity for tasks requiring complicated coordination increases by 24 percent compared to the mean value, significant at the 1 percent significance level. Thus, improved economic outcomes associated with fluoride exposure below the permissible threshold may be mediated not solely through better dental health—as previously emphasized in the literature—but also through enhanced fine motor skills and manual dexterity.

The previous literature concluded that there is a positive impact of fluoride exposure on cognitive and economic outcomes. However, these results were only representative of this relationship within a highly developed nation with a strongly regulated water supply, Sweden, in which the variation in fluoride levels is narrow and very rarely exceeds the WHO-permissible limit of 1.5 mg/L. Our novel results show that this causal effect of fluoride exposure at low levels is also exhibited and may be even stronger in a sample of rural children in a developing country context.

5.2 When Fluoride Exceeds the WHO permissible limit for Drinking Water

Despite the consistency of our findings in the previous section with the work of Aggeborn and Öhman (2021b), a large scientific gap remains when considering whether the benefit of low-level childhood fluoride exposure on cognition persists, attenuates, or reverses when higher levels of fluoride are considered in a developing country setting. In this section, we address this gap by using our full analytical sample, which, as in most developing countries, contains a substantial number of households with fluoride variation above the WHO permissible limit.

We start by examining the impact of fluoride exposure at levels above the WHO-permissible limit on cognition and human capital. Columns (1) to (3) in Panel A of Table 7 provide estimates of model 1 and columns (4) to (6) provide estimates of model 2 on the full support of fluoride in our sample when using normed CPM percentile rank as the dependent variable. In each of these analyses, the point estimate is negative, and when individual, household, water characteristics, and water contaminants are included as controls, we find there is an economically and statistically significant adverse relationship between fluoride exposure above 1.5 mg/L and intelligence. Our results indicate that children exposed to fluoride levels above the WHO-permissible limit rank 16% (or 4.5% points) worse, compared to the mean, on the CPM than children exposed to water containing less than 1.5 mg/L of fluoride. A second takeaway from these results is, to the extent that any bias-inducing factors excluded from columns (1) and (4) are captured by the over 20 characteristics we observe and include in our full specification, the similarity in the estimates across the columns of Panel A of Table 7 suggests that omitted variable bias is not an obvious concern for our interpretation of these findings.

As in the previous section, we also explore the effects of fluoride exposure on MISIC. When using the full sample, as seen in Panel B of Table 7 and Appendix Table A11 we find corroborating evidence that the relationship between elevated fluoride and these outcomes is negative, but that these estimates are generally small and statistically insignificant. For these outcomes, though, the estimates using equations 1 and 2 hide relevant nonlinearities in the relationships. Specifically, as seen in Appendix Tables A12 and A13, when linear splines knotted at 1.5 mg/L of fluoride are used, we uncover a statistically significant increase for the spline below 1.5 and a large and statistically significant decline for the spline above the threshold of 1.5 mg/L. In particular, the gains at low fluoride levels are completely offset at fluoride levels that exceed the WHO-permissible safe limit.

Our estimates provide strong and consistent evidence that children exposed to fluoride above the WHO permissible limit of 1.5 mg/L display poorer performance on cognitive assessment tests. We next explore whether this decrease in cognition translates into measures more closely associated with academic performance and human capital. In Table 8, we estimate the effect of fluoride exposure above 1.5 mg/L on Math, English, and Hindi proficiency test scores. Columns (1)-(3) show that unlike the conclusions from Table 5 math and Hindi Language scores are *negatively* impacted by the fluoride exposure when the sample's full variation in water quality is exploited. More precisely, a one SD increase in fluoride level reduces math and Hindi scores by a statistically significant 5% and 6%, respectively. Similarly, Columns (4)-(6) reveals a qualitatively similar negative relationship between childhood fluoride exposure above 1.5 mg/L and the proficiency test scores. While the coefficients in Columns (4)-(6) are not statistically significant, this is most likely driven by a lack of power rather than a non-existent relationship, as similar estimates that also include children without a CPM score, provide quantitatively equivalent, but statistically significant estimates (Appendix Table A14).

The strong, consistent, and negative relationship between childhood exposure to elevated levels of fluoride and determinants of important labor market skills further highlights its potential to generate long-term and persistent gaps in socioeconomic status, productivity, and general welfare. Understanding these developmental losses requires a closer look at the physiological channels through which fluoride acts on the body during childhood. Guided by the medical literature, we therefore turn to an examination of the mechanisms, starting with the role of dental health as a primary and observable manifestation of chronic fluoride exposure. To this end, we estimate equations 1 and 2 using the presence of pitting, staining or opaque surfaces on the child's teeth as the outcome of interest. Columns (1) through (4) in Panel A of Table 9 confirms the predicted adverse relationship and shows that a one SD increase in fluoride increases the likelihood of dental decay by 6-7 percentage points (columns 1 to 3) and that the likelihood of dental decay increases by 16 percentage points when fluoride exceeds 1.5 mg/L.

Increased rates of dental fluorosis are also likely to cause harm to general health. Beyond the physical limitations of skeletal fluorosis, sensitivity and loss of teeth can non-trivially effect nutrient intake and absorption. To test the impact of elevated fluoride exposure on general health, we focus on two main outcomes. First, we estimate equations 1 and 2 on ADLs. The results using ADLs to measure children's health are reported in columns (1) to (6) in Panel B of Table 9. Using either specification, we find that the probability of having difficulty performing at least one ADL is positively and statistically significantly related to fluoride exposure. Our estimates indicate a 10-13% increase in having one of these limitations when fluoride levels exceed 1.5 mg/L in drinking water.

Second, we examine whether elevated fluoride exposure affects dexterity and motor coordination. Appendix Table A15 shows that the coefficients are generally negative, though imprecisely estimated. However, as with the MISIC scores, these relationships appear non-linear. Table A16 shows that once we allow for linear splines with a knot at 1.5 mg/L, we uncover meaningful heterogeneity: performance improves significantly at fluoride levels below 1.5 mg/L, but declines sharply and significantly once fluoride concentrations exceed this threshold.

6 Adaptive Behaviors: Dietary Changes and Intake of Water

An important behavioral response to elevated fluoride levels that these households may take is to change their diet and consumption of water. Since certain foods are known to increase or decrease fluoride absorption in the body, we collected data on household's food intake. We then created two indices, the *fluoride-inhibiting index*, which is the average of binary variables indicating whether the child consumed foods which reduce the absorption of fluoride, and the *fluoride-augmenting index*, which is the average of binary variables indicating whether the child consumed foods which typically contain fluoride.[33] Appendix Figures A.2 and A.3 show that the *fluoride-inhibiting index* and the *fluoride-augmenting index* are flat throughout our sample's fluoride support, indicating that there is no evidence of a dietary behavioral response based on the household's fluoride exposure level.

Similarly, when examining potential behavioral adaptations in fluid intake, we find no significant differences in the amount of water or milk consumed across fluoride exposure levels (Appendix Tables A17 and A18). Given that fluid intake may directly influence total fluoride ingestion, this result strongly implies that children in high-exposure areas are in fact ingesting larger absolute amounts of fluoride than those in lower-exposure regions.

Taken together, these analyses suggest that despite the substantial health burden imposed by elevated fluoride exposure, households exhibit minimal behavioral adaptation. This aligns with the broader literature that shows low rates of preventive health investments among poor households despite the long-term benefits in a variety of settings (Kremer and Miguel, 2007; Ashraf et al., 2010; Meredith et al., 2013).

7 Robustness Tests

7.1 Are There Demographic Differences?

Our models would not provide causal identification if family characteristics differ across low and high fluoride levels in our sample. In order to test this, we construct an index of demographic covariates to reduce the dimensionality of the controls.[34] In Figure A.4, we show that the index is flat and smooth across the safe drinking levels threshold established by the World Health Organization. Similarly, in Figure A.5, we show that the village index, which is a projection of village-level covariates on the normed CPM percentile outcome, is uncorrelated with fluoride levels and continuous across the WHO-permissible level of fluoride.

[33] Data Appendix A2: Covariate Indices, provides a discussion on the creation of two indexes: *fluoride-inhibiting index* and *fluoride-augmenting index* based on the consumption of these foods.

[34] The construction details are provided in Appendix Section A3: Covariate Indices.

7.2 Are the Results Robust to Geographical Variation and Constructed Indices?

We next test whether our conclusions about the relationship between elevated fluoride exposure and cognition are robust to a variety of additional controls on top of the demographic and water characteristics that are already included in the models. In Table 10, we add block-level fixed effects to equations 1 and 2, respectively. Blocks are the administrative divisions where development and welfare policies are decided for several villages. Our results are robust to their inclusion. We sequentially add the toxin index (column 2), the fluoride inhibiting and fluoride-augmenting diet indices (Column 3), a village characteristics index in column 4, and an investments index in column 5.[35] Despite this array of controls, our results are stable, and our conclusions are unchanged lending strong support for our identifying assumption.

7.3 Are there Differential Missing Values in the Data?

As mentioned in the description of the data, we were unable to collect information on cognitive batteries for all children due to sudden increases in the costs of surveys. Although this was not systematic, one potential concern would be that the missing observations are different between low and high levels of fluoride. Such differential missingness can potentially bias our estimates. To determine whether we have systematic differences in missing observations, we run a regression of the likelihood that an observation is missing on a dummy variable, which takes the value of one if the fluoride of the water level exceeds the safe WHO threshold level of 1.5 mg/L. The results are reported in Appendix Table A19. The estimates, found in Columns (1) and (3), are not significant at the 10% level, implying that the probability of missing an observation is not related to different levels of fluoride. We also check for systematic attrition by interacting our fluoride exposure measure with other baseline characteristics. As seen in columns (2) and (4), none of the interaction variables is statistically significant, suggesting that selective attrition is not a threat to our identification.

7.4 Is there Differential Avoidance Behavior?

Households exposed to elevated levels of fluoride could invest in adaptive technologies or other means to avoid fluoride. Since we detect deleterious effects on health and cognition for children at elevated fluoride levels, in the absence of such adaptive actions, the estimates

[35] Instead of adding a vast number of controls, we have reduced the dimensionality issue by constructing the indices.

would be even larger in magnitude. However, we directly shed light on some possible adaptive behaviors. Table A20 estimates equation 1 using purchasing a non-electric filter, walking to lower sources of fluoride, purchasing water from other villages, using reverse osmosis or water ATMs, and changing diet or nutrition as the dependent variables. None of these tests detect any significant difference in avoidance behaviors.

8 Concluding Remarks

Our research uses an in-depth household survey, laboratory-tested household water samples, and cognitive assessments to examine whether exposure to elevated fluoride has a causal impact on children's cognition, human capital, and health. We leverage quasi-random variation in naturally occurring fluoride generated by local geological characteristics to show that elevated fluoride exposure, in excess of the WHO permissible safe limit, lowers IQ in children. It also results in tooth decay and generates physical limitations in affected children.

Like many other developing countries, developmental surveillance is not a policy priority in India. In our survey, we asked whether children are screened for elevated neurotoxin exposure, including fluoride, lead, and arsenic. No child was ever screened. Around 70 percent of the mothers are not educated, and for 36 percent of households, food expenditure comprises 50 percent or more of total monthly expenditure, revealing that these households are impoverished. Credit constraints and lack of awareness might be the reason for not screening the children.

Given this, children would benefit substantially from government's initiating policies that help with the detection of childhood exposure to neurotoxins and, subsequently, developing assistance programs that help develop risk prevention plans. Our findings indicate that policies prioritizing the mitigation of exposure to elevated fluoride, as is common for more generally accepted neurotoxins, will help reduce the immediate and persistent distributional impact of environmental exposure and potentially improve long-term economic growth.

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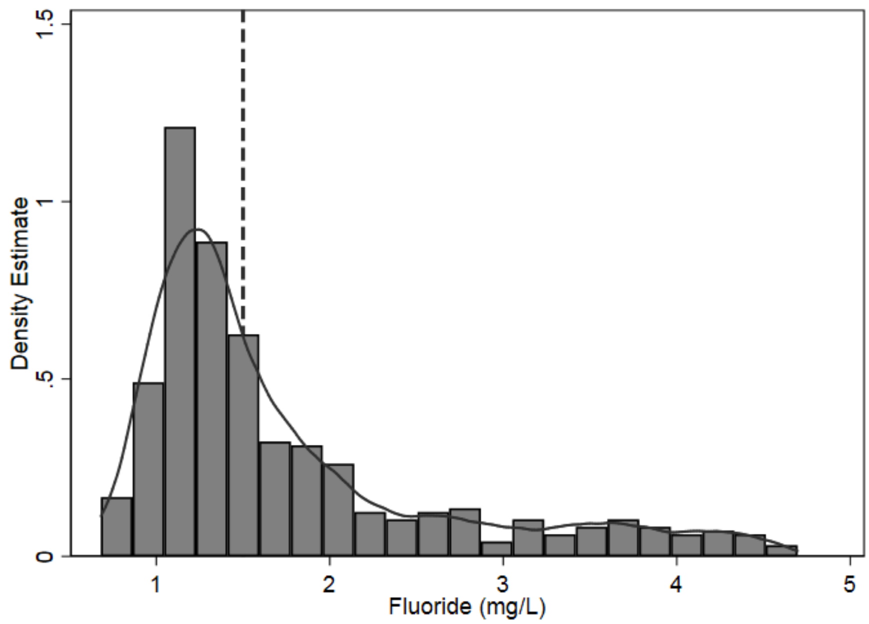
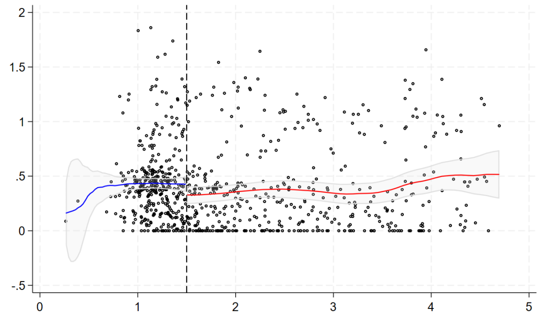
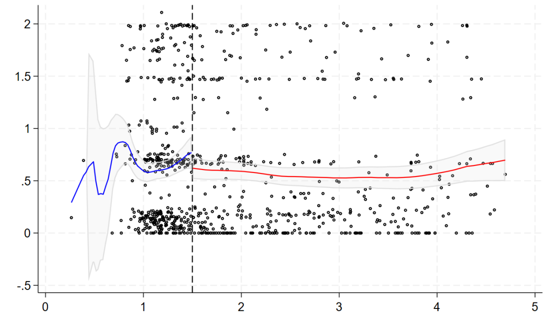


Figure 1: Distribution of Fluoride in Water Samples in Our Population

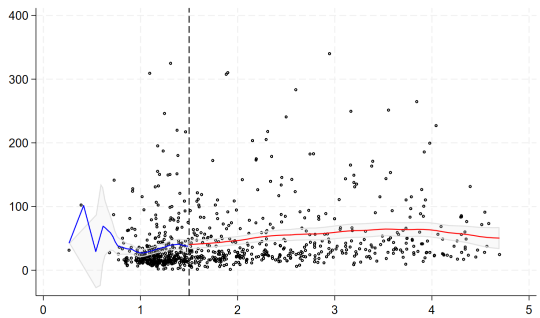
Notes: The figure plots the histogram, the kernel density estimate (epanechnikov kernel), and the WHO permissible threshold (dashed line at 1.5 mg/L) for fluoride in drinking water in our sample.



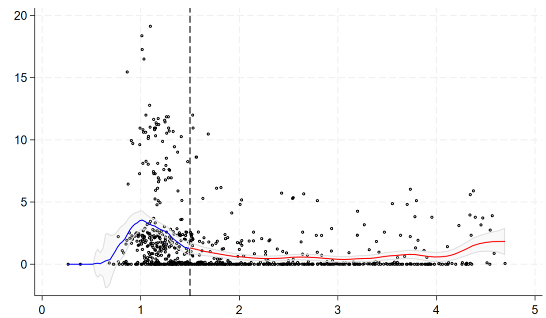
(a) Lead



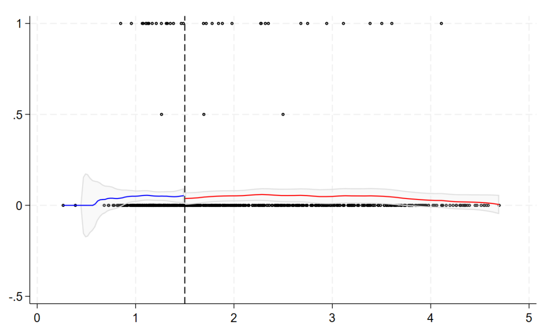
(b) Mercury



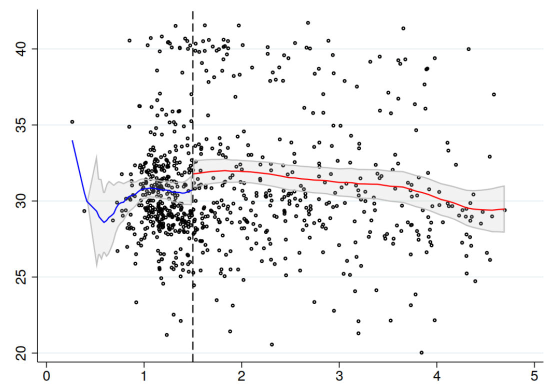
(c) Nitrates



(d) Arsenic



(e) E-coli



(f) Toxins Index

Figure 2: Balance across threshold, different toxins

Notes: Panels (a) to (e) of this figure plots different types of toxins around the fluoride threshold of 1.5 mg/L. Panel (f) plots the toxins index, which is a projection of variables that are potential toxins in drinking water (lead, mercury, arsenic, Nitrates, and E. coli.) on the normed CPM percentile outcome. The linear model's coefficients are estimated from the subset of observations with Fluoride levels not exceeding the WHO permissible limit (i.e., those observations below 1.5 mg/L). The predicted values from this regression (on the y-axis) are plotted against the Fluoride level in the household's drinking water, measured in mg/L (on the x-axis).

Table 1: Summary statistics: outcome variables

	mean	sd	min	max	count
Normed percentile CPM	28.24	23.46	0.10	99.00	509
MISIC normed score (IQ)	91.76	10.41	66.33	123.00	411
MISIC normed coding	95.86	17.59	56.00	149.00	454
MISIC normed digit span	84.16	10.75	59.00	130.00	421
MISIC normed mazes	94.58	15.42	55.00	150.00	443
ADL's: difficulty with any routine activity	0.59	0.49	0.00	1.00	503
Any tooth pitting, staining, opaque surface	0.45	0.50	0.00	1.00	334
Purdue Pegboard: right hand	10.56	2.09	4.00	17.33	506
Purdue Pegboard: left hand	9.80	2.12	0.00	16.67	505
Purdue Pegbord: both hands	7.70	1.95	0.00	12.67	504
Purdue Pegbord: sum of right, left, and both	27.97	6.08	0.00	46.67	505
Purdue Pegboard: assembly	19.44	6.06	0.00	36.00	502
Observations	509				

Notes: This table reports summary statistics for outcome variables. Normed percentile CPM refers to the child's percentile score on the Raven's Colored Progressive Matrices, with reference to a table of norms for the child's agre group. MISIC is Malin's Intelligence Scale for Indian Children, another test of cognitive ability, and scores are calculated with reference to a table of norms such that a child of average ability in the normed population scores 100. ADL's refers to activities of daily life, which is an average of five binary variables, each indicating difficulty in a distinct, routine activity. Tooth pitting, staining, or opaque surface is an indicator of whether the enumerator observed any of these three symptoms on the child's teeth at the time of the survey. Purdue pegboards measure manual dexterity, using either right, left, or both hands to inster small pegs into the slots in a board; the sum of these three is a measure of total manual dexterity, with assembly measuring their dexterity at coordinating a single task with both hands. For all outcomes, higher scores indicate higher ability, except for ADL's and the indicator for observed teeth issues.

Table 2: Summary statistics: child and household demographic characteristics

	mean	sd	min	max
Female	0.48	0.50	0.00	1.00
Assetindex	9.85	3.13	2.00	24.00
MotherEd	0.29	0.45	0.00	1.00
FatherEd	0.74	0.44	0.00	1.00
Share expenditure on child	0.23	0.19	0.00	0.98
Cognitive age	8.41	1.72	4.03	11.99
Hindu	0.98	0.14	0.00	1.00
Muslim	0.01	0.12	0.00	1.00
Jain	0.01	0.08	0.00	1.00
General Caste	0.12	0.33	0.00	1.00
Other Backward Caste	0.58	0.49	0.00	1.00
Scheduled Caste or Tribe	0.30	0.46	0.00	1.00
Mother's number of miscarriages	0.01	0.14	0.00	2.00
Mother's number of stillbirths	0.01	0.08	0.00	1.00
Mother's total number of children died after birth	0.01	0.12	0.00	1.00
Sum of miscarriages, stillbirths, and child deaths	0.03	0.21	0.00	2.00
Fluoride (mg/L)	1.75	0.88	0.68	4.70
Observations	509			

Notes: This table reports summary statistics for child and household demographic characteristics. Assetindex is the sum of the number of assets reported at the time of surveying, MotherEd and FatherEd are indicators of whether the mother or father completed primary school. Share expenditure on child is the share of household expenditure which the household reported spending on the sample child at the time of the survey. Cognitive age is the age of the child at the time of visit by the psychology team, based exclusively on their age according to government-issued documents. Hindu, Muslim, and Jain are indicators of the household's reported religion, and similarly for general caste, other backward caste, and scheduled caste or tribe.

Fluoride Under Safe Limit

Table 3: The effect of standardized fluoride exposure (below 1.5 mg/L) on different measures of intelligence

	Normed CPM Percentile			MISIC average		
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
Standardized Fluoride	10.14	7.75	8.08	9.26**	8.75**	9.19**
	(7.27)	(7.17)	(7.61)	(3.57)	(3.74)	(3.86)
Observations	282	282	282	230	230	230
Demographic Controls	No	Yes	Yes	No	Yes	Yes
Water quality Controls	No	Yes	Yes	No	Yes	Yes
Toxins Controls	No	No	Yes	No	No	Yes
Mean of dep. var	30.19	30.19	30.19	92.16	92.16	92.16

Notes: Columns (1) to (3) present coefficients and standard errors from a regression of normed CPM percentile rank on standardized Fluoride in the household's drinking water, conditional on Fluoride levels below 1.5 mg/L. Normed percentile CPM refers to the child's percentile score on the Raven's Colored Progressive Matrices, i.e. the percentage of children in the normed population who scored less than the sample child's raw score (number of items correct), given the child's age group. Columns (4) to (6) present coefficients and standard errors from a regression of normed MISIC IQ estimate on standardized Fluoride in the household's drinking water, conditional on Fluoride levels below 1.5 mg/L. MISIC is Malin's Intelligence Scale for Indian Children, a test of cognitive ability designed for Indian children, and scores are calculated with reference to a table of norms such that a child of average ability in the normed population scores 100, given the child's age group. Control variables include sample child gender and household share of expenditure on sample child, as well as household characteristics including an asset index, indicators of mother's and father's completion of primary school, household's religion and caste, and household drinking water qualities: dissolved oxygen, pH, conductivity, and turbidity. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates.

Table 4: The effect of standardized fluoride exposure (below 1.5 mg/L) on MISIC subscale performance

	Mazes			Coding			Digit Span		
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Standardized Fluoride	13.92***	13.17***	14.54***	6.29	6.47	6.63	6.80**	6.14*	6.16*
	(4.43)	(4.69)	(5.03)	(5.95)	(6.31)	(6.43)	(3.35)	(3.27)	(3.22)
Observations	245	245	245	247	247	247	232	232	232
R-squared	0.03	0.12	0.16	0.00	0.08	0.12	0.02	0.16	0.18
Demographic Controls	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Water Quality Controls	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Toxins controls	No	No	Yes	No	No	Yes	No	No	Yes
Mean of dep. var	95.05	95.05	95.05	96.70	96.70	96.70	83.92	83.92	83.92

Notes: Table presents coefficients and standard errors from a regression of MISIC component sub-scales on standardized Fluoride in the household's drinking water, conditional on Fluoride levels below 1.5 mg/L. MISIC is Malin's Intelligence Scale for Indian Children, a test of cognitive ability designed for Indian children, and scores are calculated with reference to a table of norms such that a child of average ability in the normed population scores 100, given the child's age group. Control variables include sample child gender and household share of expenditure on sample child, as well as household characteristics including an asset index, indicators of mother's and father's completion of primary school, household's religion and caste, and household drinking water qualities: dissolved oxygen, pH, conductivity, and turbidity. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates.

Table 5: Proficiency score: Fluoride level less than 1.5 mg/L

	Math			English			Hindi		
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Standardized Fluoride	0.89***	0.72**	0.77***	0.74**	0.57*	0.61*	0.50	0.32	0.38
	(0.31)	(0.29)	(0.28)	(0.30)	(0.33)	(0.34)	(0.37)	(0.37)	(0.38)
Observations	281	281	281	281	281	281	281	281	281
Demographic Controls	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Toxins Controls	No	No	Yes	No	No	Yes	No	No	Yes
Mean of dep. var	1.780	1.780	1.780	1.360	1.360	1.360	2.330	2.330	2.330

Notes: This table reports coefficients and standard errors from a regression of proficiency score in Math, English and Hindi on standardized fluoride level. Standard errors clustered at the village of residence level. Demographic controls include individual and household characteristics such as gender, cognitive age, an index of household assets, the mother and father's education level, the share of expenditure on the child, and religion and caste fixed effect. Attributes of the water include dissolved oxygen, pH, conductivity, turbidity of water. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates. Mathematics, English, and Hindi Scores are on a scale of four. For Mathematics, the skills are: (a) can recognize numbers between 0 to 9, (b) can recognize numbers between 0 to 99, (c) can subtract two-digit numbers, and (d) can divide a three-digit number with a single-digit number. Both the English test and Hindi tests measure the following skills: (a) Can recognize a letter, (b) can read a word, (c) can read a paragraph, (d) can read a story fluently. Each test score ranges from a minimum of zero (child does not have any skill) to a maximum of four (child possesses all four skills). *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 6: The effect of standardized fluoride exposure (below 1.5 mg/L) on Purdue Pegboard manual dexterity performance

VARIABLES	(1)	(2)	(3)
Panel A: Outcome variable: Right			
Standardized Fluoride	0.84	0.85	0.97*
	(0.61)	(0.53)	(0.56)
Mean of dep. var	10.51	10.51	10.51
Panel B: Outcome variable: Left			
Standardized Fluoride	0.72	0.81	0.92*
	(0.59)	(0.51)	(0.54)
Mean of dep. var	9.740	9.740	9.740
Panel C: Outcome variable: Both			
Standardized Fluoride	0.77	0.87**	1.03**
	(0.54)	(0.43)	(0.45)
Mean of dep. var	7.600	7.600	7.600
Panel D: Outcome variable: Sum			
Standardized Fluoride	2.30	2.55*	2.97**
	(1.64)	(1.35)	(1.44)
Mean of dep. var	27.82	27.82	27.82
Panel E: Outcome variable: Assembly			
Standardized Fluoride	3.74**	4.52***	4.64***
	(1.83)	(1.67)	(1.69)
Mean of dep. var	19.28	19.28	19.28
Demographic Controls	No	Yes	Yes
Water Quality Controls	No	Yes	Yes
Toxins	No	No	Yes

Notes: Table presents coefficients and standard errors from a regression of Purdue Pegboard sub-scales on standardized Fluoride in the household's drinking water, conditional on Fluoride levels below 1.5 mg/L. Each sub-scale reports a number of correctly completed manual tasks within a fixed amount of time. Control variables include sample child gender, cognitive age, and household share of expenditure on sample child, as well as household characteristics including an asset index, indicators of mother's and father's completion of primary school, household's religion and caste, and household drinking water qualities: dissolved oxygen, pH, conductivity, and turbidity. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates.

Fluoride Exceeds Safe Limit

Table 7: The effect of elevated fluoride exposure on different measures of intelligence

	Standardized Fluoride			Fluoride $\geq 1.5mg/L$		
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Normed CMP Percentile Rank						
Treatment	-1.69*	-1.37	-1.38	-4.38*	-4.44**	-4.53**
	(1.00)	(0.97)	(1.01)	(2.23)	(2.17)	(2.19)
Observations	509	509	509	509	509	509
Mean of dep. var	28.24	28.24	28.24	28.24	28.24	28.24
Panel B: MISIC						
Standardized Fluoride	-0.46	-0.34	-0.44	-1.09	-0.87	-0.88
	(0.47)	(0.49)	(0.50)	(1.02)	(1.07)	(1.06)
Observations	431	431	431	431	431	431
Mean of dep. var	91.45	91.45	91.45	91.45	91.45	91.45
Demographic Controls	No	Yes	Yes	No	Yes	Yes
Water Quality Controls	No	Yes	Yes	No	Yes	Yes
Toxins Controls	No	No	Yes	No	No	Yes

Notes: Panel A presents coefficients and standard errors from a regression of Normed Percentile of Raven's Colored Progressive Matrices, which is the percentile rank of the estimated IQ measure of the child relative to a normed population, on two different measures of fluoride. Panel B presents coefficients and standard errors from a regression of normed MISIC IQ estimate on two different measures of fluoride. Coefficients are reported for standardized fluoride in columns (1) to (3), and for a binary indicator of exceeding the WHO permissible limit of 1.5 mg/L in columns (4) to (6). Control variables include sample child gender, cognitive age, and household share of expenditure on sample child, as well as household characteristics including an asset index, indicators of mother's and father's completion of primary school, household's religion and caste, and household drinking water qualities: dissolved oxygen, pH, conductivity, and turbidity. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates.

Table 8: Effect of elevated fluoride exposure on proficiency test

	Standardized Fluoride			Fluoride $\geq 1.5mg/L$		
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Math Score						
Standardized Fluoride	-0.10**	-0.09**	-0.09*	-0.17*	-0.14	-0.10
	(0.04)	(0.05)	(0.05)	(0.10)	(0.10)	(0.10)
Observations	506	506	506	506	506	506
Mean of dep. var	1.710	1.710	1.710	1.710	1.710	1.710
Panel B: English Score						
Standardized Fluoride	0.08	0.03	0.02	-0.04	-0.15	-0.15
	(0.06)	(0.06)	(0.06)	(0.10)	(0.11)	(0.11)
Observations	506	506	506	506	506	506
Mean of dep. var	1.340	1.340	1.340	1.340	1.340	1.340
Panel C: Hindi Score						
Standardized Fluoride	-0.02	-0.14*	-0.14*	0.01	-0.19	-0.18
	(0.07)	(0.07)	(0.07)	(0.14)	(0.14)	(0.14)
Observations	506	506	506	506	506	506
Mean of dep. var	2.330	2.330	2.330	2.330	2.330	2.330
Demographic Controls	No	Yes	Yes	No	Yes	Yes
Water Quality Controls	No	Yes	Yes	No	Yes	Yes
Toxins Controls	No	No	Yes	No	No	Yes

Notes: This table reports coefficients and standard errors from a regression of proficiency score in Math, English and Hindi on two different measures of fluoride: Standardized fluoride in columns (1) to (3) and a binary indicator of exceeding the WHO permissible limit of 1.5 mg/L in columns (4) to (6). Standard errors clustered at the village of residence level. All regressions include individual and household characteristics such as gender, cognitive age, an index of household assets, the mother and father's education level, the share of expenditure on the child, and religion and caste fixed effect and attributes of the water such as dissolved oxygen, pH, conductivity and turbidity of water. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates. Mathematics, English, and Hindi Scores are on a scale of four. For Mathematics, the skills are: (a) can recognize numbers between 0 to 9, (b) can recognize numbers between 0 to 99, (c) can subtract two-digit numbers, and (d) can divide a three-digit number with a single-digit number. Both the English test and Hindi tests measure the following skills: (a) Can recognize a letter, (b) can read a word, (c) can read a paragraph, (d) can read a story fluently. Each test score ranges from a minimum of zero (child does not have any skill) to a maximum of four (child possesses all four skills).

Table 9: The effect of elevated fluoride exposure on dental health and activities of daily life (ADL)

	Standardized Fluoride			Fluoride $\geq 1.5mg/L$		
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Any pitting, staining, or opaque surfaces on teeth						
Treatment	0.07***	0.06**	0.06**	0.18***	0.16***	0.16***
	(0.03)	(0.03)	(0.02)	(0.05)	(0.05)	(0.05)
Observations	509	509	509	509	509	509
Mean of dep. var	0.619	0.619	0.619	0.619	0.619	0.619
Panel B: Failure to perform any routine daily activity						
Treatment	0.06**	0.06**	0.07***	0.10*	0.13**	0.14***
	(0.02)	(0.02)	(0.02)	(0.05)	(0.05)	(0.05)
Observations	503	503	503	503	503	503
Mean of dep. var	0.594	0.594	0.594	0.594	0.594	0.594
Demographic Controls	No	Yes	Yes	No	Yes	Yes
Water Quality Controls	No	Yes	Yes	No	Yes	Yes
Toxins Controls	No	No	Yes	No	No	Yes

Notes: Panel A presents coefficients and standard errors from a regression of a binary indicator of the presence of visible pitting, staining, or opaque surfaces on the sample child's teeth observed by the surveyor at the time of survey, on two different measures of fluoride. Panel B presents coefficients and standard errors from a regression of a binary indicator of the failure to perform any of five routine daily activities, on two different measures of fluoride. The five routine activities are: walking for one kilometer, carrying 10kg of rice for 250 meters, drawing a bucket of water from a well, using a ladder to climb two meters, and bathing without help. Coefficients are reported for standardized fluoride in columns (1), (2) and (3), and for a binary indicator of exceeding the WHO permissible limit of 1.5 mg/L in columns (4), (5) and (6). Control variables include sample child gender, cognitive age, and household share of expenditure on sample child, as well as household characteristics including an asset index, indicators of mother's and father's completion of primary school, household's religion and caste, and household drinking water qualities: dissolved oxygen, pH, conductivity, and turbidity. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates.

Table 10: The effect of fluoride on normed CPM percentile rank, robustness to controls

	(1)	(2)	(3)	(4)	(5)
Panel A					
Standardized Fluoride Treatment	-2.68**	-2.67**	-2.57*	-3.03**	-2.99**
	(1.33)	(1.32)	(1.33)	(1.32)	(1.33)
Demo & water controls	Yes	Yes	Yes	Yes	Yes
Block FE	Yes	Yes	Yes	Yes	Yes
Toxins index	No	Yes	Yes	Yes	Yes
Diet indices	No	No	Yes	Yes	Yes
Village index	No	No	No	Yes	Yes
Investments index	No	No	No	No	Yes
Observations	507	507	506	506	505
Panel B					
Fluoride exceeds 1.5 mg/L	-7.45***	-7.09***	-6.90**	-6.74**	-6.70**
	(2.73)	(2.72)	(2.73)	(2.71)	(2.71)
Demo & water controls	Yes	Yes	Yes	Yes	Yes
Block FE	Yes	Yes	Yes	Yes	Yes
Toxins index	No	Yes	Yes	Yes	Yes
Diet indices	No	No	Yes	Yes	Yes
Village index	No	No	No	Yes	Yes
Investments index	No	No	No	No	Yes
Observations	507	507	506	506	505

Notes: We use two different measures of fluoride exposure in Panel A and B. The table presents coefficients and standard errors from a regression of Normed Percentile of Raven's Colored Progressive Matrices, which is the percentile rank of the estimated IQ measure of the child relative to a normed population, on standardized Fluoride in the household's drinking water (Panel A) and on the indicator variable for fluoride exceeding the 1.5 mg/L limit . Demographic controls include sample child gender, cognitive age, and household share of expenditure on sample child, as well as household characteristics including an asset index, indicators of mother's and father's completion of primary school, household's religion and caste; water controls include dissolved oxygen, pH, conductivity, and turbidity; block fixed effects (administrative subdivisions of each district); and four indices. These indices are: a toxins index which captures the presence of various water contaminants which are likely to be neurotoxins, a diet index which captures separately the consumption of fluoride-inhibiting and fluoride-augmenting foods, a village index which captures the presence of village-level amenities such as electricity and the presence of a bank branch, and an investment index which captures maternal investments before and after the child's birth. These covariate indices are described in more detail in the data appendix.

Appendix A

A1 Domains Tested, Norms, and Standardizing

Attention

- Reason for interest in the domain: Moderate and severe fluorosis have been indicated to cause significant deficits in digit span scores, suggesting that children's auditory span or working memory may be particularly affected by chronic fluoride exposure Choi et al. (2015).
- Chosen test: Digit Span Test (forward & backward), which tests sustained attention and auditory working.
- Validity evidence: Malin Malin (1969); Kurani and colleaguesKurani et al. (2009); Arun and colleagues Arun et al. (2013).

Executive Function

- Reason for interest in the domain: Animal studies have indicated that the prefrontal cortex may be one of the main target areas for fluoride, causing excitotoxicity, oxidative stress, and possible neuronal death Mullenix et al. (1995); Akinrinade et al. (2013). The prefrontal cortex is known to be key in performing executive functions, sending signals, and mediating neuronal activity Funahashi and Andreau (2013); Ball et al. (2011).
- Mazes: This subtest is taken from the Malin's Intelligence Scale for Indian Children. It measures planning ability, perceptual organization, visual-motor coordination, and self-control.
- Validity evidence (methodology used with Indian population): Kishore and colleagues Kishore et al. (2019); Kotnala and Halder Kotnala and

Halder (2018).

Processing Speed

- Reason for interest in the domain: Offspring of fluoride-exposed mice have been indicated to have significantly decreased locomotor ability and significant dysfunction with sensorimotor development Bartos et al. (2015).
- Chosen test: Coding, which tests attention, visual and motor integration, and visual discrimination (visual-motor dexterity, associative nonverbal learning, nonverbal short-term memory).
- Validity evidence: Malin and colleagues Malin (1969); Kurani and colleagues Kurani et al. (2009); Arun and colleagues Arun et al. (2013).

Dexterity/ Motor Coordination

- Reason for interest in the domain: Skeletal fluorosis is characterized by immobilization of joints of the axial skeleton and major joints of the extremities, effectively impacting dexterity by increasing cases of fracturing, osteoarthritis, and impaired joint mobility Krishnamachari (1986). Poor performance may also be "a sign of deficits in complex, visually guided, or coordinated movements which are likely mediated by circuits involved with the basal ganglia" Martino and Leckman (2013). Fluoride may play a role in basal ganglion calcification Blaylock et al. (2004), which can cause motor function, speech, seizures, and other involuntary movement deterioration.
- Chosen test: Purdue Pegboard Test peg, which measures manual dexterity, speed, and fine motor coordination.

- Validity evidence (methodology used with Indian population): von Ehrenstein and colleagues von Ehrenstein et al. (2007); Choi and colleagues Choi et al. (2015).
- General test validity: Tiffin and Asher Tiffin and Asher (1948).

A2 Data Appendix

Sample Design

To establish a population for sampling villages, we used data from the Ministry of Drinking Water and Sanitation (MDWS), India. Between 2009 and 2015, the ministry collected over half a million water samples from water sources in habitations (nested within villages) across more than 35,700 of 45,000 villages of Rajsthan. We aggregated fluoride, total dissolved solids (TDS), and nitrate measurements from the habitation level to derive village averages.

We created a heat map of fluoride concentrations across Rajasthan (see Appendix Figure A.6). This revealed two distinct belts with naturally occurring fluoride hotspots in Western and Central Rajasthan. We focused on the central belt, as the western districts are predominantly desert. We then obtained a geological map of the central belt, detailing rock formations and soil groups (Appendix Figures A.7 - A.8). Based on rock composition and inherent fluoride content, we categorized the central belt into three groups: high fluoride concentration (majority of rocks are fluoride-rich), low fluoride concentration (minimal presence of fluoride-containing rocks), and medium fluoride concentration (soil with weathered particles of fluoride rocks). Districts without geological data were excluded. We stratified the western belt according to these three rock groups and selected eight districts for fieldwork based on cost considerations: Nagaur, Jodhpur, Bhilwara, Pali, Tonk, Ajmer, Bundi, and Sirohi (see Appendix Figure A.9).

For village selection, we used village-level averages of water parameters. Villages exceeding permissible limits for TDS and nitrates in drinking water were excluded. We then stratified the remaining villages into high, medium, and low fluoride concentration categories based on MDWS drinking water standards: less than 1.5 mg/L, between 1.5 and 4 mg/L, and greater than

4 mg/L. From this pool, we randomly sampled 300 villages. This sample size was determined through power calculations for a randomized control trial evaluating a point-of-use technology's effectiveness in reducing fluoride in drinking water. With a significance level of 5%, 80% power for a two-sided test, 50% of villages treated, an intra-cluster correlation of 0.04 for behavioral outcomes (0.11 for cognition, based on pilot studies), and an expected attrition rate of 10%, the minimum detectable treatment effect with 300 villages was calculated to be 0.25 standard deviations.

Within each selected village, we randomly chose one habitation and compiled a roster of all households with children aged 5-11. From this roster, we randomly selected three households for the study. If a selected household declined to participate, it was replaced with another from the list. A team of psychologists with MPhil or Master's degrees was trained to administer cognitive tests. These psychologists visited the sample children to collect data using a battery of cognitive tests.

Covariate Indices

To reduce the dimensionality of the covariates that we want to control and show our results are unencumbered when we control these covariates, we construct several indices – a demographic index, village index, drinking water toxin index, investments index, and an index for fluoride-inhibiting and fluoride-augmenting diet.

Our *demographic index* is a projection of the demographic controls asset index, the share of household expenditure on the sampled child, mother's education, father's education, religion, caste, and sex, and age on the normed CPM percentile outcome, conditional on falling below the WHO permissible limit of 1.5 mg/L Fluoride. In other words, the demographic index for a child i is the predicted value $\hat{Y}_i$, obtained from the linear regression:

$$Y_i = \beta X_i + \epsilon_i \quad , \quad X_i < 1.5\text{mg/L} \tag{3}$$

where Y_i is the normed CPM percentile outcome, and X_i are the demographic controls including age. Each sample child's index value is the fitted value, $\hat{Y}_i$ [36].

We perform the same exercise to obtain our *village index*, except the X_i variables are replaced with a set of variables that vary at the village level. These variables are: the average temperature and precipitation in the village over the previous 30 years, average well depth, presence of banking or commercial banking facility, distance to the nearest town, connection to power supply, percentage of the village area irrigated, total village population, and the share of the village population literate, female, or scheduled caste. We perform the same exercise to obtain our *toxin index*, except the X_i variables are replaced with the variables that are potential toxins in drinking water. These include lead, mercury, arsenic, Nitrates, and E. coli. We repeat the exercise once more to obtain our *investments index*, where the X_i variables are replaced with three binary indicators for maternal investments: whether the mother received antenatal care, received postnatal care, and whether the child was breastfed.

The *fluoride-inhibiting index* is the average of binary variables indicating whether the child consumed foods which inhibit the absorption of fluoride[37], and the *fluoride-augmenting index* is constructed in the same manner, with foods which typically contain fluoride[38].

[36] Note that predicted values are obtained as long as X_i is observed (and missing otherwise). Y_i need not be observed.

[37] These are: plain water, milk, tea with milk, yogurt, wheat bread, white flour bread, lentils, pumpkin; carrots; squash; or sweet potatoes, dark green leafy vegetables, milk products, mangoes; bananas; papaya; or oranges, Indian gooseberries, other fruits or vegetables, meat, organs, and eggs.

[38] These are: juice, aracanut, canned fish, fish or shellfish, pickles with black salt, other packaged salty snacks, and rock salt digestives.

Appendix Figures and Tables

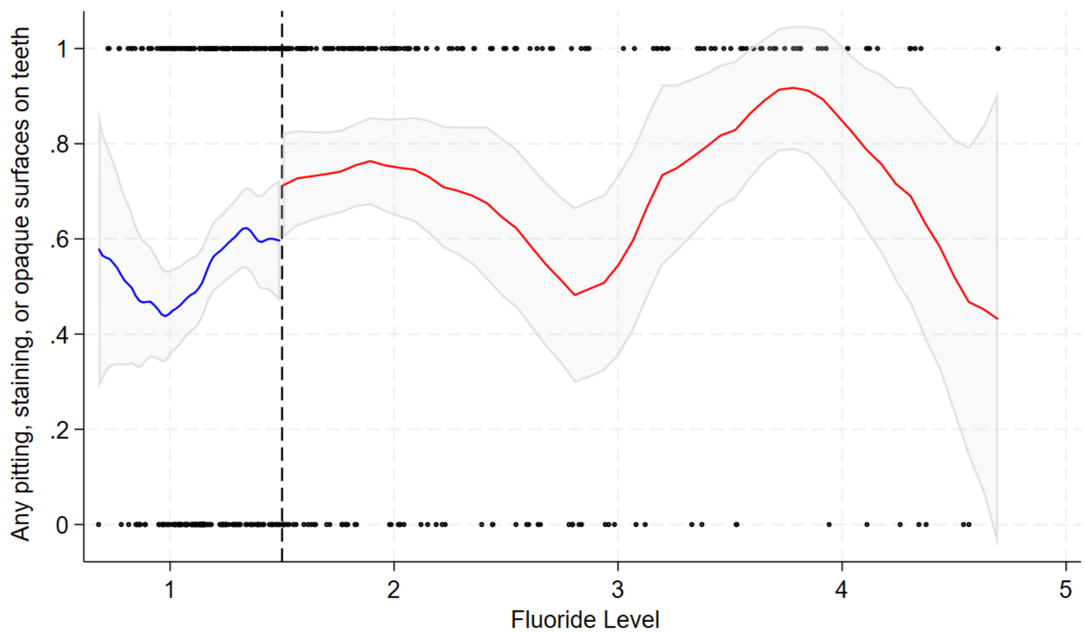


Figure A.1: The effect of standardized fluoride exposure (below 1.5 mg/L) on dental health

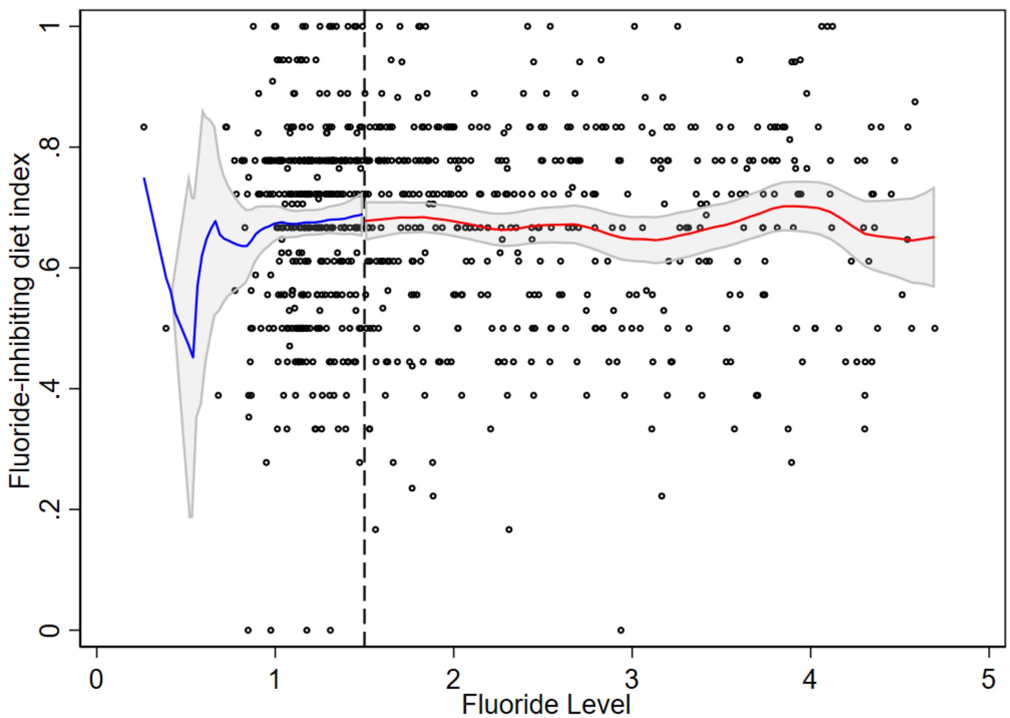


Figure A.2: Balance across threshold, Fluoride-inhibiting diet index

Notes: This figure plots the fluoride-inhibiting diet index, which is a projection of the demographic controls asset index, the share of household expenditure on the sampled child, mother's education, father's education, religion, caste, and sex, and age on the fluoride-inhibiting diet measure. This measure of fluoride-inhibiting diet is a simple average of a series of binary indicators for consumption of foods which inhibit the absorption of fluoride. The linear model's coefficients are estimated from the subset of observations with Fluoride levels not exceeding the WHO permissible limit (i.e., those observations below 1.5 mg/L). The predicted values from this regression (on the y-axis) are plotted against the Fluoride level in the household's drinking water, measured in mg/L (on the x-axis).

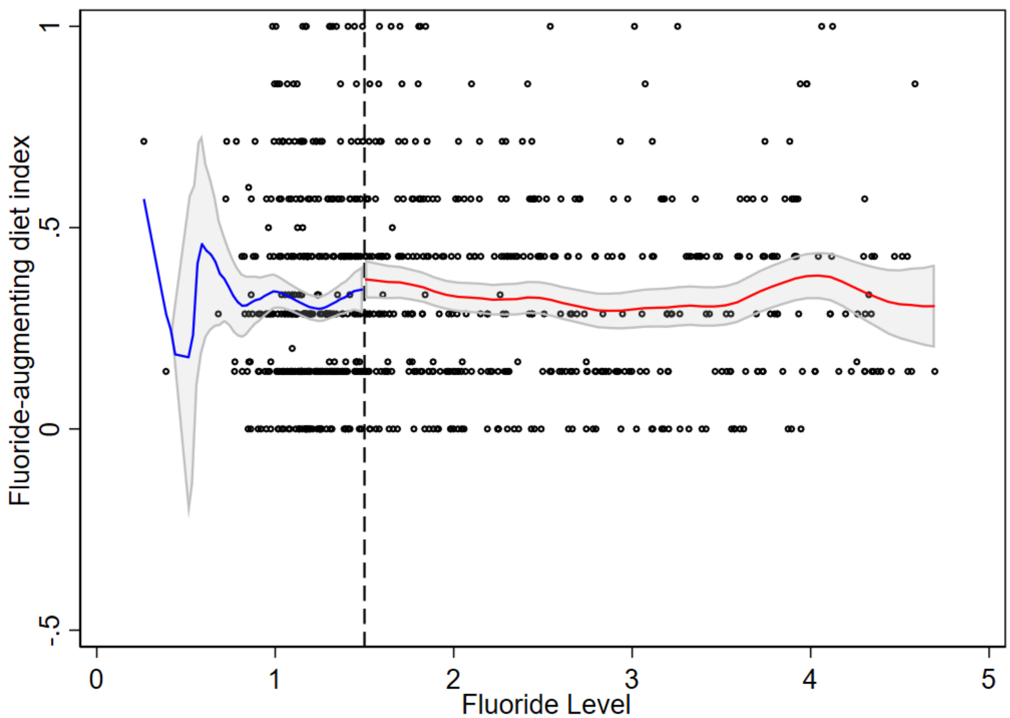


Figure A.3: Balance across threshold, Fluoride-augmenting diet index

Notes: This figure plots the fluoride-augmenting diet index, which is a projection of the demographic controls asset index, the share of household expenditure on the sampled child, mother's education, father's education, religion, caste, and sex, and age on the fluoride-inhibiting diet measure. This measure of fluoride-augmenting diet is a simple average of a series of binary indicators for consumption of foods which increase the absorption of fluoride. The linear model's coefficients are estimated from the subset of observations with Fluoride levels not exceeding the WHO permissible limit (i.e., those observations below 1.5 mg/L). The predicted values from this regression (on the y-axis) are plotted against the Fluoride level in the household's drinking water, measured in mg/L (on the x-axis).

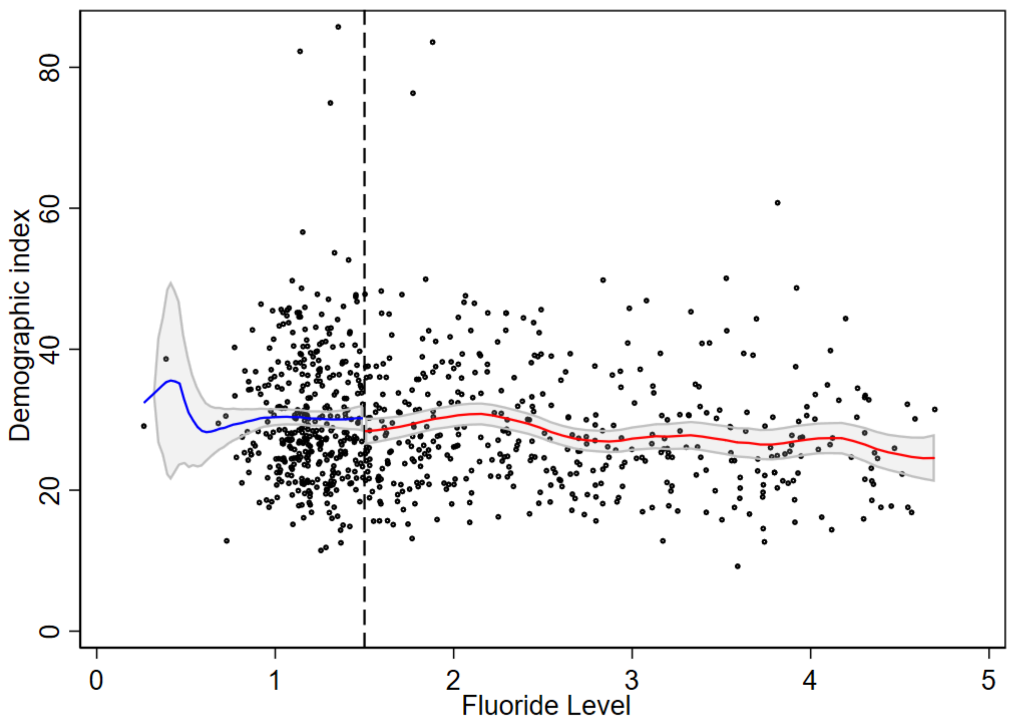


Figure A.4: Balance across threshold, demographic index

Notes: This figure plots the demographic index, which is a projection of the demographic controls asset index, the share of household expenditure on the sampled child, mother's education, father's education, religion, caste, and sex, and age on the normed CPM percentile outcome. The linear model's coefficients are estimated from the subset of observations with Fluoride levels not exceeding the WHO permissible limit (i.e., those observations below 1.5 mg/L). The predicted values from this regression (on the y-axis) are plotted against the Fluoride level in the household's drinking water, measured in mg/L (on the x-axis).

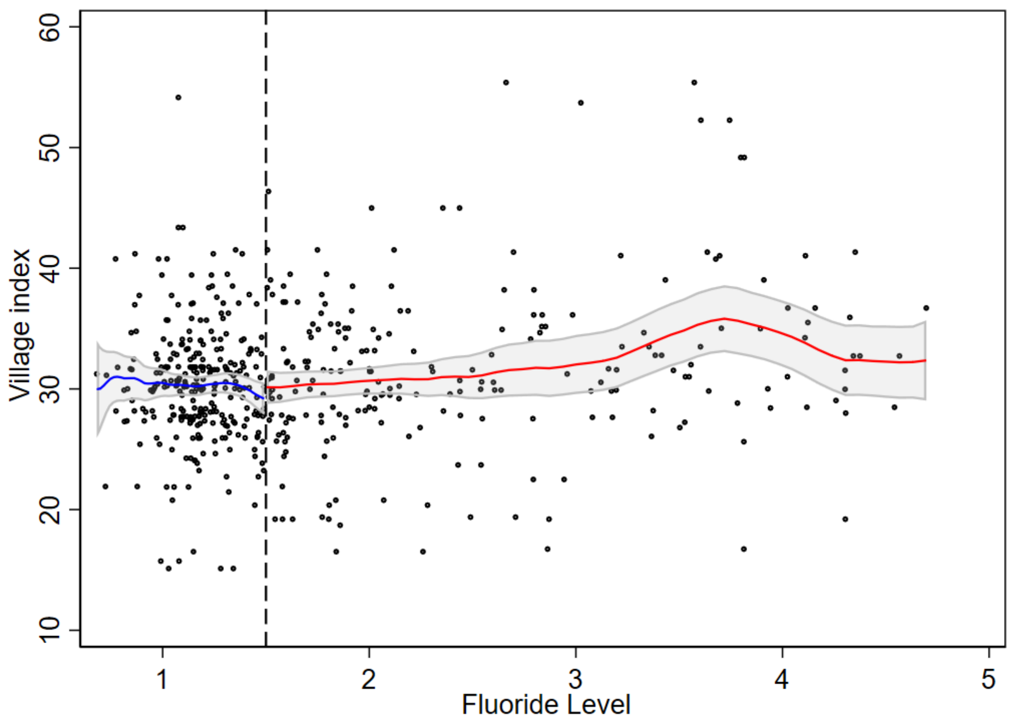


Figure A.5: Balance across threshold, village index

Notes: This figure plots the village index, which is a projection of village-level covariates: the average temperature and precipitation in the village over the previous 30 years, average well depth, presence of banking or commercial banking facility, distance to the nearest town, connection to powersupply, percentage of the village area irrigated, total village population, and the share of the village population literate, female, or scheduled caste on the normed CPM percentile outcome. The linear model's coefficients are estimated from the subset of observations with Fluoride levels not exceeding the WHO permissible limit (i.e., those observations below 1.5 mg/L). The predicted values from this regression (on the y-axis) are plotted against the Fluoride level in the household's drinking water, measured in mg/L (on the x-axis).

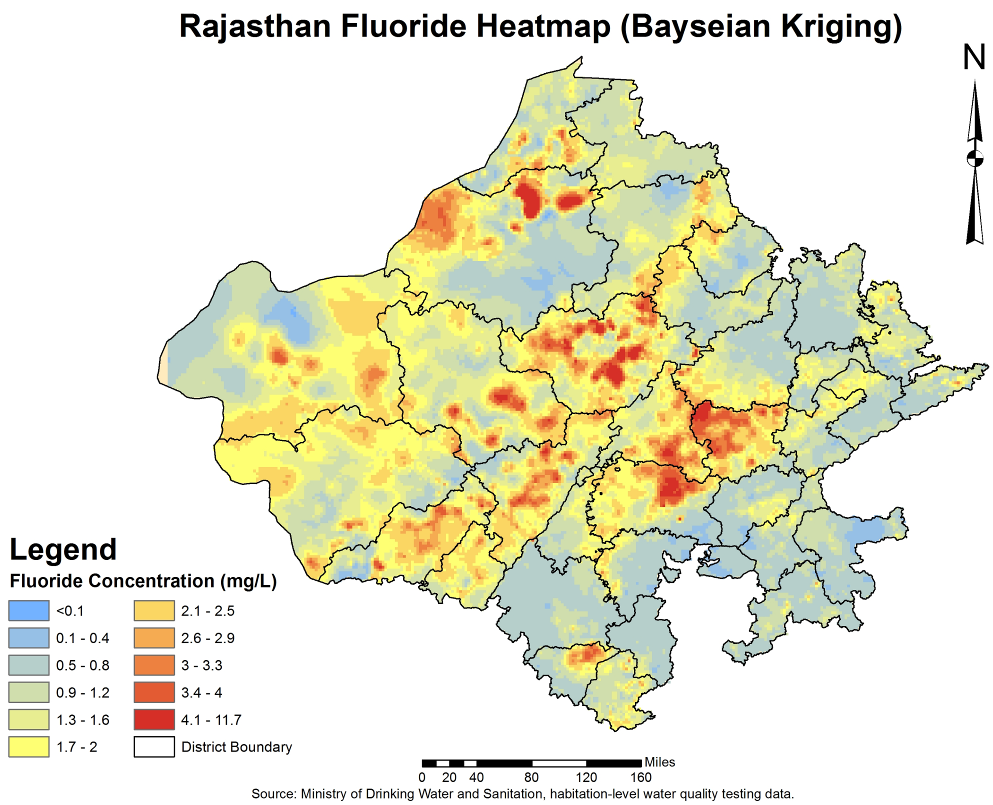


Figure A.6: Heatmap - Fluoride in Rajasthan

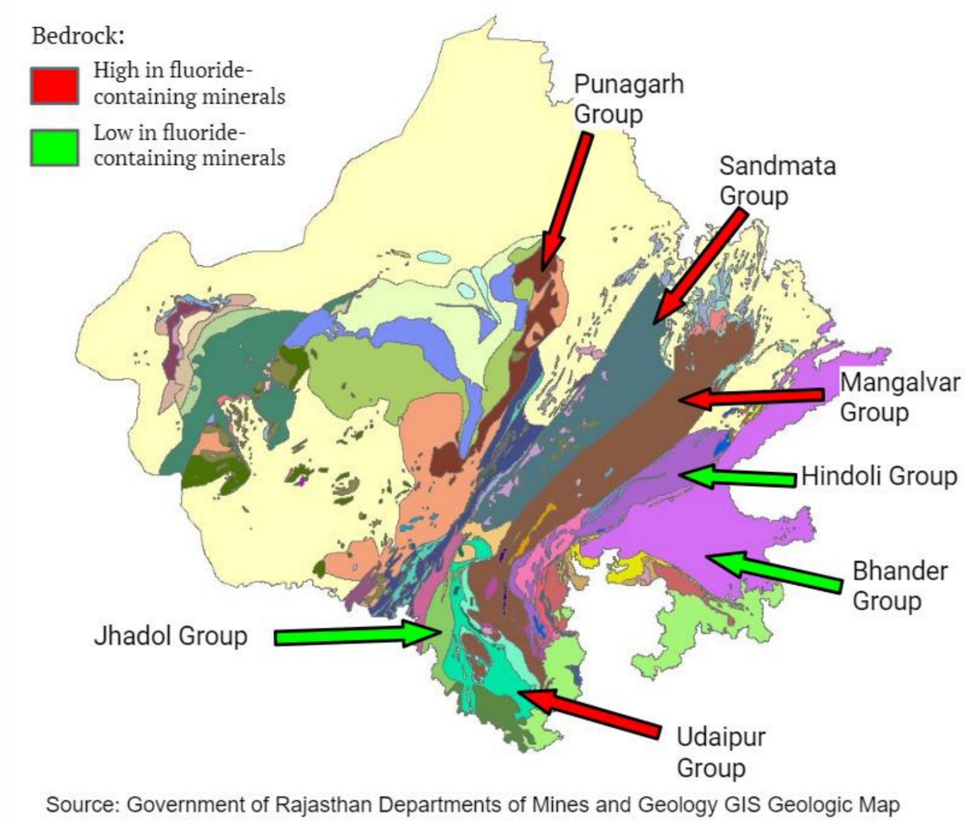


Figure A.7: Map of the rock formations along with soil groups

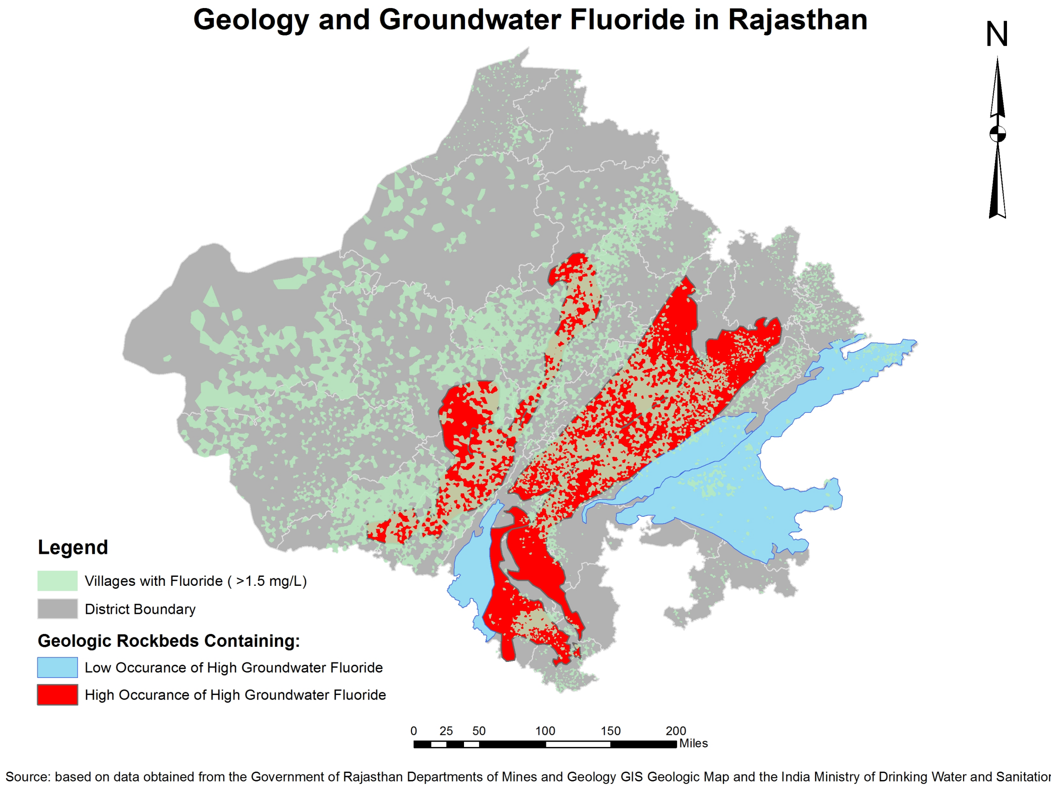


Figure A.8: Rock formations and village fluoride in drinking water

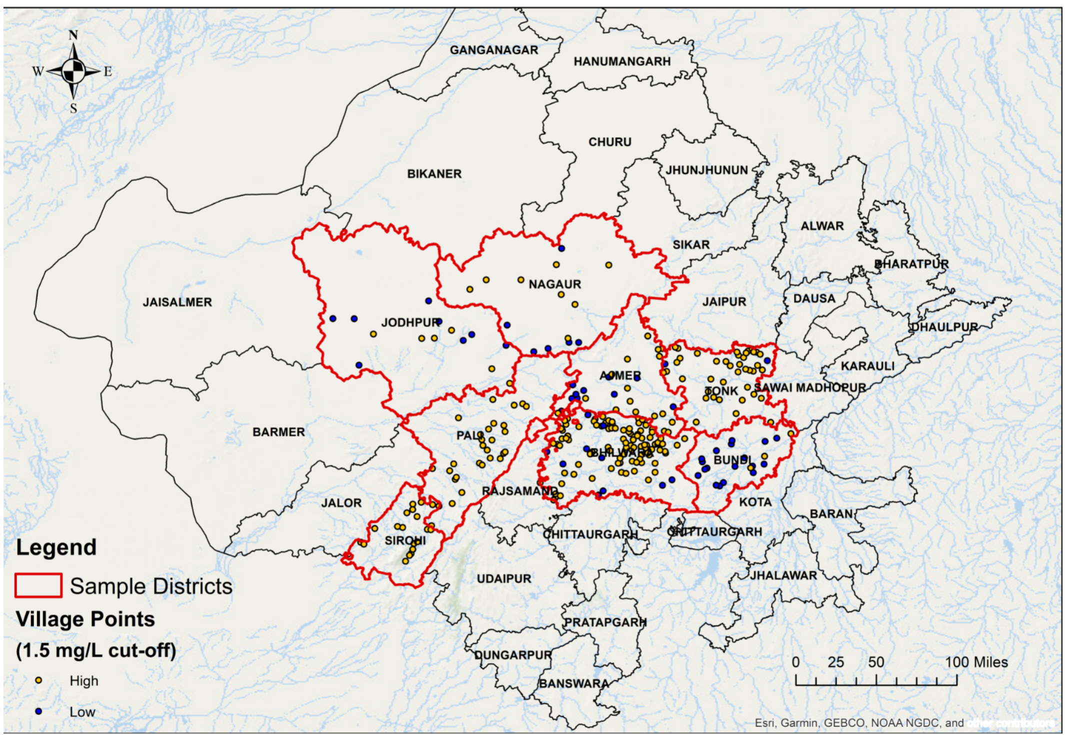


Figure A.9: Sample districts and villages

Table A1: Summary statistics: child and household demographic characteristics (Full sample)

	Observations	Mean	SD	Minimum	Maximum
Female	790	0.47	0.50	0	1
Assetindex	790	9.84	3.14	1	24
MotherEd	790	0.29	0.45	0	1
FatherEd	790	0.71	0.45	0	1
Share expenditure on child	790	0.21	0.18	0	1
Cognitive age	546	8.57	1.93	4.03	15.31
Hindu	790	0.98	0.14	0	1
Muslim	790	0.02	0.13	0	1
Jain	790	0.00	0.06	0	1
General caste	790	0.11	0.32	0	1
Other backward caste	790	0.58	0.49	0	1
Schedule caste or tribe	790	0.30	0.46	0	1
Mother's number of miscarriages	790	0.01	0.12	0	2
Mother's number of stillbirths	790	0.00	0.06	0	1
Mother's total number of children died after birth	790	0.01	0.12	0	2
Sum of miscarriages, stillbirths, and child deaths	790	0.03	0.19	0	2
Fluoride (mg/L)	790	1.96	0.97	0.26	4.70

Notes: This table reports summary statistics for child and household demographic characteristics. Assetindex is the sum of the number of assets reported at the time of surveying, MotherEd and FatherEd are indicators of whether the mother or father completed primary school. Share expenditure on child is the share of household expenditure which the household reported spending on the sample child at the time of the survey. Cognitive age is the age of the child at the time of visit by the psychology team, based exclusively on their age according to government-issued documents. Hindu, Muslim, and Jain are indicators of the household's reported religion, and similarly for general caste, other backward caste, and scheduled caste or tribe.

Table A2: Summary statistics: water contaminants in household water supply

	mean	sd
Fluoride $\geq$ 1.5 mg/L	0.45	0.50
Lead $\geq$ 1.5 μg/L	0.00	0.00
Nitrates $\geq$ 50 mg/L	0.19	0.39
Mercury $\geq$ 6 μg/L	0.00	0.00
Arsenic $\geq$ 10 μg/L	0.05	0.21
E. coli present in water	0.05	0.22
Observations	509	

Notes: This table reports summary statistics for indicators of whether various water contaminants in the household's water supply exceed safe limits, as well as the presence of E. coli (Escherichia coli) bacteria.

Table A3: Correlation between fluoride and other contaminants

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Dependent variable: Continuous Measure of Fluoride						
Lead	0.192					0.168
	(0.130)					(0.143)
Arsenic		-0.0121				-0.00867
		(0.0173)				(0.0181)
Mercury			0.101			0.116
			(0.0679)			(0.0794)
Nitrates				-0.00147		-0.00133
				(0.00102)		(0.000974)
E-coli					0.00318	-0.0400
					(0.172)	(0.169)
Panel B: Dependent variable: Fluoride Exceeds 1.5 mg/L						
Lead	0.0189					-0.00836
	(0.0741)					(0.0795)
Arsenic		-0.0122				-0.0112
		(0.00854)				(0.00868)
Mercury			0.0416			0.0507
			(0.0362)			(0.0384)
Nitrates				-0.000359		-0.000202
				(0.000645)		(0.000592)
E-coli					-0.0572	-0.0864
					(0.0748)	(0.0709)
Observations	509	509	509	509	509	509
Demographic controls	Yes	Yes	Yes	Yes	Yes	Yes
Water quality controls	Yes	Yes	Yes	Yes	Yes	Yes

Notes: This table shows the correlation between different measures of fluoride and other contaminants. Standard errors clustered at the village of residence level. All regressions include individual and household characteristics such as gender, cognitive age, an index of household assets, the mother and father's education level, the share of expenditure on the child, and religion and caste fixed effect and attributes of the water such as dissolved oxygen, pH, conductivity, and turbidity.

Table A4: Correlation between fluoride and other water contaminates at different indicator bins of fluoride

Fluoride level	(1) Lead	(2) Arsenic	(3) Mercury	(4) Nitrates	(5) E-coli
1 mg/L to 2 mg/L	0.282	0.165	-0.0616	-2.516	-0.00993
	(0.308)	(0.423)	(0.0987)	(4.962)	(0.0331)
2 mg/L to 3 mg/L	0.335	0.428	0.0516	-8.487	-0.0471
	(0.324)	(0.463)	(0.138)	(6.874)	(0.0357)
3 mg/L to 4 mg/L	0.355	-0.176	0.181	-12.71*	-0.00224
	(0.324)	(0.493)	(0.147)	(7.175)	(0.0465)
Observations	509	509	509	509	509
R-squared	0.641	0.402	0.214	0.242	0.048

Notes: This table shows the correlation between different measures of fluoride and other contaminants at different indicator bins of fluoride. **0 mg/L to 1 mg/L is the omitted category**. Standard errors clustered at the village of residence level. All regressions include individual and household characteristics such as gender, cognitive age, an index of household assets, the mother and father's education level, the share of expenditure on the child, and religion and caste fixed effect and attributes of the water such as dissolved oxygen, pH, conductivity and turbidity of water.

Table A5: Father never moved

	Standardized Fluoride		Binary: $I(Fluoride \geq 1.5mg/L)$	
	(1)	(2)	(3)	(4)
Treatment	0.01	0.00	-0.00	-0.00
	(0.01)	(0.01)	(0.01)	(0.02)
Controls	No	Yes	No	Yes
Observations	509	509	509	509
Outcome SD	0.16	0.16	0.16	0.16

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Notes: This table reports coefficients and standard errors from a regression of a binary indicator of whether the sample child's father was not born in the surveyed village, on two different measures of fluoride. Coefficients are reported for standardized fluoride in columns (1) and (2), and for a binary indicator of exceeding the WHO permissible limit of 1.5 mg/L in columns (3) and (4). Controls variables include sample child gender, cognitive age, and household share of expenditure on sample child, as well as household characteristics including an asset index, indicators of mother's and father's completion of primary school, household's religion and caste, and household drinking water qualities: dissolved oxygen, pH, conductivity, and turbidity. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates.

Table A6: Fertility of mother

	Standardized Fluoride			Fluoride $\geq 1.5 mg/L$		
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
Treatment	0.02	-0.03	-0.02	0.07	-0.03	-0.03
	(0.05)	(0.05)	(0.05)	(0.10)	(0.11)	(0.11)
Observations	509	509	509	509	509	509
Demographic Controls	No	Yes	Yes	No	Yes	Yes
Water Quality Controls	No	Yes	Yes	No	Yes	Yes
Toxins Controls	No	No	Yes	No	No	Yes
Mean of dep. var	2.831	2.831	2.831	2.831	2.831	2.831

Notes: This table reports coefficients and standard errors from a regression of the mother's fertility count on two different measures of fluoride. Coefficients are reported for standardized fluoride in columns (1) to (3), and for a binary indicator of exceeding the WHO permissible limit of 1.5 mg/L in columns (4) to (6). Control variables include sample child gender, cognitive age, and household share of expenditure on sample child, as well as household characteristics including an asset index, indicators of mother's and father's completion of primary school, household's religion and caste, and household drinking water qualities: dissolved oxygen, pH, conductivity, and turbidity. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates.

Table A7: The effect of exceeding WHO permissible limit on measures of child mortality, and sample child birth size

Outcome Variables	Coef. (SE)
Miscarriages, abortions, and stillbirths	-0.0040
	(0.013)
Household surviving children	-0.038
	(0.13)
Household child mortality rate	-0.0039
	(0.0026)
Sample child born premature	0.017
	(0.035)
Sample child low birth weight	-0.020
	(0.024)
Observations	501

Notes: This table reports coefficients and standard errors from a regression of several measures of maternal reproductive health (fertility, mortality, premature birth, and birth weight) on a binary indicator of exceeding the WHO permissible limit of 1.5 mg/L. Control variables include sample child gender, cognitive age, and household share of expenditure on sample child, as well as household characteristics including an asset index, indicators of mother's and father's completion of primary school, household's religion and caste, and household drinking water qualities: dissolved oxygen, pH, conductivity, and turbidity. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates.

Table A8: Summary statistics of outcome variables (Sample with Fl <1.5 mg/L)

	mean	sd	min	max	count
Normed percentile CPM	30.19	25.29	0.10	97.70	282
MISIC normed score (IQ)	92.16	10.80	66.33	123.00	230
MISIC normed coding	96.70	18.17	56.00	149.00	247
MISIC normed digit span	83.92	10.56	59.00	115.00	232
MISIC normed mazes	95.05	15.73	55.00	150.00	245
ADL's: difficulty with any routine activity	0.55	0.50	0.00	1.00	278
Any tooth pitting, staining, opaque surface	0.38	0.49	0.00	1.00	198
Purdue Pegboard: right hand	10.51	2.22	4.00	17.33	281
Purdue Pegboard: left hand	9.74	2.18	3.67	16.67	279
Purdue Pegbord: both hands	7.60	1.98	0.00	12.67	279
Purdue Pegbord: sum of right, left, and both	27.82	6.18	0.00	46.67	279
Purdue Pegboard: assembly	19.28	6.13	0.00	34.67	277
Fluoride (mg/L)	1.18	0.17	0.68	1.49	282

Notes: This table reports summary statistics for outcome variables, conditional on Fluoride levels below 1.5 mg/L in household drinking water. Normed percentile CPM refers to the child's percentile score on the Raven's Colored Progressive Matrices, with reference to a table of norms for the child's agre group. MISIC is Malin's Intelligence Scale for Indian Children, another test of cognitive ability, and scores are calculated with reference to a table of norms such that a child of average ability in the normed population scores 100. ADL's refers to activities of daily life, which is an average of five binary variables, each indicating difficulty in a distinct, routine activity. Tooth pitting, staining, or opaque surface is an indicator of whether the enumerator observed any of these three symptoms on the child's teeth at the time of the survey. Purdue pegboards measure manual dexterity, using either right, left, or both hands to inster small pegs into the slots in a board; the sum of these three is a measure of total manual dexterity, with assembly measuring their dexterity at coordinating a single task with both hands. For all outcomes, higher scores indicate higher ability, except for ADL's and the indicator for observed teeth issues.

Table A9: Proficiency Score: Fluoride level less than 1.5 mg/L

	Math			English			Hindi		
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Standardized Fluoride	0.60*	0.50*	0.55*	0.28	0.08	0.10	0.12	-0.08	-0.11
	(0.32)	(0.30)	(0.29)	(0.33)	(0.31)	(0.30)	(0.35)	(0.30)	(0.31)
Observations	368	368	367	368	368	367	368	368	367
Demographic Controls	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Water Quality Controls	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Toxins Controls	No	No	Yes	No	No	Yes	No	No	Yes
Mean of dep. var	1.750	1.750	1.760	1.300	1.300	1.310	2.210	2.210	2.200

Notes: This table reports coefficients and standard errors from a regression of proficiency score in Math, English and Hindi on standardized fluoride level. Standard errors clustered at the village of residence level. All regressions include individual and household characteristics such as gender, cognitive age, an index of household assets, the mother and father's education level, the share of expenditure on the child, and religion and caste fixed effect. Water quality controls include dissolved oxygen, pH, conductivity and turbidity of water. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates. Mathematics, English, and Hindi Scores are on a scale of four. For Mathematics, the skills are: (a) can recognize numbers between 0 to 9, (b) can recognize numbers between 0 to 99, (c) can subtract two-digit numbers, and (d) can divide a three-digit number with a single-digit number. Both the English test and Hindi tests measure the following skills: (a) Can recognize a letter, (b) can read a word, (c) can read a paragraph, (d) can read a story fluently. Each test score ranges from a minimum of zero (child does not have any skill) to a maximum of four (child possesses all four skills).

Table A10: Dental health and activities of daily livings (ADLs): Fluoride level less than 1.5 mg/L

	Any pitting, staining, or opaque surfaces on teeth			Failure to perform any routine daily activity		
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
Standardized Fluoride	0.26	0.27	0.26	-0.08	-0.03	-0.03
	(0.17)	(0.17)	(0.17)	(0.14)	(0.15)	(0.14)
Observations	282	282	282	278	278	278
Demographic Controls	No	Yes	Yes	No	Yes	Yes
Water Quality Controls	No	Yes	Yes	No	Yes	Yes
Toxins Controls	No	No	Yes	No	No	Yes
Mean of dep. var	0.539	0.539	0.539	0.550	0.550	0.550

Notes: This table reports coefficients and standard errors from from a regression of a binary indicator of the failure to perform any of five routine daily activities, on the standardized measure of fluoride. The five routine activities are: walking for one kilometer, carrying 10kg of rice for 250 meters, drawing a bucket of water from a well, using a ladder to climb two meters, and bathing without help. Standard errors clustered at the village of residence level. All regressions include individual and household characteristics such as gender, cognitive age, an index of household assets, the mother and father's education level, the share of expenditure on the child, and religion and caste fixed effect and attributes of the water such as dissolved oxygen, pH, conductivity, and turbidity of water. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates.

Table A11: The effect of elevated fluoride exposure on MISIC subscale performance

	Standardized Fluoride			Fluoride geq 1.5 mg/L		
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Mazes						
Standardized Fluoride	-0.62	-0.52	-0.87	-1.05	-0.79	-0.97
	(0.80)	(0.83)	(0.86)	(1.50)	(1.61)	(1.70)
Observations	443	443	443	443	443	443
Mean of dep. var	94.58	94.58	94.58	94.58	94.58	94.58
Panel B: Coding						
Standardized Fluoride	-0.58	-0.45	-0.67	-1.86	-1.93	-2.49
	(0.84)	(0.84)	(0.89)	(1.63)	(1.63)	(1.75)
Observations	454	454	454	454	454	454
Mean of dep. var	95.86	95.86	95.86	95.86	95.86	95.86
Panel C: Digit span						
Standardized Fluoride	-0.17	-0.07	-0.05	0.53	1.07	1.42
	(0.49)	(0.54)	(0.54)	(1.18)	(1.23)	(1.27)
Observations	421	421	421	421	421	421
Mean of dep. var	84.16	84.16	84.16	84.16	84.16	84.16
Demographic Controls	No	Yes	Yes	No	Yes	Yes
Water Quality Controls	No	Yes	Yes	No	Yes	Yes
Toxins Controls	No	No	Yes	No	No	Yes

Notes: Table presents coefficients and standard errors from a regression of normed MISIC subscales on a spline of Fluoride in the household's drinking water. MISIC is Malin's Intelligence Scale for Indian Children, a test of cognitive ability designed for Indian children, and scores are calculated with reference to a table of norms such that a child of average ability in the normed population scores 100, given the child's age group. The spline specification allows for the linear relationship to vary above and below the WHO permissible limit of 1.5 mg/L Fluoride. Control variables include sample child gender and household share of expenditure on sample child, as well as household characteristics including an asset index, indicators of mother's and father's completion of primary school, household's religion and caste, and household drinking water qualities: dissolved oxygen, pH, conductivity, and turbidity. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates.

Table A12: The effect of elevated fluoride exposure on MISIC average

	MISIC average		
VARIABLES	(1)	(2)	(3)
Spline, below 1.5 mg/L	5.62*	5.96*	6.44**
	(2.85)	(3.13)	(3.14)
Spline, above 1.5 mg/L	-7.27**	-7.39**	-8.11**
	(3.18)	(3.42)	(3.41)
Observations	411	411	411
R-squared	0.01	0.12	0.14
Controls	No	Yes	Yes
Toxins	No	No	Yes
SD of dep. var	91.76	91.76	91.76

Notes: Table presents coefficients and standard errors from a regression of normed MISIC average on a spline of Fluoride in the household's drinking water. MISIC is Malin's Intelligence Scale for Indian Children, a test of cognitive ability designed for Indian children, and scores are calculated with reference to a table of norms such that a child of average ability in the normed population scores 100, given the child's age group. The spline specification allows for the linear relationship to vary above and below the WHO permissible limit of 1.5 mg/L Fluoride. Control variables include sample child gender and household share of expenditure on sample child, as well as household characteristics including an asset index, indicators of mother's and father's completion of primary school, household's religion and caste, and household drinking water qualities: dissolved oxygen, pH, conductivity, and turbidity. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates.

Table A13: The effect of elevated fluoride exposure on MISIC subscale performance

VARIABLES	(1)	(2)	(3)
Panel A: Mazes			
Spline, below 1.5 mg/L	8.87**	9.54**	10.63***
	(3.86)	(3.92)	(4.00)
Spline, above 1.5 mg/L	-11.34**	-11.81***	-13.56***
	(4.59)	(4.50)	(4.54)
Observations	443	443	443
Mean of dep. var	94.58	94.58	94.58
Panel B: Coding			
Spline, below 1.5 mg/L	1.21	0.95	0.46
	(4.87)	(5.09)	(5.15)
Spline, above 1.5 mg/L	-2.22	-1.70	-1.42
	(5.51)	(5.69)	(5.73)
Observations	454	454	454
Mean of dep. var	95.86	95.86	95.86
Panel C: Digitspan			
Spline, below 1.5 mg/L	6.75**	7.40**	7.96***
	(2.95)	(2.98)	(2.95)
Spline, above 1.5 mg/L	-8.20**	-8.68***	-9.31***
	(3.33)	(3.33)	(3.26)
Observations	421	421	421
Mean of dep. var	84.16	84.16	84.16
Demographic Controls	No	Yes	Yes
Water Quality Controls	No	No	Yes
Toxins Controls	No	No	Yes

Notes: Table presents coefficients and standard errors from a regression of normed MISIC subscales on a spline of Fluoride in the household's drinking water. MISIC is Malin's Intelligence Scale for Indian Children, a test of cognitive ability designed for Indian children, and scores are calculated with reference to a table of norms such that a child of average ability in the normed population scores 100, given the child's age group. The spline specification allows for the linear relationship to vary above and below the WHO permissible limit of 1.5 mg/L Fluoride. Control variables include sample child gender and household share of expenditure on sample child, as well as household characteristics including an asset index, indicators of mother's and father's completion of primary school, household's religion and caste, and household drinking water qualities: dissolved oxygen, pH, conductivity, and turbidity. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates.

Table A14: Effect of elevated fluoride exposure on proficiency test: Full sample

	Standardized Fluoride			Fluoride geq 1.5 mg/L		
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Math Score						
Standardized Fluoride	-0.08**	-0.07*	-0.07*	-0.21**	-0.20**	-0.17*
	(0.04)	(0.04)	(0.04)	(0.09)	(0.10)	(0.10)
Observations	784	784	779	784	784	779
Mean of dep. var	1.640	1.640	1.650	1.640	1.640	1.650
Panel B: English Score						
Standardized Fluoride	0.02	0.00	0.00	-0.12	-0.18*	-0.19**
	(0.04)	(0.05)	(0.05)	(0.09)	(0.10)	(0.09)
Observations	784	784	779	784	784	779
Mean of dep. var	1.240	1.240	1.250	1.240	1.240	1.250
Panel C: Hindi Score						
Standardized Fluoride	-0.04	-0.11*	-0.11*	-0.08	-0.23*	-0.22*
	(0.06)	(0.06)	(0.06)	(0.13)	(0.13)	(0.13)
Observations	784	784	779	784	784	779
Mean of dep. var	2.170	2.170	2.170	2.170	2.170	2.170
Demographic Controls	No	Yes	Yes	No	Yes	Yes
Water Quality Controls	No	Yes	Yes	No	Yes	Yes
Toxins Controls	No	No	Yes	No	No	Yes

Notes: This table reports coefficients and standard errors from a regression of proficiency score in Math, English and Hindi on two different measures of fluoride: Standardized fluoride in columns (1) to (3) and a binary indicator of exceeding the WHO permissible limit of 1.5 mg/L in columns (4) to (6) . Standard errors clustered at the village of residence level. All regressions include individual and household characteristics such as gender, cognitive age, an index of household assets, the mother and father's education level, the share of expenditure on the child, and religion and caste fixed effect. Water quality controls include dissolved oxygen, pH, conductivity, and turbidity of water. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates. Mathematics, English, and Hindi Scores are on a scale of four. For Mathematics, the skills are: (a) can recognize numbers between 0 to 9, (b) can recognize numbers between 0 to 99, (c) can subtract two-digit numbers, and (d) can divide a three-digit number with a single-digit number. Both the English test and Hindi tests measure the following skills: (a) Can recognize a letter, (b) can read a word, (c) can read a paragraph, (d) can read a story fluently. Each test score ranges from a minimum of zero (child does not have any skill) to a maximum of four (child possesses all four skills).

Table A15: The effect of elevated fluoride exposure on Purdue Pegboard manual dexterity performance

	Standardized Fluoride			Fluoride $\geq 1.5 mg/L$		
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Right						
Standardized Fluoride	0.19**	0.03	0.01	0.11	-0.05	-0.08
	(0.09)	(0.07)	(0.08)	(0.18)	(0.15)	(0.16)
Mean of dep. var	10.56	10.56	10.56	10.56	10.56	10.56
Panel B: Left						
Standardized Fluoride	0.13	-0.02	-0.04	0.12	0.03	0.03
	(0.09)	(0.08)	(0.08)	(0.19)	(0.17)	(0.17)
Mean of dep. var	9.800	9.800	9.800	9.800	9.800	9.800
Panel C: Both						
Standardized Fluoride	0.15	0.01	-0.02	0.23	0.15	0.11
	(0.09)	(0.08)	(0.08)	(0.17)	(0.15)	(0.16)
Mean of dep. var	7.700	7.700	7.700	7.700	7.700	7.700
Panel D: Sum						
Standardized Fluoride	0.36	-0.09	-0.17	0.34	0.06	-0.01
	(0.29)	(0.25)	(0.26)	(0.55)	(0.44)	(0.46)
Mean of dep. var	27.97	27.97	27.97	27.97	27.97	27.97
Panel E: Assembly						
Standardized Fluoride	0.39	0.10	0.05	0.35	0.27	0.21
	(0.29)	(0.26)	(0.27)	(0.56)	(0.56)	(0.57)
Mean of dep. var	19.44	19.44	19.44	19.44	19.44	19.44
Demographic Controls	No	Yes	Yes	No	Yes	Yes
Water Quality Controls	No	Yes	Yes	No	Yes	Yes
Toxins Controls	No	No	Yes	No	No	Yes

Notes: Table presents coefficients and standard errors from a regression of Purdue Pegboard sub-scales on a spline of Fluoride in the household's drinking water. Each sub-scale reports a number of correctly completed manual tasks within a fixed amount of time. The spline specification allows for the linear relationship to vary above and below the WHO permissible limit of 1.5 mg/L Fluoride. Control variables include sample child gender, cognitive age, and household share of expenditure on sample child, as well as household characteristics including an asset index, indicators of mother's and father's completion of primary school, household's religion and caste, and household drinking water qualities: dissolved oxygen, pH, conductivity, and turbidity. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates.

Table A16: The effect of elevated fluoride exposure on Purdue Pegboard manual dexterity performance

	Right (1)	Left (2)	Both (3)	Sum (4)	Assembly (5)
		Fluoride: spline specification			
Spline, below 1.5 mg/L	0.42	0.73*	0.92**	2.20**	3.50**
	(0.40)	(0.41)	(0.36)	(1.07)	(1.47)
Spline, above 1.5 mg/L	-0.44	-0.87*	-1.06**	-2.68**	-3.93**
	(0.47)	(0.46)	(0.41)	(1.25)	(1.65)
Observations	506	505	504	505	502
Outcome SD	2.09	2.12	1.95	6.08	6.06
Controls	Yes	Yes	Yes	Yes	Yes

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Notes: Table presents coefficients and standard errors from a regression of Purdue Pegboard sub-scales on a spline of Fluoride in the household's drinking water. Each sub-scale reports a number of correctly completed manual tasks within a fixed amount of time. The spline specification allows for the linear relationship to vary above and below the WHO permissible limit of 1.5 mg/L Fluoride. Control variables include sample child gender, cognitive age, and household share of expenditure on sample child, as well as household characteristics including an asset index, indicators of mother's and father's completion of primary school, household's religion and caste, and household drinking water qualities: dissolved oxygen, pH, conductivity, and turbidity. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates.

Table A17: Intake of water not higher by those exposed to elevated fluoride

	Standardized Fluoride			Fluoride $\geq 1.5mg/L$		
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
Treatment	-0.11	-0.07	-0.07	-0.06	0.28	0.32
	(0.41)	(0.36)	(0.37)	(0.74)	(0.74)	(0.76)
Observations	509	509	509	509	509	509
Demographic Controls	No	Yes	Yes	No	Yes	Yes
Water Quality Controls	No	Yes	Yes	No	Yes	Yes
Toxins Controls	No	No	Yes	No	No	Yes
Mean of dep. var	11.96	11.96	11.96	11.96	11.96	11.96

Notes: Table presents coefficients and standard errors from a regression of water intake (number of glasses of water) on two different measures of fluoride. Coefficients are reported for standardized fluoride in columns (1) and (2), and for a binary indicator of exceeding the WHO permissible limit of 1.5 mg/L in columns (3) and (4). Control variables include sample child gender, cognitive age, and household share of expenditure on sample child, as well as household characteristics including an asset index, indicators of mother's and father's completion of primary school, household's religion and caste, and household drinking water qualities: dissolved oxygen, pH, conductivity, and turbidity. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates.

Table A18: Intake of servings of milk per week is not higher in those exposed to elevated fluoride

	Standardized Fluoride			Fluoride $\geq 1.5mg/L$		
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
Treatment	-0.38	-0.29	-0.27	-0.15	-0.06	0.03
	(0.24)	(0.24)	(0.24)	(0.48)	(0.50)	(0.51)
Observations	505	505	505	505	505	505
Demographic Controls	No	Yes	Yes	No	Yes	Yes
Water Quality Controls	No	Yes	Yes	No	Yes	Yes
Toxins Controls	No	No	Yes	No	No	Yes
Mean of dep. var	9.004	9.004	9.004	9.004	9.004	9.004

Notes: Table presents coefficients and standard errors from a regression of number of servings of milk per week on two different measures of fluoride. Coefficients are reported for standardized fluoride in columns (1) and (2), and for a binary indicator of exceeding the WHO permissible limit of 1.5 mg/L in columns (3) and (4). Control variables include sample child gender, cognitive age, and household share of expenditure on sample child, as well as household characteristics including an asset index, indicators of mother's and father's completion of primary school, household's religion and caste, and household drinking water qualities: dissolved oxygen, pH, conductivity, and turbidity. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates.

Table A19: The probability that an observation is missing around the 1.5 mg/L cut-off

	Normed CPM Percentile		MISIC average	
VARIABLES	(1)	(2)	(3)	(4)
Fluoride exceeds 1.5 mg/L	0.0251	0.364	0.0106	0.274
	(0.0298)	(0.425)	(0.0470)	(0.630)
Fluoride exceeds 1.5 mg/L x Female		0.0631		0.0878
		(0.0418)		(0.0610)
Fluoride exceeds 1.5 mg/L x Assetindex		0.00623		-0.0111
		(0.00671)		(0.00928)
Fluoride exceeds 1.5 mg/L x Mother's Education		-0.0564		0.0684
		(0.0454)		(0.0761)
Fluoride exceeds 1.5 mg/L x Father's Education		-0.0325		-0.0438
		(0.0496)		(0.0703)
Fluoride exceeds 1.5 mg/L x Hindu		-0.0404		-0.190
		(0.0492)		(0.251)
Fluoride exceeds 1.5 mg/L x General caste		-0.0393		0.0748
		(0.0700)		(0.102)
Fluoride exceeds 1.5 mg/L x child's age		-0.0338		0.00272
		(0.0230)		(0.0194)
Fluoride exceeds 1.5 mg/L x DO		-0.00610		0.000480
		(0.0166)		(0.0223)
Fluoride exceeds 1.5 mg/L x PH		0.00573		-0.000565
		(0.0459)		(0.0631)
Fluoride exceeds 1.5 mg/L x Conductivity		-0.0362		-0.00999
		(0.0239)		(0.0379)
Fluoride exceeds 1.5 mg/L x Turbidity		-0.0226		-0.0354
		(0.0186)		(0.0247)
Observations	552	552	552	552
R-squared	0.105	0.138	0.327	0.336

Notes: Each regression shows the coefficient of a regression of the likelihood that an observation is missing for an outcome variable on the dummy that fluoride exceeds the threshold level. Each regression controls for a linear function of fluoride value in drinking water. Clustered standard errors have been used to construct the confidence intervals.

Table A20: The effect of standardized fluoride on fluoride avoidance behavior

Dependent Variables	(1)	(2)	(3)
Purchasing a personal non-electric filter	0.006	0.005	0.006
	(0.006)	(0.006)	(0.006)
Walking to collection sources lower in fluoride	-0.003	-0.001	-0.001
	(0.008)	(0.009)	(0.008)
Purchasing tanker water from another village	-0.009	-0.009	-0.007
	(0.007)	(0.008)	(0.008)
Using RO plant/water ATM	-0.000	-0.003	-0.002
	(0.000)	(0.003)	(0.002)
Change in diet/nutrition	-0.001	-0.002	-0.002
	(0.001)	(0.002)	(0.002)
Observations	509	509	509
Demographic Controls	No	Yes	Yes
Water Quality Controls	No	Yes	Yes
Toxins	No	No	Yes

Notes: Table presents coefficients and standard errors from a regression of each of five fluoride avoidance behaviors on standardized fluoride. Control variables include sample child gender, cognitive age, and household share of expenditure on sample child, as well as household characteristics including an asset index, indicators of mother's and father's completion of primary school, household's religion and caste, and household drinking water qualities: dissolved oxygen, pH, conductivity, and turbidity. Toxins controls include arsenic, lead, mercury, e-coli, and nitrates.