Beyond Cavities: The Effects of Low-Level Fluoride Exposure in Childhood on Dental Health, Cognitive Ability and Self-Esteem*

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Abstract

The effects of fluoride in drinking water on dental health and human capital remain central to public health debates. We estimate the causal impacts of childhood fluoride exposure at levels lower than those typically used in artificial fluoridation, exploiting quasi-exogenous variation in naturally occurring concentrations shaped by regional geology in Japan. Linking this variation with unique longitudinal survey data, nationally representative medical claims, and patient surveys, we provide comprehensive evidence on fluoride's benefits. Even at low concentrations, fluoride substantially improves dental health in childhood and adolescence, with particularly strong effects for girls and children from lower socioeconomic backgrounds. In contrast to concerns raised by studies of higher exposures, we find no adverse effects on cognitive performance or educational attainment. Strikingly, fluoride exposure enhances self-esteem among females, operating through improved appearance: reduced cavities lower the likelihood of malocclusion and other visible dental issues, which matter especially during adolescence. These improvements in dental aesthetics boost confidence and socio-emotional skills. Our findings highlight the role of oral health in shaping non-cognitive development and underscore the broader policy relevance of fluoride exposure.

JEL Codes: I10, I12, J16, J24
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1 Introduction

The effectiveness of fluoride in drinking water on dental health and child development is currently at the center of serious debate. The Centers for Disease Control and Prevention (CDC) has listed community water fluoridation among the ten greatest public health achievements of the 20th century, emphasizing its large role in reducing dental cavities and its cost-effectiveness (CDC, 1999). Yet the consensus has eroded in recent years: while many studies confirm significant reductions in cavity rates, others have raised concerns about possible neurotoxic effects of childhood exposure. For example, recent systematic reviews highlight consistent associations with impaired cognitive outcomes (Grandjean, 2019), and even a well-executed causal analysis using high-quality data finds potential negative impacts of early-life exposure to fluoridated water on cognitive functions and academic achievement (Roberts, 2024).

Another important, yet often overlooked, aspect of fluoride in drinking water is the issue of dosage and external validity. Much of the existing economic literature has focused on settings with artificially fluoridated water in the United States, where concentrations typically range from 1.0 to 1.5 mg/L (Glied and Neidell, 2010; Roberts, 2024). In some instances, levels have even exceeded the CDC's recommended limit due to lack of monitoring. This leaves open the question of whether lower levels of fluoride have any meaningful effects on dental health and human capital development.

Thus, the first objective of this paper is to study the causal effect of childhood exposure to fluoride in drinking water—at levels lower than those typically used in artificial fluoridation programs—on dental health outcomes and human capital during adolescence. Our identification strategy builds on that of Aggeborn and Öhman (2021), who leverage geological variation in natural fluoride concentrations in Sweden, a setting without community water fluoridation and with a high-quality public water supply system. Similarly, we take advantage of exogenous variation in fluoride concentrations across municipalities in Japan, driven by local geological characteristics, in a context where artificial fluoridation is also absent. In terms of the dosage, national water quality regulations stipulate that fluoride concentrations in drinking water must not exceed 0.8 mg/L, and in practice, almost all observed levels fall below 0.4 mg/L. Moreover, Japan's rigorously regulated public water system ensures that tap water is safe for direct consumption, minimizing the risk that our results are confounded by other water contaminants.[1]

While most prior studies on fluoride exposure have examined potential risks for cognitive function or educational attainment—often focusing on higher dosages or relying on correlational designs (Choi et al., 2015; Gopu et al., 2022; Roberts, 2024)—little attention has been paid to its effects on other important aspects of human capital, such as self-esteem. From an economic and psychological perspective, self-esteem is a key determinant of long-term outcomes in education, labor markets, and health (Waddell, 2006; Drago, 2011; Orth et al., 2012; Page and Ruebeck, 2025). This paper fills this gap by examining the impact of childhood fluoride exposure on the development of self-esteem.

The second objective is to shed light on the gender heterogeneity of the role of fluoride exposure in dental health and skill formation. Prior studies suggest that improvements in dental health may have different downstream consequences for women and men. Glied and Neidell (2010), for example, find that women who lived in areas with community water fluoridation during childhood earned more as adults than those who did not, with no comparable effect for men. Similarly, Gallego et al. (2024) show that providing free dental care improved oral health for both sexes, but only women experi-

[1] Drinking water contamination is not uncommon even in developed countries. In the United States, for example, violations of the Safe Drinking Water Act have been documented in cases such as the Flint water crisis (Grossman and Slusky, 2019) and in widespread non-compliance across community water systems (U.S. Environmental Protection Agency, 2022). In such contexts, isolating the effect of a single contaminant in drinking water can be challenging. By contrast, as discussed in Section 2.1, more than 99% of water suppliers in Japan meet the standards of the Water Supply Act, ensuring the quality and safety of drinking water.

enced gains in self-esteem and smiling behavior. Guided by this evidence, we examine whether the effects of early-life fluoride exposure on dental health and skill formation differ by gender.

Our empirical analysis yields several key findings. First, we reconfirm robust evidence that childhood fluoride exposure substantially improves dental health during both childhood and adolescence. We find that a 0.1 mg/L increase in fluoride concentration in drinking water during childhood reduces the probability of outpatient visits for dental cavities (excluding routine checkups) by 9.4 percent relative to the sample mean. Additional analyses using nationally representative medical claims and patient survey data further show that fluoride exposure lowers monthly dental expenditures and increases the interval between visits—patterns consistent with improved oral health.[2] We also confirm that access to dental services—as measured by the number of dentists per capita—is uncorrelated with fluoride levels, suggesting that geographic availability of care is unlikely to drive the observed differences. These findings underscore that fluoride exposure has benefits for oral health even in a setting where universal health insurance guarantees generous coverage for pediatric dental care and where preventive checkups are widely institutionalized.

Heterogeneity analysis reveals that the beneficial effects of fluoride are stronger among children from lower socio-economic backgrounds, defined as those whose fathers have a high school education or less, which is consistent with findings of Glied and Neidell (2010). We also document notable gender heterogeneity in dental health effects—a dimension that has received limited attention in the existing literature. For example, while Aggeborn and Öhman (2021) also demonstrate that naturally occurring fluoride improves a range of oral health outcomes in Sweden, their analysis does not explore

[2] A potential concern is that reduced utilization simply reflects fewer referrals following school checkups. However, this is unlikely in Japan, where annual school dental checkups are mandatory through high school, ensuring equal diagnostic opportunities regardless of fluoride exposure.

gender differences.[3] The improvement in dental health outcomes is significantly larger among girls than boys, suggesting that early-life fluoride exposure may play a particularly important protective role for female oral health. One possible explanation is biological differences in oral physiology. Compared to males, females typically have lower salivary flow rates and lower calcium concentrations in saliva (Inoue et al., 2006; Sewón et al., 1998). Because fluoride aids remineralization by promoting calcium redeposition in enamel, individuals with lower salivary calcium (i.e., females) may benefit more from fluoride exposure.

Second, consistent with the findings of Aggeborn and Öhman (2021) based on Swedish male cohorts observed at ages 18–20 through mandatory military conscription tests, we find no evidence that fluoride exposure affects cognitive skill formation as measured by educational attainment. In particular, fluoride exposure has no significant impact on the academic quality of the high school attended or on the likelihood of college admission. Extending beyond Aggeborn and Öhman (2021), however, our sample includes men and women, and we find no evidence of cognitive effects for either of them.

Third, we find that childhood fluoride exposure significantly enhances self-esteem among adolescent females, with no corresponding effects observed for males. Specifically, a 0.1 mg/L increase in fluoride concentration in drinking water between ages 2 and 11 is associated with a 4.6% standard deviation (SD) increase in self-esteem among girls. To the best of our knowledge, this is among the first studies to identify early-life fluoride exposure as a determinant of self-esteem, and to document its clear gender heterogeneity during adolescence—an important transitional period between childhood and adulthood (Almond et al., 2018).[4]

[3] An exception is Chankanka et al. (2011), who analyze longitudinal dental data from the Iowa Fluoride Study and find that the protective effects of fluoride against dental caries are consistently stronger in girls than in boys.

[4] Almond et al. (2018) emphasize that while the short-term and very long-term impacts of in utero or early childhood exposures are well documented, evidence on the consequences of exposures during adolescence remains scarce. They highlight adolescence as a transitional stage marked by both opportunities for intervention and heightened vulnerability (see Section 7 of Almond et al. 2018).

The beneficial effects on self-esteem in the female sample appear to be driven by enhanced facial appearance resulting from better dental health. Using survey questions from our dataset, we find that girls exposed to higher levels of fluoride report significantly lower levels of appearance-related anxiety. This finding aligns with the established consensus in dentistry that childhood dental caries can adversely affect dentition development and increase the risk of malocclusion later in life (Zou et al., 2018; Singh and Purohit, 2021).

Our findings provide a significant policy implication. We show that even in Japan—where children's dental health ranks among the best in the world, universal health insurance ensures generous coverage for pediatric dental care, and preventive checkups are mandatory—exposure to low levels of naturally occurring fluoride still generates measurable improvements in oral health and non-cognitive skills, particularly among females. This suggests that our estimates likely represent a lower bound on the potential benefits of fluoride exposure in other institutional contexts, particularly in countries where baseline oral health is poorer and access to preventive dental care is more limited. Importantly, we find no evidence of negative effects on cognitive outcomes at lower dosages in Japan.

Taken together, our results support a more nuanced approach to fluoridation policy. Rather than *entirely* eliminating community water fluoridation altogether—as recently advocated by Robert F. Kennedy Jr.[5]—policy discussions should focus on identifying appropriate dosage levels. A complete withdrawal may lead to substantial increases in dental caries, especially among socioeconomically disadvantaged populations (Glied and Neidell, 2010; Choi and Simon, 2025).[6] Moreover, we argue that the evaluation of fluoride exposure should go beyond the conventional trade-off between dental benefits and potential cognitive risks. Our study introduces an often-overlooked dimension: its

[5]Some U.S. states have already followed this trend. For example, Utah has enacted a statewide ban, and Florida is considering similar legislation (The New York Times, 2025).

[6]Choi and Simon (2025) estimate that eliminating fluoridation would disproportionately affect children covered by public insurance or with no coverage, compared to those with private dental insurance.

positive impact on self-esteem, particularly for adolescent girls. Given growing evidence on the importance of self-esteem in the labor market—especially for women (Edin et al., 2022)—these broader effects deserve greater attention in the design and assessment of future fluoridation policies.

The remainder of this paper is organized as follows. First, we review the related literature to elucidate the intended contributions of our work. In Section 2, we introduce background information on water supply service in Japan and the determinants of fluoride levels in drinking water. Section 3 discusses the data used in this study. In Section 4, we describe the empirical strategy to identify the effect of fluoride exposure on dental health,educational attainment, and self-esteem. The main results are shown in Section 5. Finally, Section 6 provides the discussion and conclusions of our study.

Related Literature This paper is closely related to three distinct strands of literature. First, it contributes to the ongoing debate in health economics and epidemiology regarding the welfare effects of water fluoridation policies (or fluoride concentration in drinking water). While community water fluoridation is widely implemented in the United States, empirical evidence on its welfare effects is mixed. Leveraging quasi-random variation in the timing of policy adoption, Glied and Neidell (2010) document beneficial effects of fluoridation on oral health and find positive impacts on women's earnings. In contrast, using a similar identification strategy and census microdata, Roberts (2024) find that children exposed to community water fluoridation from birth to age five are *worse off* as adults on measures of high school dropout, economic self-sufficiency, physical ability, and overall health—suggesting that the fluoride concentrations commonly used in the United States (1.0–1.5 mg/L), and at times even higher due to insufficient monitoring, may be excessively high.

Our study departs from this literature by focusing on lower fluoride doses, which arise primarily from *natural* variation in fluoride concentrations across municipalities in Japan (see Section 2.2). Aggeborn and Öhman (2021) represents the study most closely related to ours. They exploit quasi-exogenous variation in natural fluoride concentrations across municipalities in Sweden and find that childhood fluoride exposure improves oral health but has precisely zero effects on cognitive and non-cognitive outcomes. However, a key limitation of their otherwise rigorous study is that cognitive and non-cognitive outcomes are measured only for men, which precludes analysis of gender-specific effects. Our findings reveal that fluoride exposure improves dental health and non-cognitive outcomes such as self-esteem only among females. This gender-specific response highlights the importance of explicitly examining heterogeneity rather than relying on average treatment effects, particularly given that dental health—through its impact on facial appearance—may have stronger psychosocial and social signaling value for adolescent girls. By studying outcomes for both sexes and estimating gender-specific effects, we provide new evidence on the distributional consequences of early-life fluoride exposure that were previously masked in the literature.

Second, our study also contributes to a growing literature on the broader social and psychological consequences of dental health. Lipton et al. (2016) examine Medicaid expansions in the 1980s and 1990s and document long-lasting improvements in dental health among non-Hispanic Black populations, suggesting that equal access to dental care can help reduce racial disparities in oral health. Gallego et al. (2024) conduct a randomized experiment providing free dental care to low-income adults living in the Santiago area of Chile. They show that the intervention improves self-esteem, increases the likelihood of smiling in photographs, raises short-run employment and earnings, and improves partner relationships—but only for women. While our study and Gallego et al. (2024) share qualitatively similar findings, the contexts are substantially different. Gallego et al. (2024) focus on adults in a low-income setting with limited access to dental care,[7] whereas we study children in a universal health coverage system. Japan's healthcare system allows direct access to specialists without gatekeeping, and many municipalities provide generous subsidies for children's dental care.[8] The fact that similar patterns emerge in both settings supports the idea that improved dental health—particularly through fluoride exposure—can foster self-esteem for girls by reducing appearance-related concerns.

Third, our paper is closely related to the economic literature on the determinants of human capital. Seminal work by Cunha and Heckman (2007) models the accumulation of cognitive and non-cognitive skills, and based on that framework, earlier studies have shown that childhood health can have long-term effects on educational attainment and the development of these skills (Currie, 2009; Almond and Currie, 2011; Almond et al., 2018). While previous literature has focused on the role of health at birth (Black et al., 2007; Royer, 2009; Figlio et al., 2014) or on serious chronic health conditions (Case et al., 2005; Fletcher et al., 2010), our study points to the possibility that relatively minor conditions—such as dental health—can also be important determinants of skill formation.

Compared to cognitive skills, whose developmental pathways are relatively well documented, much less is known about the processes through which non-cognitive skills are formed (Deming, 2022). Yet extensive evidence demonstrates that non-cognitive skills, such as locus of control and self-esteem, are powerful predictors of educational attainment and labor market success, even after accounting for cognitive ability (Heckman and Rubinstein, 2001). Building on this insight, subsequent studies have shown that self-esteem in particular is associated with future earnings (Murnane et al., 2001; Waddell, 2006; Drago, 2011) and with the likelihood of dropping out of school (Mendolia and Walker, 2015). We provide new causal evidence on the formation of self-esteem dur-

[7] Gallego et al. (2024) report that a nationally representative survey conducted in 2009–2010 found that 28.7 percent of adults in Chile had not visited a dentist in the past five years—18 percent in the top income quintile and 32 percent in the bottom quintile.

[8] See Iizuka and Shigeoka (2022), Iizuka and Shigeoka (2023), and Kang et al. (2022) for detailed analyses.

ing adolescence, highlighting the role of early-life fluoride exposure through improved dental health and appearance.

2 Background

2.1 Water Supply Service in Japan

In Japan, water supply services are primarily operated by local governments, such as municipalities and inter-municipal cooperatives, under the framework of local public enterprises. These entities are responsible for managing infrastructure, financing, and the daily operations of water systems within their jurisdictions. While the central government does not directly manage water utilities, it provides national-level oversight and guidance through the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and the Ministry of the Environment.[9]

Japan's water supply service is governed by the Water Supply Act (WSA), enacted in 1957. This legislation provides a comprehensive framework regulating the entire water supply process—from source and treatment to distribution and household delivery—to ensure public health and safety. It also establishes strict standards for water quality management, disaster preparedness, and operational reliability, all aimed at maintaining a stable and safe supply of drinking water nationwide.

Under the WSA, tap water in Japan must meet 51 specific quality standards, including limits on coliform bacteria, Escherichia coli (E. coli), lead, arsenic, and fluoride compounds. Despite the rigor of these regulations, compliance has been exceptionally high: over the past 20 years, more than 99.9% of water suppliers have consistently met all required benchmarks. Importantly, due to these stringent standards and high compliance rates, tap water in Japan is treated under the assumption that it will be consumed

[9]As of April 1, 2024, responsibilities related to water supply administration have been transferred to MLIT and the Ministry of the Environment from the Ministry of Health, Labour and Welfare.

directly from the tap—unlike in many other countries. For fluoride, the WSA sets a maximum allowable concentration of 0.8 mg/L, and all water suppliers in our dataset fully comply with this standard throughout the observation period.

WSA also classifies water supply services based on the population served. Virtually the entire population is covered by one of the following two categories: (1) Public Water Supply Services (*Jo-Suido* in Japanese) and (2) Small-Scale Water Supply Services (*Kan-i-Suido* in Japanese). Public water supply services refer to large-scale municipal systems that provide water to communities with more than 5,000 people through extensive piped networks. These systems account for the vast majority of water provision: as of 2022, 98.7% of the population is covered by Public water supply services.[10] The remaining small and rural communities are served by Small-Scale water supply services, which cater to communities with populations of fewer than 5,000 people. These systems are typically found in mountainous, island, or otherwise remote regions where connecting to the larger public network is technically or economically unfeasible. Although they are also regulated under the Water Supply Act, they often operate with simpler infrastructure and fewer resources. A more thorough view of the water supply service system in Japan is provided in Appendix H.

Our data on fluoride concentrations in tap water—discussed in detail in Section 3.3—are sourced from official databases covering water supply plants operated under the Public Water Supply Services (*Jo-Suido*). As a result, the fluoride exposure measures used in this study reflect the conditions experienced by nearly the entire population and can be considered highly representative at the national level.

[10] Authors' calculation based on the data as of 2022. Source: https://www.mlit.go.jp/mizukokudo/watersupply/content/001737264.pdf (in Japanese, accessed April 9, 2025).

2.2 Determinants of Fluoride Exposure

Publicly provided drinking water in Japan is regulated under the Water Supply Act, which requires routine monitoring of water quality by local suppliers. As a result, the overall composition of tap water reflects both strict national safety standards and the natural characteristics of local water sources. Importantly, unlike in many countries, no municipality in Japan currently implements community water fluoridation,[11] so the observed fluoride concentration in drinking water is entirely determined by natural geological variation.

Geochemical studies have documented a strong association between granitic rock formations and elevated fluoride concentrations in groundwater (Mukherjee and Singh, 2020). To assess whether a similar relationship holds in Japan, we link municipal-level water quality data from the Database of Water Quality of Aqueduct (DWQA) with information from the Seamless Digital Geological Map of Japan.[12] Figures 1A and 1B display the geographic distributions of fluoride concentration and granitic rock, respectively, and reveal a clear positive relationship. Figure 1C provides a binned scatterplot of this association, controlling for prefecture fixed effects and other types of volcanic rocks. Appendix Table A1 further shows in a regression framework that municipalities with larger granite shares exhibit systematically higher fluoride concentrations, and the result is robust to controlling for other rock types.

Although granitic rock is not the sole determinant of fluoride levels, the strong and consistent association indicates that natural geological factors play a dominant role. Because each bedrock category includes multiple subtypes, there remains meaningful within-category variation in fluoride concentrations, which provides plausibly exoge-

[11] Between the 1950s and 1970s, a few local governments briefly experimented with water fluoridation: Yamashina in Kyoto Prefecture (1952–1965, 0.6 mg/L), Asahi in Mie Prefecture (1967–1971, 0.6 mg/L), and Okinawa under U.S. administration (1957–1972, typically 0.7–1.0 mg/L). All of these programs were discontinued by 1972, and no municipality in Japan has implemented community water fluoridation since then (see Appendix for more detail).

[12] Source: https://gbank.gsj.jp/seamless/ (in Japanese).

nous differences across municipalities. In our data, measured fluoride levels range from near zero to the regulatory maximum of 0.8 mg/L, with almost all observations falling below 0.4 mg/L —see Figure 2, which plots average childhood fluoride exposure in our main sample introduced in the next section. This pattern suggests that the observed variation is driven by natural geological conditions rather than policy choices. The absence of bunching at the regulatory maximum further suggests that the observed variation reflects natural geological conditions rather than policy intervention.[13]

In addition to the cross-sectional variation in fluoride concentrations across municipalities, a second source of variation in individual-level exposure during childhood arises from moving patterns. Migration is undoubtedly endogenous in many respects, but as long as the choice of destination is not systematically related to fluoride concentration, residential moves generate an additional layer of plausibly exogenous differences in treatment intensity. In our setting, exposure intensity depends on the number of years a child spends in each municipality between ages 2 and 11 (See the detailed structure of our main data in Section 3.1). We further show in Section 5.5 that moving behavior is not systematically associated with local fluoride levels at the origin, supporting the interpretation that residential patterns provide an additional exogenous source of variation in long-term fluoride treatment.

3 Data

3.1 Skill Formation in Adolescence

Our primary data source is the Longitudinal Survey of Newborns in the 21st Century (LSN21), conducted by Japan's Ministry of Health, Labour and Welfare (MHLW) and the

[13] If fluoride concentrations were artificially manipulated, we would expect to see clustering at the regulatory maximum of 0.8 mg/L, which is not the case.

Ministry of Education, Culture, Sports, Science and Technology (MEXT).[14] The survey follows *all* individuals born during two specific weeks in 2001: January 10–17 and July 10–17.[15] The first survey was conducted when the children were 6 months old, and subsequent surveys have been conducted annually. Currently, surveys up to the 21st round (i.e., the one conducted when the children are approximately 21 years old) are available. Although this survey covered only children born in specific weeks in January or July, MHLW reported that the number of births does not differ greatly across months (Nakayama and Matsushima, 2023).

LSN21 has several unique features that are beneficial to our study. First, it collects a wide range of information on non-cognitive skills and educational attainments, which is crucial to our study. Second, because this survey *annually* tracks the municipalities where the surveyed participants are living from the 1-15th survey, we can precisely define individual-level exposure to fluoride during childhood. This feature overcomes a limitation in previous studies: for example, Glied and Neidell (2010), one of the closely related studies to us, uses the residential information as of fifteen years old to make the intensity of exposure to fluoridated water during childhood. This might introduce a measurement error in their estimates. Third, LSN21 collects a wide array of parental and family-level characteristics, which are not limited to socio-economic status such as education. This feature provides us with an opportunity to make a stronger statement about the plausibility of the exogeneity of the fluoride exposure.

As an important component of non-cognitive skills that can be substantially affected by the dental health (Gallego et al., 2024), we primarily focus on self-esteem. In LSN21, respondents' self-esteem are measured using the Rosenberg Self-Esteem Scale developed by Rosenberg (1965), which has been a widely accepted measure in the field of

[14] Specifically, the 1st to 15th rounds of the survey were administered by MHLW, while MEXT has overseen the survey from the 16th round onward.

[15] LSN21 has two cohorts, where the first one targeted children born in 2001 and the second one targeted children born in 2011. Because our main outcome variables are measured in the adolescence period as described below, we do not use the second cohort in this paper.

psychology and, more recently, in economics (such as Drago, 2011). It consists of ten statements related to overall feelings of self-worth and self-acceptance that respondents rate on a five-point Likert scale, ranging from “strongly agree” to “strongly disagree”. LSN21 uses the Japanese translated version of this scale (Mimura and Griffiths, 2007) for surveyed children between ages 16-21. For the following analysis, we used the standardized scores calculated separately for each survey round.

We also report regression results for additional non-cognitive skill outcomes —perseverance (GRIT) and Big-Five personality index —in Appendix B.

LSN21 collects information on the name of the high school and university (college) that the surveyed child is enrolled in at the 16th and 19th round of the survey, respectively (i.e., when most children are freshmen in high school or university).Based on these information, we consider the following outcomes related to educational attainment:

- Quality of High School Measured by Deviation Score

  In Japan, the quality or academic competitiveness of high schools is often evaluated using a metric known as the deviation score (known in Japanese as *Hensachi*). This score is widely used by cram schools and examination agencies to indicate the relative difficulty of gaining admission to a particular high school. It is calculated based on standardized test performance, with a national average set to 50 and a standard deviation of 10. A higher deviation score implies a more selective and academically competitive school. For our analysis, we assign deviation scores to each high school based on published information from major cram school networks called Everyone’s School Information (*Minkou* in Japanese).[16] The distribution of this deviation score is provided in Figure A1 in Appendix A.

- College Attendance

[16]We scrape deviation score information from https://www.minkou.jp/hischool/ (Accessed on April 8th, 2025. The website is in Japanese)

LSN21 collects information on whether the respondent is enrolled in a university or college in the 19th round of the survey, which corresponds to the time when most children are in their first year of higher education. We construct a binary indicator that equals one if the child is not attending college at this round, and zero otherwise. This variable serves as our measure of college enrollment outcome.

3.2 Dental Health Measurement

As a measure of the extensive margin of dental care utilization, the LSN21 survey asked parents whether the surveyed child had visited a medical institution for dental cavities in the previous year. This question was administered in survey rounds 3 through 12, and we use these responses as a proxy for children's dental health.

This proxy, however, has some limitations. Because it is based on parent-reported data, measurement error is possible. Moreover, it only captures whether a child visited a medical institution until age 12, providing no information on the intensity or severity of dental problems, nor on their outcomes during adolescence.

To address these limitations, we incorporate additional datasets. First, we use universal health insurance claims data for outpatient visits to medical institutions, known as the Statistics of Medical Care Activities (SMCA). These claims were collected every June from randomly selected medical institutions between 1984 and 2010. The outpatient records in the SMCA provide data on individual patients' monthly medical expenditures,[17] conditional on visiting a medical institution at least once in this month. Because the Japanese national fee schedule standardizes the fees for medical procedures and this schedule is uniformly applied across all healthcare institutions regardless of location or ownership ensuring consistency in medical pricing nationwide, we can iden-

[17]More precisely, the data provides the total medical fee points. In Japan's universal health insurance system, medical service fees are determined by a nationally standardized fee schedule, known as the medical fee points system. Each medical procedure, treatment, or service is assigned a specific number of points, with one point equivalent to JPY 10.

tify an accurate measurement of their monetary value for all patients. It is much more challenging under the healthcare system without universal coverage or uniform price schedule since a procedure is priced differently across insurers (Fu et al., 2021). In addition to expenditure data, the SMCA includes patient characteristics such as age, gender, type of insurance coverage, and the municipality where the medical institution is located. To focus on dental health during childhood and adolescence, we restrict our main analysis sample to individuals under the age of 18.

Second, we draw on the Patient Survey (PS), a repeated cross-sectional administrative survey that collects individual-level data on healthcare utilization from randomly selected medical institutions across Japan. The PS is conducted every three years, and we use three rounds from the 2000s and 2010s —specifically, the 2005, 2008, and 2011 waves—during which information on fluoride is available.

The PS consists of two components: one on outpatient visits and one on inpatient discharges. Since most dental-related illnesses are treated through outpatient care, we focus on outpatient visit records. These records include data on all patients who visited the sampled medical institutions on a designated day in October of the survey year. As with the analysis with SMCA, we primarily use a sample of less than 18 years old. Importantly, the dataset provides information on visit intervals, measured as the number of days since the previous visit. We interpret this interval as a proxy for the severity of the condition: shorter intervals suggest a need for more intensive or frequent care.

3.3 Information on Fluoride in Drinking Water

We sourced information on natural fluoride levels in tap water from the Database of Water Quality of Aqueduct (DWQA) for the period from 2003 to 2012. This data consists of water quality test results from all water treatment plants, reported by the responsible water suppliers. The DWQA includes results for all test items, such as E. coli, cadmium, and mercury. Among these, we collected data on the amount of fluoride and its compounds. While the water suppliers are often municipalities, in some cases, the responsibility of water supply is managed by an Inter-Municipal Water Supply Authority (IWSA). IWSA in japan is a cooperative organization established by multiple local municipalities to efficiently manage water supply services. These authorities work together to secure water sources, manage water quality, and construct and maintain water supply facilities.

Because the municipality is the finest geographic unit identifiable in LSN21, we aggregate the water treatment plant-level observations in the DWQA to the municipality level. For plants managed by a single municipality, we take a weighted average based on the volume of purified water at each plant. For plants managed by a IWSA (multiple municipalities), we first distribute the volume of purified water to each municipality based on the total population, and then aggregate the data to the municipality level. For example, suppose there are two water treatment plants, A and B, in municipality m_1. Plant A is managed solely by municipality m_1 and purifies 1,000 cubic meters of water per day with a fluoride level of 0.2 mg/L. Plant B is managed by both m_1 and m_2, purifies 2,000 cubic meters of water per day with a fluoride level of 0.1 mg/L. Municipality m_1 has a population of 80,000, while municipality m_2 has a population of 40,000. For plant A, the fluoride level is 0.2 mg/L. For plant B, by allocating 1,333 cubic meters (i.e. two-thirds of total volume) to m_1 and 667 cubic meters (i.e., the rest one-third of total volume) to m_2. The weighted average fluoride level for m_1 is calculated as (1,000 * 0.2 + 1,333 * 0.1) / 2,333, which is approximately 0.14 mg/L.

3.4 Summary Statistics

Figure 2 presents the histogram of average fluoride exposure between ages 2 and 11 for our main sample drawn from LSN21. The distribution indicates that exposure levels are concentrated at the lower end, well below those observed under artificial water fluoridation programs such as those in the United States, where typical concentrations range from 1.0 to 1.5 mg/L. As noted in Section 2.1, all water suppliers in our dataset comply with the Japanese regulatory upper limit of 0.8 mg/L, and in practice, the almost all of exposure values fall below 0.4 mg/L. This institutional setting—characterized by naturally occurring, low-level variation in fluoride concentration—provides a plausibly exogenous source of exposure, allowing us to identify the causal effects of early-life fluoride exposure at lower-dosage on a wide range of outcomes.

Table 1 reports descriptive statistics for the main variables from LSN21, separately for males and females. The average fluoride exposure between ages 2 and 11 is about 0.75 (in 0.1 mg/L units) with a standard deviation of 0.38, indicating that average exposure levels in Japan are substantially lower than those typically observed under artificial water fluoridation programs. Approximately 25% of individuals visited a dental clinic as outpatients at age 12, with boys slightly more likely to do so (26%) than girls (24%).

Regarding non-cognitive outcomes, the Rosenberg self-esteem score is standardized to have a mean of zero and a standard deviation of one, with boys scoring slightly above the mean (0.11) and girls slightly below (–0.11). For cognitive outcomes, the mean high school deviation score is roughly 54, and about 60% of the sample attended college, with a higher rate among girls (63%) compared to boys (58%).

4 Empirical Framework

4.1 Effects of Fluoride Exposure on Dental Health

Indicator of Outpatient Visit Due to Dental Cavity To examine the effect of fluoride levels in tap water on children's dental health, we begin by analyzing the extensive margin of visits to medical institutions due to dental cavity, using a survey question from

LSN21 (see Section 3.2). Specifically, we estimate the following equation:

$$\text{Outpatient(Dental)}_{i,12} = \beta\overline{Fluoride}_i + \gamma X_m + \delta_p + \varepsilon_{it} \tag{1}$$

where $\text{Outpatient(Dental)}_{i,12}$ represents a binary indicator for whether the child had dental cavities that required a visit to a hospital or clinic for medical care in the past year, as reported in the LSN21 12th round of the survey (i.e. when the child is 12 years old).[18] On the right-hand side, the main regressor in this equation is $\overline{Fluoride}_i$, which represents the average exposure to fluoride in the tap water of child i during childhood (between ages 2 to 11, given that the oldest available data of fluoride is in 2003). This is based on the municipality where the child lived at each age. To construct it, we first calculate municipality-level exposure at each age, that is $Fluoride_{m(i,2)}, \cdots, Fluoride_{m(i,11)}$ (where $m(i,a)$ stands for the municipality of residence of child i at age a), based on the municipality of residence reported at each survey round. Then, we take an arithmetic mean of these quantities: $\overline{Fluoride}_i = \frac{1}{10}\sum_{a=2}^{11} Fluoride_{m(i,a)}$. X_m includes other municipality-level economic characteristics during childhood (the unemployment rate and taxable income per capita, measured in the 2005 census). Finally, we include province fixed effects δ_p, defined by province of residence at age 12, to capture unobserved regional heterogeneity.[19]. We include the province-level fixed effect (δ_p) controlling for the province of residence at age 12.[20]

Medical Cost and Visit Interval For a wider range of dental health outcomes, we sourced the data from SMCA and PS. While the analysis using SMCA and PS is free from measurement error given that it is based on representative sampling from the universe of

[18] Let us note again that the twelfth round was the final round in which this question was included in the survey.

[19] In robustness checks, we also consider specifications with province fixed effects at alternative ages, as well as models with municipality fixed effects.

[20] We conduct the robustness tests which controls for the province fixed effects at different timing or municipality fixed effects.

medical institutions in Japan, these datasets do not have a panel structure unlike LSN21, which prevents us from tracking the same individuals over time. As a result, we consider contemporaneous exposure to fluoride at the municipality level, rather than constructing individual-level average exposure over time as we specified in Eq. (1). Thus, the regression equation we estimate is

$$\log(\text{Monthly Cost})_{imy} = \beta Fluoride_{my} + \gamma X_m + \psi X_{imy}^{SMCA} + \delta_p + \delta_y + \varepsilon_{imt}, \tag{2}$$

$$\text{Visit Interval}_{imy} = \beta Fluoride_{my} + \gamma X_m + \psi X_{imy}^{PS} + \delta_p + \delta_y + \varepsilon_{imt}. \tag{3}$$

In both equations, the main regressor of interest is $Fluoride_{my}$, the fluoride level in tap water in municipality m in year y. X_m represents municipality-level characteristics as in Equation (1). We control for individual characteristics X_i, province fixed effects (δ_p), and year fixed effects (δ_y). In Equation (2), the outcome $\log(\text{Monthly Cost})_{imy}$ is the monthly cost associated with dental cavities for patient i, conditional on visiting a medical institution at least once in month y, as observed in SMCA. X_{imy}^{SMCA} includes patient age, type of insurance coverage, and an indicator for whether the visit is the patient's first consultation or a follow-up visit.[21] In Equation (3), the outcome Visit Interval$_{imy}$ is the time (in days) between consecutive visits by patient i to the same medical institution, as observed in PS. X_{imy}^{PS} includes patient age and type of insurance coverage.

4.2 Effects of Fluoride Exposure on Skill Formation

To estimate the effect of childhood exposure to fluoride in drinking water on cognitive function and self-esteem measured during adolescence, we employ the following re-

[21] In Japan's fee-for-service reimbursement system, consultation fees differ substantially between the first and subsequent visits. For example, under the 2024 fee schedule, the basic consultation fee is 288 points (= 2,880 yen) for a first visit but only 73 points (= 730 yen) for a follow-up visit in medical outpatient care, and 234 points versus 48 points, respectively, in dental care. These differences make it particularly important to control for whether an initial consultation fee is billed when analyzing patient costs.

gression specification:

$$Y_{it} = \beta \overline{Fluoride}_i + \gamma X_m + \delta_p + \delta_t + \varepsilon_{it} \tag{4}$$

In this equation, Y_{it} denotes the cognitive skills proxied by educational attainment and self-esteem of child i observed at survey round t. The key explanatory variable, $\overline{Fluoride}_i$, represents the average fluoride concentration in drinking water during childhood defined in Eq. (1). X_m is a vector of municipality-level control variables sourced from the census, δ_p denotes prefecture fixed effects, and δ_t captures survey round fixed effects.

4.3 Identification Assumption

An important identifying assumption underlying the interpretation of the parameter β in Eq. (4)-(1) as the causal effect of childhood fluoride exposure on dental health, cognitive outcomes, or self-esteem is that fluoride exposure is conditionally exogenous. This assumption is plausible in our setting for several reasons.

We exploit geographic variation in naturally occurring fluoride concentrations across municipalities in Japan. The average land area of a municipality in Japan is approximately 60 square miles, substantially smaller than counties in the United States and other administrative units typically used in similar studies. This high level of geographic granularity allows us to exploit fine-scale spatial variation in fluoride exposure, reducing the risk of confounding due to unobserved regional characteristics that vary at broader geographic levels.

We also control for province fixed effects, which capture unobserved heterogeneity at a higher administrative level.[22] By comparing individuals living in different municipalities within the same prefecture, we further mitigate concerns about omitted vari-

[22] In one of the robustness tests, we additionally include municipality fixed effects, leveraging within-individual variation.

ables that may be correlated with both fluoride concentration and child development outcomes.

Most importantly, fluoride levels in drinking water in Japan are not determined by human intervention or public health policy, but rather reflect natural geological variation in water sources such as the density of granitic rock (see Section 2.2). Japan does not implement community water fluoridation programs in any municipalities. This institutional feature ensures that variation in fluoride concentration is plausibly independent of unobserved factors that could affect child dental health and skill outcomes.

To assess the plausibility of this assumption, we conduct a series of placebo tests using alternative outcomes.

Birth outcomes. We first examine whether fluoride concentration is correlated with health status at birth. Specifically, we regress birthweight, gestational age, an indicator for low birthweight (less than 2,500g), and an indicator for preterm birth (less than 37 weeks) on fluoride concentration. These data are collected in the first round of LSN21 and linked to the Vital Statistics of Japan, ensuring high reliability. As shown in Panel A of Table 2, there is no meaningful correlation between these outcomes and fluoride levels, suggesting that fluoride concentration in drinking water is unlikely to be correlated with health endowments at birth.

Parental characteristics. Next, we examine whether fluoride concentration is associated with parental socioeconomic background, which could confound our results if families self-select into high-fluoride areas. We analyze maternal employment status at birth and parental age at birth (first round),[23] parental education (second round), and a

[23] The relationship between maternal age and child outcomes is known to be non-linear. For example, Royer (2004) documents that women under age 18 and over age 35 are approximately 30 percent more likely to experience preterm delivery compared to those aged 26–29. With this in mind, we regress indicators for maternal age at birth being below 20 and above 35 on average childhood fluoride exposure. We find no statistically significant association in either indicator variable. These results suggest that the risk of bias due to maternal age is minimal.

parenting quality score (fourth round).[24] As shown in Panel B of Table 2, none of these variables are systematically related to fluoride exposure.

Childhood illnesses. We then turn to health conditions unrelated to dental care. Using the 12th round of LSN21, which asks whether the child required a hospital or clinic visit in the past year for illnesses other than dental cavities, we test for associations with fluoride concentration. The outcomes include indicators for asthma, allergy, injury by accident, influenza, and common cold. The results, reported in Panel C of Table 2, show no significant correlations, indicating that fluoride levels are not systematically related to non-dental health conditions.

Non-dental medical utilization. Finally, we examine the intensive margin of medical care utilization using SMCA and PS data, restricting the sample to patients under 18. We focus on (1) monthly medical costs for non-dental conditions and (2) the interval between visits to non-dental medical institutions. As shown in Panel D of Table 2, there is no evidence of a significant relationship. Notably, the magnitudes of the coefficients are also small compared with those in Table **??**, reinforcing the interpretation that fluoride concentration is not systematically associated with non-dental medical utilization.

5 Results

5.1 Dental Health

We first estimate the effect of fluoride exposure on the extensive margin of dental health by running Eq. (1). Table 3 summarizes the results for the overall sample, as well as by gender to examine heterogeneity. From column (1), we reconfirm the well-established

[24] Following Yamaguchi et al. (2018), we construct the parenting quality score based on responses to the question, "How do you respond when your child behaves badly?" The five possible responses are: "Explain why your child should not do it," "Just say 'no' without explanation," "Ignore your child," "Spank your child," and "Confine your child in a place like a closet." For each response, caregivers are asked to indicate the frequency—"Always," "Sometimes," or "Never." We then apply multiple correspondence analysis to construct the parenting quality score. See Appendix D for details.

positive relationship between fluoride and dental health: 0.1 mg/L higher average fluoride exposure during childhood decreases the probability of visiting a hospital or dental clinic due to dental cavities or caries by 2.0 percentage points (8 percent relative to the mean). The estimates in columns (2) and (3) suggest gender heterogeneity. The effect is stronger among girls: a 1.3 percentage points (4.6 percent relative to the mean) decrease for boys, which is not statistically significant, and a statistically significant 3.3 percentage points (11.7 percent relative to the mean) decrease for girls.

Columns (4) and (5) highlight heterogeneity by parental SES, measured by father's education. The protective effect of fluoride is concentrated among children whose fathers have lower educational attainment (less than or equivalent to high shool graduate): their probability of outpatient visits falls by 4.8 percentage points (17.5 percent relative to the mean). By contrast, the estimate is close to zero and statistically insignificant among children with highly educated fathers, consistent with the findings from previous literature that the fluoridation or insurance expansion in the US substantially improved the dental health of lower SES population (Glied and Neidell, 2010; Lipton et al., 2016).

Given the limitations of the LSN21 data discussed in Section 3.2—specifically, measurement error due to self-reporting and the lack of detailed information on the intensive margin—we estimate the effect of fluoride concentration in tap water on the intensive margin of children's dental health (for those under age 15) using Eq.(2) and (3), drawing on data from both SMCA and PS. Table 4 presents the results: columns (1)–(3) report the effects on logarithm of monthly dental-related medical expenditures (in JPY), while columns (4)–(6) display the effects on the time elapsed since the last dental visit.

Interestingly, even using nationally representative survey data, we continue to find that higher fluoride levels in drinking water have a beneficial effect on children's dental health, particularly among female patients. The results indicate that a 0.1 mg/L increase in municipality-level fluoride concentration is associated with a reduction of

1.95% monthly dental care expenditures, an effect that is primarily driven by the female subsample. For female children, a 0.1 mg/L increase in fluoride concentration is associated with 5.26% decrease in monthly dental spending, corresponding to a JPY 410 reduction.

Regarding the visit interval, we find that children residing in municipalities with higher fluoride levels tend to have longer intervals between dental visits. A 0.1 mg/L increase in fluoride concentration in drinking water is associated with a 2.57 day increase in the interval between dental clinic visits. This pattern suggests that children living in the regions exposed to higher fluoride in drinking water visit dental clinics less frequently. Again, the effects are more pronounced among girls: the visit interval increases by 3.54 days for girls (statistically significant at 5% level), compared to 1.24 days for boys.

The finding that the effect is larger among women is consistent with biological sex differences in salivary composition. Men typically exhibit higher salivary flow rates than women (Inoue et al., 2006) and have higher concentrations of calcium in their saliva (Sewón et al., 1998). Given that fluoride promotes remineralization by facilitating the redeposition of calcium into tooth enamel, it is plausible that individuals with lower salivary calcium levels—such as females—derive greater benefit from fluoride exposure. This biological mechanism may help explain the observed gender heterogeneity in observed effects.

In sum, the above results imply that children residing in municipalities with higher fluoride concentrations in drinking water experience better dental health outcomes, both at the extensive and intensive margins such as reduced probability of dental-related outpatient visits in the previous year, lower monthly dental expenditures, and longer intervals between dental visits. One potential concern is that these results may be driven by differences in access to medical care rather than the effects of fluoride itself. To address this, we source data on the locations of all medical institutions in Japan from each wave of Static Survey of Medical Institutions[25] and examine the correlation between fluoride concentration and the per capita density of medical institutions at the municipality level.

Table A2 column (1) suggests that the level of fluoride in drinking water is not significantly correlated with the number of medical institutions (excluding dental clinics). Column (2) indicates insignificant positive correlation between fluoride levels and the density of dental clinics. These findings do not support the hypothesis that the less frequent dental visits observed in high-fluoride areas are due to limited access to care.

5.2 Skill Formation

Educational Attainment We also examine the relationship between fluoride exposure and educational attainment. Several previous studies, primarily in the medical and public health literature, have suggested that childhood exposure to fluoride may be associated with lower IQ scores (Xiang et al., 2003; Green et al., 2019). However, more recent research—such as Aggeborn and Öhman (2021)—has cast doubt on this association, finding a precisely estimated null effect of fluoride exposure on the cognitive ability of men in Sweden.

Table 5 shows that fluoride exposure has small and statistically insignificant effects on both high school quality and college attendance for men and women. These results suggest that childhood fluoride exposure does not adversely affect cognitive ability, as proxied by educational attainment, in a nationally representative sample of Japanese adolescents.[26][27] This finding further supports the null effects reported by Aggeborn and Öhman (2021).

[25] Static Survey of Medical Institution is conducted by MHLW once every three years.

[26] Although high school quality scores are only observed for those who attend high school, the high school enrollment rate among the surveyed population exceeded 95% as of 2016 (MEXT 2021).

[27] The null effects are not driven by proximity to universities. In a specification where we regress college attendance on both the municipality-level number of university campuses and the average fluoride concentration between 2003–2012 (0.1mg/L unit), the coefficient on fluoride is 0.138 (s.e. = 0.170), which remains statistically insignificant.

Self-Esteem We then estimate the effect of fluoride exposure during childhood on non-cognitive outcomes. Table 6 summarizes the effects of fluoride exposure on standardized measures of the Rosenberg self-esteem score Interestingly, while we find no statistically significant effects in the full sample, the coefficients are positive and statistically significant in the female subsample. Specifically, a 0.1 mg/L increase in average fluoride exposure during childhood (ages 2–12) increases the self-esteem score in the adolescent period (during 16-21 years old) This finding suggests that improvements in dental health induced by fluoride exposure in drinking water contribute to the development of self-esteem among girls.

These results are highly consistent with previous evidence, such as Gallego et al. (2024), who, through a randomized experiment, show that providing low-income group of people with free access to dental care significantly improves women's self-esteem, perceived appearance, short-term earnings—while finding no such effects for men.

In Appendix B, we examine additional non-cognitive traits: perseverance (GRIT) and the Big Five personality dimensions. Table A4 and Table A5 show that a 0.1 mg/L increase in childhood fluoride exposure improves perseverance by 5.1% of a standard deviation and openness by 4.8% of a standard deviation among females. Consistent with our main results, no corresponding effects are detected for males.

5.3 Appearance as a Mechanism

In the preceding discussion, we argue that childhood exposure to fluoride in drinking water has beneficial effects on dental health and positively influences certain aspects of non-cognitive skill development among females, without detrimental effects on cognitive skills measured by educational attainment. To explore the underlying mechanisms, we examine some of LSN21's survey responses collected during the puberty years (ages 13–15), which serve as a bridge between childhood and adolescence.

First, we examine how fluoride exposure affects self-confidence in one's appearance, using responses to the survey question: "Do you have concerns or worries about your own appearance?" Columns (1)–(3) of Table 7 show that fluoride exposure significantly reduces the likelihood of such concerns—but only among girls. An increase of 0.1 mg/L in fluoride concentration in drinking water reduces the probability of reporting appearance-related concerns by 1.9 percentage points, which corresponds to a 15% reduction relative to the overall mean.

While LSN21 does not provide detailed information on the underlying factors that cause adolescents to worry about their appearance, previous research such as Arduini et al. (2019) highlights the role of body weight, especially relative obesity among peers, as a significant determinant of body image concerns among females. However, in our data, we do not find any meaningful relationship between fluoride exposure and Body Mass Index (BMI) during ages 13-15 (see Appendix C), which suggests the BMI is not a driving factor of worry about appearance. In addition, prior work has shown that visible skin conditions—such as Atopic dermatitis—can negatively impact life satisfaction among females by shaping their self-perceptions of appearance (Holm et al., 2004). Yet, we also find no significant correlation between fluoride exposure and an indicator of outpatient visit due to Atopic dermatitis in the previous year at age 12, further suggesting that skin condition is not a likely mediator of the observed effects either.

Motivated by an intriguing finding of Gallego et al. (2024) —access to free dental care improves the quality of romantic partnerships among women —we also examine whether fluoride exposure affects adolescents' concerns about romantic relationships. As shown in Table A3 and Figure A2, fluoride exposure significantly reduces such concerns—but only among females—mirroring the gender-specific patterns observed in appearance-related anxiety. These results suggest that improvements in dental health and physical appearance due to fluoride exposure may facilitate interpersonal romantic relationships during adolescence, particularly for girls.

5.4 Age-specific Effect

The results suggest that childhood exposure to fluoride in drinking water positively affects dental health and non-cognitive skills of women on average. In this section, we exploit the panel structure of LSN21, which allows us to identify the level of fluoride exposure at each age, to investigate the critical developmental periods during which fluoride exposure has the most significant impact among women.

First, we estimate the following specification for the extensive margin of the dental health proxy:

$$\text{Outpatient(Dental)}_{i,12} = \beta_a Fluoride_{m(i,a)} + \gamma X_m + \delta_p + \delta_t + \varepsilon_{it} \quad \text{for } a = 2, 3, \ldots, 11, \tag{5}$$

where $Fluoride_{m(i,a)}$ represents the level of fluoride exposure in the municipality where child i resided at age a. While Eq. (1) captures the effect of average fluoride exposure during childhood (as defined in the previous subsection) on a single episode of an outpatient visit at age 12, Eq. (5), estimates the age-specific effect of fluoride exposure—i.e., how fluoride exposure at each age a affects the likelihood of any outpatient dental visit at age 12.

In the same way, we consider the age-specific specification for non-cognitive skills of women to identify the critical timing of the exposure:

$$Y_{it} = \beta_a Fluoride_{m(i,a)} + \gamma X_m + \delta_p + \delta_t + \varepsilon_{it} \text{ for } a = 2, 3, \cdots, 11. \tag{6}$$

Here, the parameter of our interest is again β_a: the effect of the level of exposure to fluoride in municipality m where the child i lived at age a on non-cognitive skill Y.

Figure 3 represents the point estimates ($\beta_a, \;\; a = 2, \cdots, 11$) and their 95% confidence intervals for Eq. (5). We find that the estimates are consistently negative across all ages, with the magnitude being particularly large and statistically significant between ages 6 and 9. This finding is consistent with the fact that this age range is generally considered critical for dental development as it coincides with the eruption and growth of permanent teeth (American Dental Association, 2006).

We also examine the critical age window for this effect on non-cognitive attributes by estimating Equation (6). Figure 4 shows that, for females, fluoride exposure between ages 5 and 7 has the strongest impact on self-esteem scores during adolescence. In particular, an additional 0.1 mg/L of fluoride in drinking water at age 6 is associated with a 0.058 standard deviation increase in self-esteem.

The effects of age-specific fluoride exposure on appearance-related concerns are illustrated in Figures 5. Overall, the point estimates for concern about appearance for the female subsample are consistently negative and the U-shaped relationship with a dip at age 6-8 emerges again.

5.5 Additional Analyses

Extended Exogeneity Check of Childhood Fluoride Exposure In Section 4.3, we showed that fluoride exposure is conditionally exogenous by finding no meaningful correlation with children's health at birth, maternal socioeconomic characteristics, or non-dental health outcomes. To further reinforce this evidence, we examine a broader set of survey questions on parenting practices and children's socioemotional development at earlier ages. These checks help confirm that fluoride exposure is not systematically related to unobserved aspects of family environment or children's own endowment of socio-emotional skills that could bias our estimates. Consistent with our baseline results, we find no meaningful correlation between fluoride exposure and these additional characteristics. Details on the results and construction of these measures are provided in Appendix E.

Attrition and Migration The response rates in LSN21 are high, at around 90% in each survey wave,[28] which exceeds those of comparable longitudinal surveys conducted in other countries, such as the National Longitudinal Survey of Children and Youth (NLSCY) in Canada (Yamaguchi et al., 2018). Nevertheless, because sample replenishment is not implemented, cumulative attrition over time may raise concerns if attrition is, by chance, systematically related to childhood fluoride concentration. However, the results presented in Appendix F confirm that this is not the case.

Another potential concern is that migration may be endogenous with respect to regional fluoride exposure. For instance, if parents with stronger preferences for child dental health systematically relocate to municipalities with lower (or higher) fluoride levels, this could bias the estimated effects.[29] Again, we examine this possiblity in Appendix F and find no meaningful relationsip beween fluoride exposure and migration patter.

5.6 Robustness Checks

This section provides a brief summary of several robustness checks. First, we examine the potential influence of other substances in drinking water aside from fluoride. As noted in Section 2.2, variation in fluoride concentrations across municipalities in Japan is largely driven by local geological characteristics—such as the presence of granitic bedrock—rather than by human intervention or artificial fluoridation. A potential concern, however, is that these geological conditions may also be correlated with the presence of other elements or contaminants—such as arsenic, lead, or nitrates—which could bias our estimates if they systematically coexist with fluoride. Using the same DWQA water quality data that underlies our fluoride exposure measure, we examine (1) whether

[28] https://www.soumu.go.jp/main_content/000516312.pdf (in Japanese; Accessed on July 31, 2025).

[29] If parents prioritize the benefits of fluoride on dental health, they might migrate to high-fluoride areas. Conversely, if they are more concerned about potential adverse effects on cognition, they may avoid such areas.

fluoride concentrations are correlated with other drinking water characteristics—such as arsenic, lead, cadmium, and nitrates—and (2) whether our baseline regression estimates remain robust when these contaminants are included as controls. The results, reported in Appendix G.1, show that correlations between fluoride and these other substances are mostly negligible (slightly high positive correlation only with sodium), and that controlling for them leaves our main estimates qualitatively unchanged.

Second, we also estimate the baseline equations for the analysis based on LSN21 (i.e., outpatient visit due to dental cavity, educational attainment, and non-cognitive skills) under a range of alternative specifications in Appendix G.2. We confirm that the estimates are insensitive to changes in control variables and fixed effects. Specifically, we add individual-level covariates and vary the timing and geographic level of fixed effects —using province fixed effects at age 2 instead of age 12, including both, and replacing them with municipality fixed effects.

Third, Appendix Table A12 and A13 demonstrate that our results are robust to alternative clustering choices. In the baseline specification, we cluster standard errors at the province level, since some water supply systems are operated by inter-municipal associations within the same province. The qualitative results remain largely unchanged when clustering at the municipality level instead. In addition, we obtain similar results when clustering at the level of IWSAs.[30] For outcomes available in LSN21 (longitudinal survey), we also examine clusters at the individual-level. Furthermore, accounting for spatial correlation in the standard errors following Conley (1999) does not materially inflate the estimates of uncertainty (see the last three rows, which vary the cutoff distance at 10, 30, and 50 km). [31][32] See Appendix G.3 for detail.

[30] For example, if municipalities A and B are served by the same IWSA, they are clustered as a single unit. For systems operated by a single municipality, the clustering unit coincides with that municipality.

[31] Municipality-level latitude and longitude are measured at the location of the municipal office.

[32] We implement this correction using the user-written Stata command `ols_spatial_HAC` (Hsiang, 2010).

6 Discussion and Conclusion

In this paper, we examine the effects of childhood exposure to fluoride in drinking water on dental health and skill formation—both cognitive and non-cognitive—at dosage levels lower than those typically studied in the context of community water fluoridation policies in the United States (Glied and Neidell, 2010; Roberts, 2024). Our empirical findings provide robust evidence that fluoride concentration in drinking water significantly improves dental health outcomes at both the extensive and intensive margins, even in a setting like Japan: a setting where dental health infrastructure, access, and preventive care are among the most advanced globally.

Moreover, contrary to concerns raised in previous studies (e.g., Grandjean, 2019; Roberts, 2024), we find no evidence of adverse effects on cognitive skills, as proxied by educational attainment. This result is consistent with the findings of Aggeborn and Öhman (2021), who exploit similar geographic variation in fluoride concentrations in Sweden and report precisely estimated null effects on cognitive ability as measured by the Armed Forces Qualification Test. Given that fluoride levels in Sweden are also lower than those typically added in the United States, our findings further support the view that fluoride exposure at low concentrations does not pose cognitive risks.

In addition to the absence of adverse cognitive effects, our study documents an additional benefit of fluoride exposure: improvements in self-esteem among females through enhanced confidence in physical appearance.

Taken together with recent evidence, these findings imply that policy debates on community water fluoridation should move beyond the binary issue of whether to fluoridate, and instead focus on the determination of an appropriate dosage. Our setting, where naturally occurring fluoride concentrations reach up to approximately 0.4 mg/L, provides evidence of a lower bound: levels sufficient to improve dental health and promote the development of self-esteem particularly female population *without* detectable harm to cognitive outcomes. Thus, future policy discussions should weigh not only the potential cognitive risks associated with higher exposure but also the potential gains in socio-emotional development that may arise from improvements in oral health and appearance.

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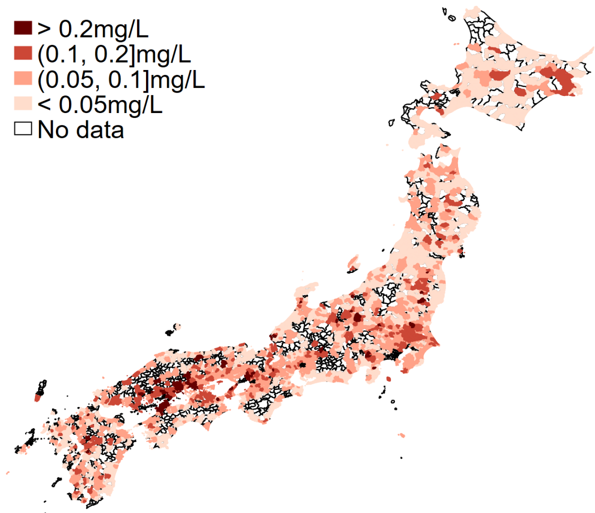
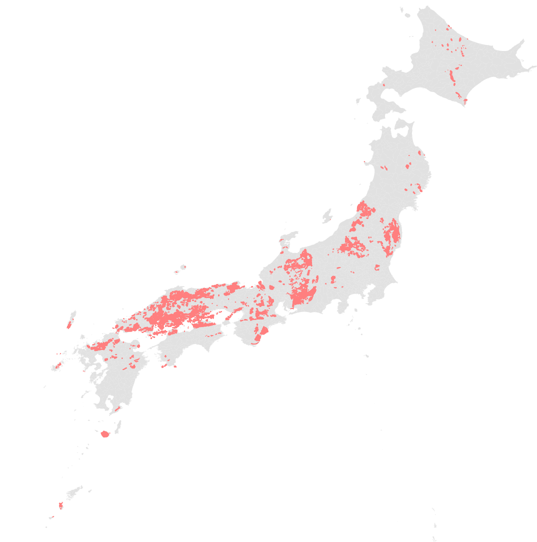
Figures and Tables

Figure 1: Distribution of Fluoride Concentration in Drinking Water

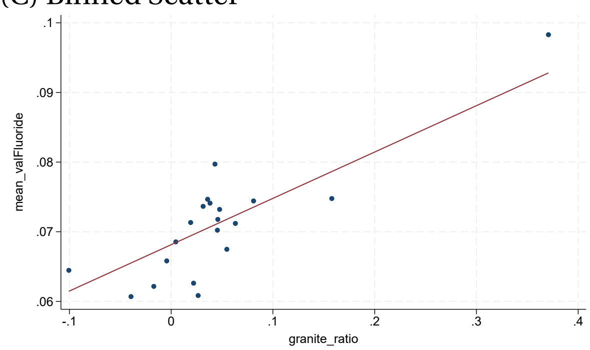
(A) Average Fluoride Concentration by Municipality



(B) Granitic Rock

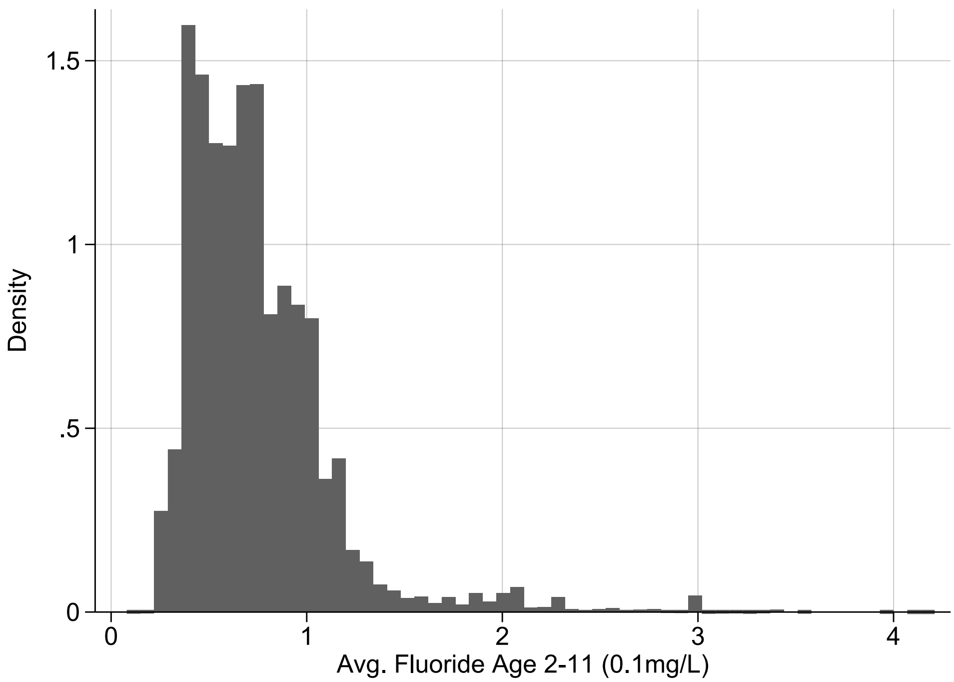


(C) Binned Scatter



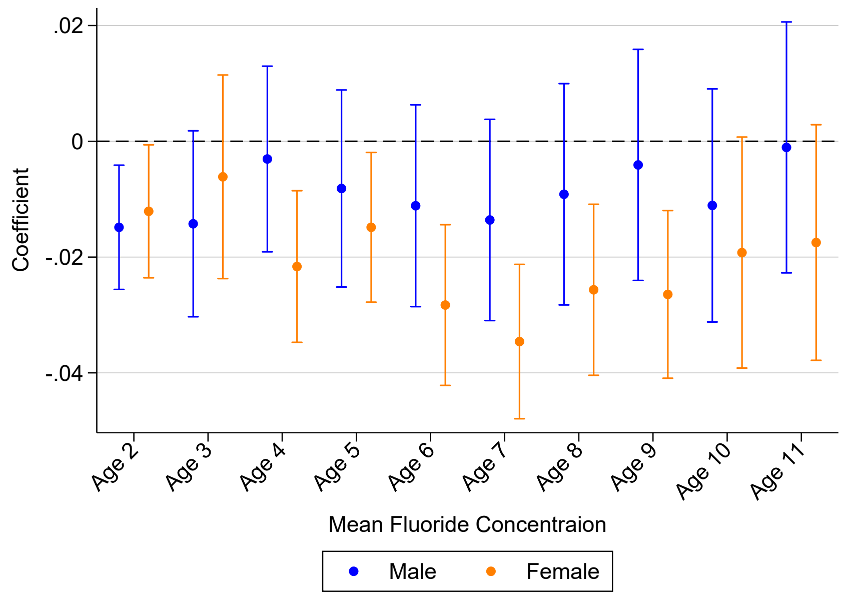
Notes: Panel A shows the municipality-level average fluoride concentration in tap water as of March 2003, calculated by aggregating plant-level data using the volume of purified water as weights. The raw data are sourced from the Database of Water Quality of Aqueduct (DWQA). Panel B displays the distribution of granitic bedrock, based on the 1:200,000 Seamless Digital Geological Map of Japan. Panel C presents a binned scatter plot of the relationship between fluoride concentration and granitic bedrock share, controlling for prefecture fixed effects and the presence of other types of volcanic bedrock.

Figure 2: Distribution of Average Fluoride Exposure During Age 2-11 (LSN21)



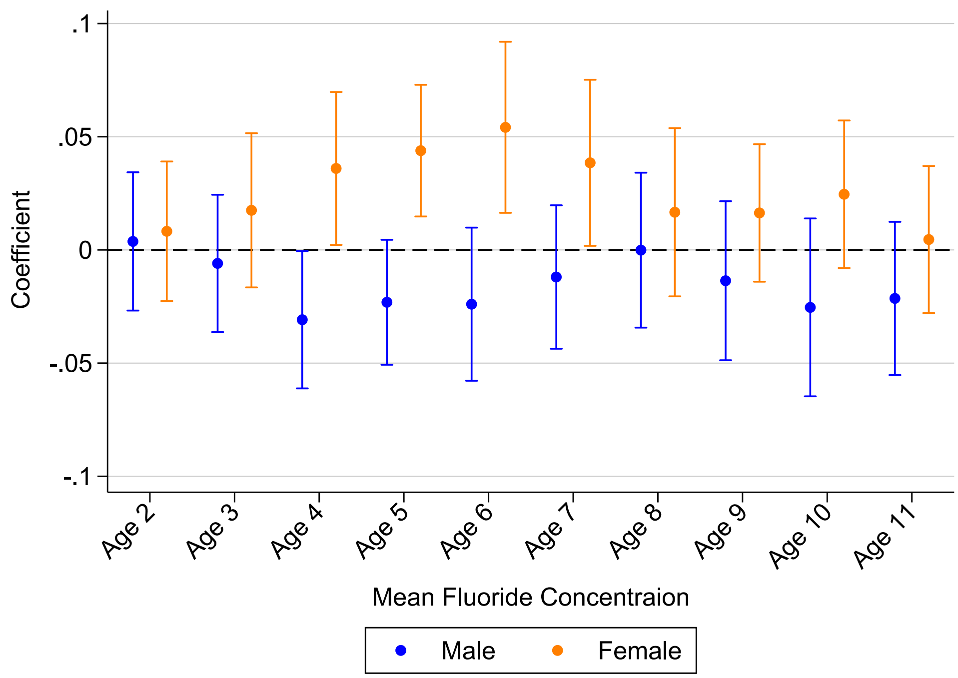
Notes: This figure displays the average fluoride concentration in tap water between ages 2 and 11 for individuals in our main sample from LSN21. The exposure is calculated as the mean of annual municipality-level fluoride concentration during this age range.

Figure 3: Age-specific Exposure and the Outpatient Visit Due to Dental Cavity



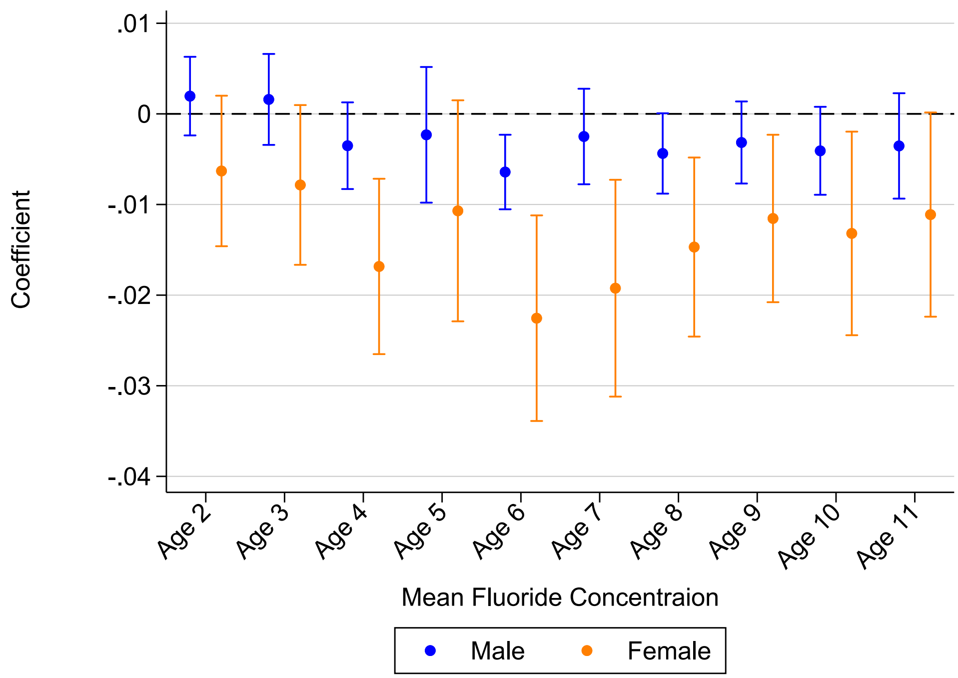
Notes: This figure reports the point estimates and 95% confidence intervals of β_a $(a = 2, \cdots, 11)$ from regressions based on Eq. (5). Standard errors are clustered at the province level, based on the location where the surveyed children resided at age 12. All models control for municipality-level characteristics as of 2005 and include province fixed effects. The outcome variable is Outpatient(Dental)$_{i,12}$, which represents a binary indicator for whether the child had a dental cavity requiring a visit to a hospital or clinic for medical care at any time in the previous year at age 12, as reported in the LSN21 surveys.

Figure 4: Age-specific Exposure and the Effects on Self-Esteem



Notes: This figure reports the point estimates and 95% confidence intervals of β_a $(a = 2, \cdots, 11)$ from regressions based on Eq. (6). Standard errors are clustered at the province level, based on the location where the surveyed children resided at age 12. All models control for municipality-level characteristics as of 2005 and include province fixed effects.

Figure 5: Age-specific Exposure and the Effect on Appearance-related Concern



Notes: This figure shows point estimates and 95% confidence intervals of β_a ($a = 2, \ldots, 11$) from regressions based on Eq. (6), where the outcome is self-reported concern about appearance during ages 13–15. Standard errors are clustered at the province level based on the residence at age 12. All regressions include municipality-level covariates (as of 2005) and province fixed effects.

Table 1: Summary Statistics

	All				Male				Female			
	Mean	SD	Total Obs	#Ind	Mean	SD	Total Obs	#Ind	Mean	SD	Total Obs	#Ind
Data: LSN21												
Avg. Fluoride Exposure Age 2–11 (0.1mg/L)	0.748	0.378	345618	38402	0.744	0.371	179658	19962	0.751	0.385	165960	18440
Outpatient (Dental, Age 12)	0.248	0.432	31425	31425	0.257	0.437	16261	16261	0.238	0.426	15164	15164
Rosenberg Self-Esteem	0.000	1.000	143708	29430	0.110	0.971	71408	14830	-0.114	1.016	70179	14072
HS Deviation Score	53.848	9.214	23396	23396	53.805	9.538	11693	11693	53.878	8.842	11356	11356
College Attendance	0.602	0.489	24341	24341	0.578	0.494	12048	12048	0.628	0.483	11924	11924
Birth Weight (g)	3036.5	429.3	357030	39670	3074.4	436.9	185679	20631	2995.5	417.0	171351	19039
Gestation Length (Weeks)	38.892	1.611	356931	39659	38.805	1.635	185652	20628	38.987	1.581	171279	19031
Mother's Age at Birth	29.346	4.379	357120	39680	29.332	4.375	185751	20639	29.361	4.384	171369	19041
Mother's Education > HS	0.567	0.496	348579	38731	0.570	0.495	181161	20129	0.563	0.496	167418	18602

Note: This table reports means and standard deviations (SD), total number of observations (Total Obs), and number of unique individuals (# Ind) for each variable, by gender.

Table 2: Balance Tests (Exogeneity of the Fluoride Concentration in Drinking Water)

Panel A: Birth Outcomes Data: LSN21 (1st)	(1) Birthweight (in g)	(2) Log Birthweight	(3) Low Birthweight (< 2500g)	(4) Gestation (in weeks)	(5) Preterm (< 37 weeks)		
$\overline{Fluoride}_i$ (0.1mg/L)	-9.469 (7.136)	-0.00268 (0.00267)	-0.00125 (0.00450)	0.0243 (0.0238)	-0.00156 (0.00345)		
Mean Dep. Var. Observations	3037.4 28938	8.008 28938	0.0826 28938	38.90 28931	0.0485 28931		
Panel B: Socioeconomic Characteristics Data: LSN21 (1st and 2nd)	(1) Mother Working at Birth	(2) Mother's Age at Birth	(3) Father's Age at Birth	(4) # of Older Sibs. Older Sibs.	(5) Mother Educ. (> HS grad)	(6) Father Educ. (> HS grad)	(7) Parenting Score
$\overline{Fluoride}_i$ (0.1mg/L)	-0.00331 (0.0101)	0.153 (0.105)	0.101 (0.0931)	-0.00150 (0.0145)	0.0151 (0.00977)	0.0172 (0.0110)	0.0162 (0.0193)
Mean Dep. Var. Observations	0.546 29609	29.55 29839	31.66 29585	0.673 29839	0.590 28382	0.592 29153	0.00998 29485
Panel C: Outpatient Visit in the Previous Year Due to Other Diseases at 12th Round of LSN21 Data: LSN21 (12th)	(1) Asthma	(2) Allergy	(3) Injury	(4) Flu	(5) Cold		
$\overline{Fluoride}_i$ (0.1mg/L)	-0.000650 (0.00337)	0.00833 (0.00696)	0.00867 (0.00614)	0.000618 (0.00623)	0.0120 (0.00777)		
Mean Dep. Var. Observations	0.0429 28943	0.223 28943	0.137 28943	0.155 28943	0.430 28943		
Panel D: Outpatient Visit (Intensive Margin) Due to Other Diseases Data: SMCA, PS	(1) Log of Monthly Spending in JPY (Non Dental-Related)	(2) Visit Interval (Excl. Dental Clinics)					
$Fluoride_{mt}$ (0.1mg/L)	0.00506 (0.00683)	0.375 (0.367)					
Mean Dep. Var. Observations	8063 248073	23.40 148382					

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All regression analyses are based on data from LSN21. Standard errors are clustered at the province level, based on where the surveyed children lived at age 12. In Panel A, birth health outcomes are reported in the first wave of the survey. In Panel B, the mother's working status, the mother's age at birth, and the number of older siblings (columns (1)–(3)) are drawn from the first wave. Maternal educational attainment (column (4)) is reported in the second wave. Column (5), the parenting score, is based on a survey question in the fourth wave asking "How do you respond when your child behaves badly?", where we apply multiple correspondence analysis; see Appendix D for details on its construction. In Panel C, the outcome variables are replaced with indicators of outpatient visits due to non-dental cavities, as defined in Equation (1). All regressions in Panels A–C control for municipality-level characteristics as of 2005 and include province fixed effects. $\overline{Fluoride}_i$ represents the child's average fluoride exposure through tap water between ages 2 and 11.

Table 3: Effect of Average Childhood Fluoride Exposure on Outpatient Dental Visits

	(1) All	(2) Male	(3) Female	(4) Low Father's Education	(5) High Father's Education
Dep. Var.	Outpatient(Dental)$_{i,12}$				
$\overline{Fluoride_i}$ (0.1mg/L)	-0.0234***	-0.0133	-0.0331***	-0.0476***	-0.00462
	(0.00697)	(0.0101)	(0.00893)	(0.0105)	(0.00865)
Data	LSN21 (12th)				
Mean. Dep. Var	0.249	0.258	0.240	0.272	0.231
Observations	29,839	15,426	14,413	13,020	16,103

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. We control for municipality-level characteristics as of 2005 and province fixed effects. Outpatient(Dental)$_{i,12}$ represents a binary indicator for whether the child had dental cavities that required a hospital or clinic visit in the past year, as reported in the LSN21's 12th round. $\overline{Fluoride_i}$ denotes average fluoride exposure in tap water during ages 2–11. Standard errors are clustered at the province where the child lived at age 12.

Table 4: Effect of Fluoride Exposure on Dental Costs and Visit Interval

	(1) All	(2) Male	(3) Female	(4) All	(5) Male	(6) Female
Dep. Var.	Log Monthly Spending (JPY) (Dental-Related)			Visit Interval (Days) (Dental Clinics)		
$Fluoride_{my}$ (0.1mg/L)	-0.0195	0.00300	-0.0579**	2.569*	1.186	3.008**
	(0.0171)	(0.0185)	(0.0251)	(1.284)	(1.289)	(1.392)
Data	SMCA (Claims)			Patient Survey (PS)		
Mean Dep. Var.	7770	7761	7779	18.25	18.12	18.38
Observations	13,075	6,601	6,474	6,296	3,113	3,183

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Columns (1)–(3): Outcome is log monthly spending on dental care (SMCA). Controls include municipality-level characteristics, patient characteristics (age, insurance type, first vs. follow-up consultation), and province fixed effects. Standard errors are clustered at the province level. Sample: individuals under 18. Columns (4)–(6): Outcome is the visit interval (days) since previous dental visit (PS). Controls include municipality-level characteristics, patient age, insurance type, and province fixed effects. Standard errors clustered at the province level. Sample: individuals under 18.

Table 5: Effects of Average Childhood Fluoride Exposure on Academic Achievement During Adolescence

	(1)All	(2)Male	(3)Female	(4)All	(5)Male	(6)Female
Dep. Var.	High School Quality Score			Attending College		
$\overline{Fluoride_i}$ (0.1mg/L)	0.0415	0.136	-0.0201	0.0197	0.0236	0.0157
	(0.354)	(0.424)	(0.371)	(0.0118)	(0.0218)	(0.0122)
Data	LSN21 (16th)			LSN21 (19th)		
Mean. Dep. Var.	53.89	53.86	53.92	0.602	0.576	0.630
Observations	21451	10853	10598	22298	11167	11131

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors are clustered at the province where the surveyed children lived when they were 12 years old. In all models, we control for municipality-level characteristics as of 2005 and the province fixed effect. $\overline{Fluoride_i}$ denotes the average exposure to fluoride in the tap water of child i during childhood (between ages 2 and 11).

Table 6: Effects of Average Childhood Fluoride Exposure on Self-Esteem During Adolescence

	(1) All	(2) Male	(3) Female
Dep. Var.	Self-Esteem (standardized)		
$\overline{Fluoride_i}$ (0.1mg/L)	0.0125	-0.0190	0.0457**
	(0.0158)	(0.0207)	(0.0202)
Data	LSN21 (16th-21st)		
Observations	131826	66297	65529

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors are clustered at the province where the surveyed children lived when they were 12 years old. In all models, we control for municipality-level characteristics as of 2005, the province fixed effect, and the survey-round fixed effect. $\overline{Fluoride_i}$ denotes the average exposure to fluoride in the tap water of child i during childhood (between ages 2 and 11) based on the municipality where the child lived at each age.

Table 7: Effect of Average Childhood Fluoride Exposure on Appearance-Related Concern During Puberty

	(1) All	(2) Male	(3) Female
Dep. Var.	Appearance-Related Concern		
$\overline{Fluoride_i}$ (0.1mg/L)	-0.0108***	-0.00381	-0.0193***
	(0.00349)	(0.00315)	(0.00582)
Data	LSN21 (13-15th)		
Mean. Dep. Var.	0.0845	0.0392	0.132
Observations	76848	39423	37425

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors are clustered at the province where the surveyed children lived at age 12. All models control for municipality-level characteristics (as of 2005) and province fixed effects. The outcome is based on the LSN21 survey question asked between rounds 13 and 15: "Do you have concerns about your appearance?". $\overline{Fluoride_i}$ indicates average childhood fluoride exposure (ages 2–11).

Online Appendix

A Supplemental Exhibits

Figure A1: Histograms of High School Quality Deviation Score

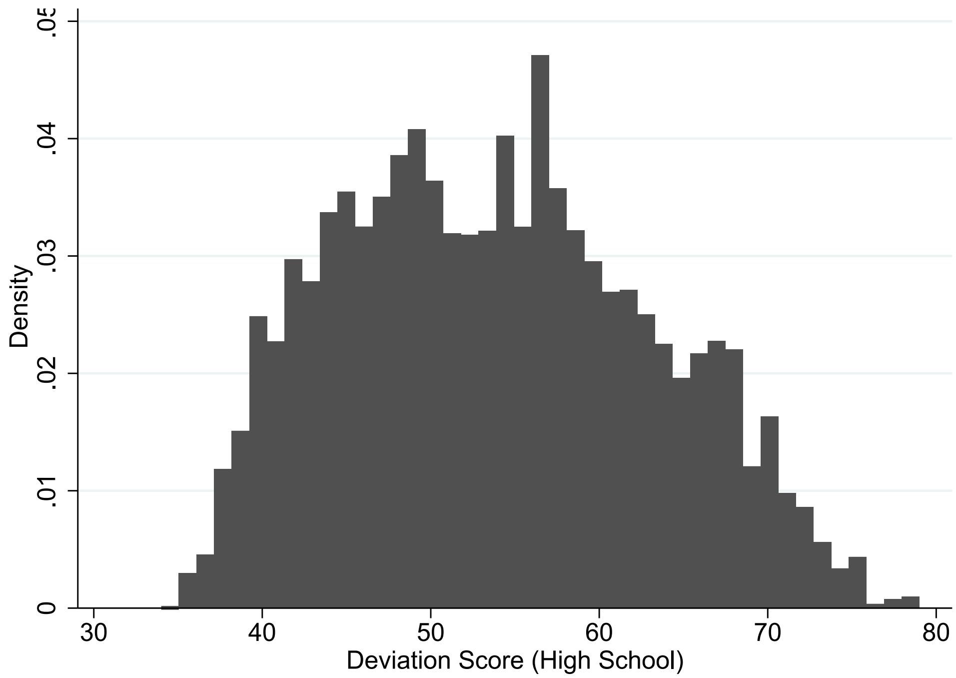
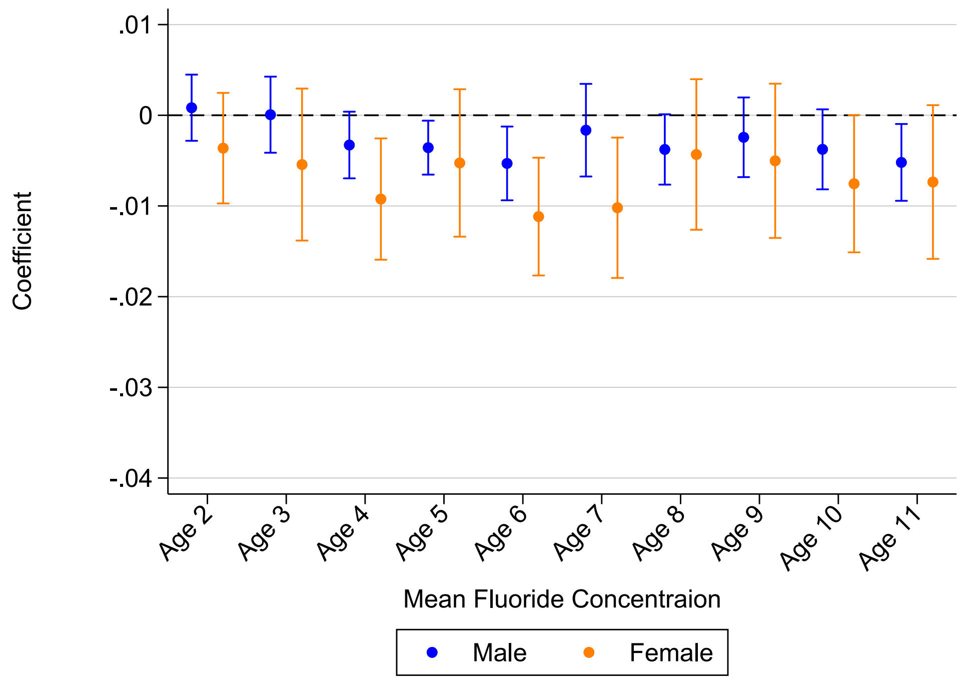


Figure A2: Age-specific Exposure and the Effect on Concerns Related to Romantic Relationship



Notes: This figure shows point estimates and 95% confidence intervals of β_a $(a = 2, \ldots, 11)$ from regressions based on Eq. (6), where the outcome is self-reported concern about romantic relationship with heterosexual ones during ages 13–15. Standard errors are clustered at the province level based on the residence at age 12. All regressions include municipality-level covariates (as of 2005) and province fixed effects.

Table A1: Rock Type and Fluoride Concentration

	(1)	(2)
Dep. Var.	$Fluoride_{mt}$	$Fluoride_{mt}$
Granite	0.0681***	0.0668***
	(0.0209)	(0.0208)
Andesite		-0.00568
		(0.00815)
Rhyolite		0.00317
		(0.0107)
Gabrro		-0.117
		(0.115)
Granodiorite		0.00790
		(0.0142)
Bassalt		0.0420
		(0.0807)
Constant	0.0680***	0.0681***
	(0.00144)	(0.00196)
Data	Geological Map	
Mean Dep. Var	0.0711	0.0711
Observations	1290	1290

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors are clustered at the municipality level. Fluoride data are merged with the geological map. We use municipal boundaries as of January 1, 2005, and fluoride data from 2005. All regressions include province fixed effects.

Table A2: Municipality-level Fluoride Concentration and Density of Medical Institutions (Non-Dentists and Dentists)

	(1)	(2)
Dep. Var.	Medical Inst. (Excl. Dental Clinics) Per 1000	Dental Clinics Per 1000
$Fluoride_{my}$	0.00914	0.0112
	(0.0245)	(0.00950)
Data	Static Survey of Medical Institutions	
Mean Dep. Var.	0.745	0.244
Observations	3909	3704

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors are clustered at the province level. Data come from the Static Survey of Medical Institutions, conducted by the Ministry of Health, Labour and Welfare once every three years. We link data from 2005, 2008, and 2011 with municipality-level aggregated fluoride concentrations.

Table A3: Effect of Average Childhood Fluoride Exposure on Concerns Related to Romantic Relationship

	(1) All	(2) Male	(3) Female
Dep. Var.	Concern Related to Romantic Relationship		
$\overline{Fluoride_i}$ (0.1mg/L)	-0.00713***	-0.00360	-0.0116***
	(0.00289)	(0.00241)	(0.00530)
Data	LSN21 (13-15th)		
Mean. Dep. Var.	0.0487	0.0286	0.0697
Observations	76848	39423	37425

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors are clustered at the province where the surveyed children lived at age 12. All models control for municipality-level characteristics (as of 2005) and province fixed effects. The outcome is based on the LSN21 survey question asked between rounds 13 and 15: "Do you have concerns about your romantic relationship?". $\overline{Fluoride_i}$ indicates average childhood fluoride exposure (ages 2–11).

B Other Non-Cognitive Skill Measures than Self-Esteem

In addition to self-esteem, LSN21 includes several other measures of non-cognitive skills:

- **Perseverance (GRIT)** GRIT, reflecting perseverance and passion for long-term goals, is commonly assessed using the Grit Scale developed by psychologist Angela Duckworth (Duckworth et al., 2007). LSN21 adopts the short version of the original scale, which includes eight items measuring perseverance of effort and consistency of interests. Respondents rate their agreement on a seven-point Likert scale. Higher scores indicate greater levels of GRIT, suggesting a stronger capacity to sustain effort and interest in goals over time. The GRIT questionnaire is included in the 19th wave of the survey.

- **Personality Traits** LSN21 assesses personality using the Ten-Item Personality Inventory (TIPI) developed by Gosling et al. (2003), which captures the Big Five personality traits:

  1. Openness to Experience (e.g., imagination, curiosity, and broad interests)
  2. Conscientiousness (e.g., organization, dependability, and self-discipline)
  3. Extraversion (e.g., sociability, assertiveness, and high energy)
  4. Agreeableness (e.g., compassion, altruism, and cooperativeness)
  5. Emotional Stability (inverse of neuroticism; resilience to anxiety and emotional volatility)

  The TIPI consists of 10 items—two per trait—comprising one positively keyed and one negatively keyed statement. For example, Openness is measured using items such as "I see myself as open to new experiences, complex" and "I see myself as conventional, uncreative." Respondents rate each item on a seven-point Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree). LSN21 uses the Japanese version of the TIPI (Mimura and Griffiths, 2007), administered to children aged 16 to 21.

Tables A4 and A5 present the estimated average effects of childhood fluoride exposure on non-cognitive traits measured during adolescence. Consistent with the findings for self-esteem reported in the main paper, we observe a statistically significant positive effect on perseverance among females, but not among males. Specifically, a 0.1 mg/L increase in average fluoride concentration during childhood is associated with a 5.1% of a standard deviation (SD) increase in GRIT scores for girls.

Turning to personality traits measured using the TIPI, Table A5 shows a similar pattern of gender-specific effects. Among females, the same increase in fluoride exposure leads to a 4.8% SD increase in Openness and a 4.1% SD increase in Conscientiousness—traits that are strongly linked to creativity, academic motivation, and long-term planning. In contrast, no statistically significant effects are found for males across any of the five Big Five personality dimensions.

Table A4: Effects of Average Childhood Fluoride Exposure on Perseverance at Age 19

	(1) All	(2) Male	(3) Female
Dep. Var.	Perseverance (GRIT) (standardized)		
$\overline{Fluoride_i}$ (0.1mg/L)	0.0221	-0.0119	0.0506**
	(0.0167)	(0.0302)	(0.0211)
Data	LSN21 (19th)		
Mean. Dep. Var.	0.00267	-0.0133	0.0186
Observations	21448	10695	10753

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors are clustered at the province where the surveyed children lived when they were 12 years old. In all models, we control for municipality-level characteristics as of 2005, the province fixed effect, and the survey-round fixed effect. $\overline{Fluoride_i}$ denotes the average exposure to fluoride in the tap water of child i during childhood (between ages 2 and 11) based on the municipality where the child lived at each age.

Table A5: Effects of Average Childhood Fluoride Exposure on Non-Cognitive Skills (Big-Five Personality) During Adolescence

	(1) All	(2) Male	(3) Female	(4) All	(5) Male	(6) Female	(7) All	(8) Male	(9) Female
Dep. Var.	Openness			Conscientiousness			Extraversion		
$\overline{Fluoride_i}$	0.0221	-0.00327	0.0475***	0.0205	-0.00101	0.0406*	0.00122	-0.00290	0.00204
	(0.0141)	(0.0176)	(0.0177)	(0.0163)	(0.0247)	(0.0205)	(0.0128)	(0.0227)	(0.0235)
Data	LSN21 (16-19th)			LSN21 (16-19th)			LSN21 (16-19th)		
Observations	88251	44546	43705	88114	44477	43637	88285	44575	43710
	(10) All	(11) Male	(12) Female	(13) All	(14) Male	(15) Female			
Dep. Var.	Agreeableness			Emotional Stability					
$\overline{Fluoride_i}$	0.00209	-0.00716	0.00990	-0.000543	-0.0253	0.0282			
	(0.0179)	(0.0218)	(0.0278)	(0.0142)	(0.0216)	(0.0181)			
Data	LSN21 (16-19th)			LSN21 (16-19th)					
Observations	88295	44573	43722	88176	44519	43657			

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors are clustered at the province where the surveyed children lived when they were 12 years old. In all models, we control for municipality-level characteristics as of 2005 and the province fixed effect. $\overline{Fluoride_i}$ denotes the average exposure to fluoride in the tap water of child i during childhood (between ages 2 and 11).

C Fluoride Exposure and Appearance-Related Outcome Other than Dental Health

LSN21 collects information on height and weight up to the 15th round. Using these components, we construct BMI and re-estimate Equation 4, replacing the outcome variable with BMI observed between the 13th and 15th surveys. The results, presented in Table A6, indicate that fluoride exposure has a statistically significant but quantitatively small effect (approximately 0.5% relative to the sample mean) for males. Importantly, for females, the estimated coefficient is smaller in magnitude and statistically insignificant. These findings suggest that the fluoride-induced reduction in appearance-related concerns among females, discussed in Section 5.3, is unlikely to be driven by differences in body image.

Table A6: Childhood Fluoride Concentration and Appearance-Related Outcomes Other Than Dental Health

	(1) All	(2) Male	(3) Female	(4) All	(5) Male	(6) Female
Dep. Var.	BMI (13-15th survey)			Outpatient Visit Atopic dermatitis (12th survey)		
$\overline{Fluoride}_i$ (0.1 mg/L)	0.0907*	0.111	0.0657	-0.00445	-0.00651	-0.00225
	(0.0475)	(0.0761)	(0.0600)	(0.00329)	(0.00459)	(0.00406)
Data	LSN21 (13-15th)			LSN21 (12th)		
Mean .Dep. Var.	18.56	18.54	18.58	0.0533	0.0541	0.0524
N	69156	35613	33543	29839	15426	14413

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors are clustered at the province where the surveyed children lived when they were 12 years old. In all models, we control for municipality-level characteristics as of 2005, the province fixed effect, and the survey-round fixed effect. $\overline{Fluoride}_i$ denotes the average exposure to fluoride in the tap water of child i during childhood (between ages 2 and 11) based on the municipality where the child lived at each age.

D Construction of Parenting Quality Index

In the 4th round of the LSN21 survey (conducted when the child was approximately 3.5 years old), parents were asked the question: "How do you respond when your child behaves badly?" Five possible disciplinary responses were provided: (1) "Explain why your child should not do it," (2) "Just say 'no' without explanation," (3) "Ignore your child," (4) "Spank your child," and (5) "Confine your child in a place like a closet." For each response, parents were asked to indicate the frequency of use: "Always," "Sometimes," or "Never."

To analyze these categorical responses, we apply Multiple Correspondence Analysis (MCA),[33] following the approach of Yamaguchi et al. (2018). We interpret the first dimension, which explains the largest share of variance in the response patterns (62.5%), as representing an underlying measure of parenting quality (shown as the horizontal axis in Figure A3). For example, parents who report always explaining why the child should not misbehave are assigned positive values on this axis, while those who report always spanking or confining the child are assigned large negative values.

Figure A3: MCA Coordinates plot

[33]We use `mca` command on Stata MP 16.1.

E Additional Exogeneity Checks

To strengthen the case for the exogeneity of childhood fluoride exposure, we utilize an extensive set of survey questions to assess its association with early-life characteristics. In particular, we begin by examining detailed measures of parenting practices collected during the fourth survey wave. The survey question asks "Which health-related practices do you consciously implement for their child?" The listed items cover a broad spectrum of daily health routines, including:

- Having the child wash their hands before meals;
- Having the child wash their hands after returning home;
- Polishing the child's teeth (e.g., after brushing);
- Encouraging regular sleep and wake routines (early to bed and early to rise);
- Avoiding exposure to tobacco smoke;
- Encouraging the child to play outside as much as possible;
- Promoting physical activity and active play;
- Keeping the indoor environment clean (e.g., cleaning, ventilation).

We construct a standardized index (mean 0, standard deviation 1) based on the number of practices for which caregivers responded "yes." This index serves as an outcome variable to assess whether fluoride exposure is systematically associated with parental health-conscious behaviors for the surveyed children.

Second, even if parenting practices are not systematically related to fluoride exposure, a potential concern remains that children residing in high-fluoride areas may be positively selected in terms of non-cognitive skill endowments. If such unobserved characteristics are correlated with both regional fluoride levels and later outcomes, our regression estimates may still be biased. To address this concern, we examine children's socioemotional development using data from the fourth survey wave, following the approach of Yamaguchi et al. (2018). Specifically, we focus on two domains: hyperactivity and aggression.

Hyperactivity symptoms are measured using five questions adapted from the Diagnostic and Statistical Manual of Mental Disorders (5th ed.) guidelines set by the American Psychiatric Association. These include:

- “Does your child listen until the other person has finished speaking?”,
- “Does your child cut in line?”,
- “Does your child scream in public places (e.g., buses, trains, hospitals)?”,
- “Does your child have a short attention span?”, and
- “Is your child restless?”

Aggression is assessed through the following three questions:

- “Does your child break books and toys?”,
- “Is your child violent?”, and
- “Is your child short-tempered?”

For each domain, we construct standardized indices (mean 0, standard deviation 1) based on the number of positive responses. These indices serve as additional outcome variables to test whether childhood fluoride exposure is systematically associated with early-life non-cognitive traits that could confound later-life outcomes.

Table A7 presents the correlations (in a regression framework) between fluoride exposure and the measures of parenting behavior and children’s socio-emotional skills defined above. We find no meaningful relationship between these factors, ensuring that the parenting style and children’s socio-emotional endowments are not likely to confound our results.

Table A7: Effects of Average Childhood Fluoride Exposure on Self-Esteem During Adolescence

	(1)	(2)	(3)
Dep. Var.	Parental Health Consciousness	Child's Hyperactivity	Child's Aggression
$\overline{Fluoride_i}$ (0.1mg/L)	0.00481	-0.00384	0.00278
	(0.0159)	(0.0142)	(0.0166)
Data		LSN21 (4th)	
Observations	29263	27965	28361

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors are clustered at the province where the surveyed children lived when they were 12 years old. In all models, we control for municipality-level characteristics as of 2005, the province fixed effect, and the survey-round fixed effect. $\overline{Fluoride_i}$ denotes the average exposure to fluoride in the tap water of child i during childhood (between ages 2 and 11) based on the municipality where the child lived at each age.

F Attrition and Migration

As described in Section 3.1, LSN21 repeatedly administers survey questionnaires to children born during specific weeks (January 10–17 and July 10–17) in 2001. The response rate to this survey has been remarkably high—around 90% in each wave—exceeding those of comparable longitudinal surveys in other countries. For example, the first cycle (1994/95) of Canada's National Longitudinal Survey of Children and Youth (NLSCY) achieved a response rate of 86.5%, which declined to 67.8% by the third cycle (1998/99).

However, according to MEXT, the cumulative response rate for LSN21 had declined to 56.5% by the 16th round. Moreover, there are observable differences in the characteristics of children and their parents between those who remained in the sample and those who attrited. For example, children who proceeded to college and those with parents of higher socioeconomic status—measured by educational attainment and self-reported income—are more likely to continue responding to the survey.

Given this, a potential threat to our analysis is that the estimates may be biased if fluoride exposure is correlated with attrition status. To address this concern, we estimate Equation (4) using an attrition indicator as the outcome variable defined over survey rounds 14 to 21. In LSN21, respondents who fail to complete and return the questionnaire for *two consecutive survey rounds* are removed from the panel and considered attrited. Accordingly, we define a child as attrited at survey round t if information is missing in both rounds $t-1$ and t.

The estimation results are presented in Figure A4. We find no significant correlation between fluoride exposure and the likelihood of attrition in any of the survey rounds. This finding provides reassurance that selective attrition is unlikely to bias our main estimates.

We also explore whether migration behavior is endogenously related to fluoride exposure. The LSN21 data include annually reported municipality codes, allowing us to track residential changes over time. However, not all changes in municipality codes represent true household moves, as many municipalities underwent administrative mergers during the 2000s as part of a nationwide consolidation effort. Consequently, changes in municipality codes may reflect either actual migration or administrative reclassification.

To account for this, we construct three alternative indicators of migration:

1. A binary indicator equal to one if the municipality code differs between survey rounds 2 and t ($t = 3, \cdots, 11$).

2. A binary indicator equal to one if the prefecture code differs between survey rounds 2 and t ($t = 3, \cdots, 11$).

Each definition has trade-offs. The municipality-based measure captures small-scale residential moves within prefectures but may misclassify individuals due to code changes from municipal mergers. In contrast, the prefecture-based measure avoids such misclassification because prefecture boundaries have remained stable, but it fails to detect some of intra-prefectural moves.

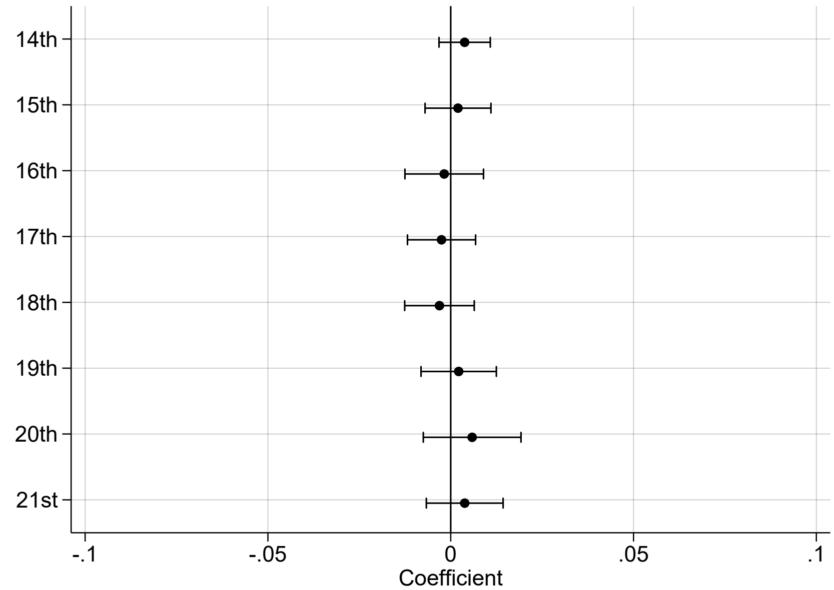
To assess robustness, we estimate the following specification using both migration definitions as outcomes:

$$\mathbb{1}[\text{Migration between wave 2 and } t]_i = \beta^{(2\to t)} Fluoride_{m(i,2)} + \gamma X_m + \delta_{p(i,2)} + \varepsilon_i \quad \text{for } t = 3, \cdots, 11 \tag{7}$$

where $\mathbb{1}[\text{Migration between wave 2 and } t]_i$ is an indicator for whether individual i changed location of residence between the survey wave 2 and t. We consider two alternative definitions of migration as described above. $Fluoride_{m(i,2)}$ denotes fluoride exposure in the municipality of residence at age 2, X_m is a vector of municipality-level controls as in the main regression in the paper, and $\delta_{p(i,2)}$ represents prefecture fixed effects based on residence at age 2. The coefficient $\beta^{(2\to t)}(t = 3, \cdots, 11)$ captures the extent to which early-life fluoride exposure is associated with subsequent migration behavior during childhood. If families systematically sort into municipalities based on local fluoride levels—either to seek the perceived dental health benefits or to avoid potential risks—then β would be significantly different from zero.

Estimation results in Figure A5 show that the estimated coefficients are close to zero and statistically insignificant across all specifications and survey rounds for both outcomes defined using municipality codes (panel A) and those based on prefecture codes (panel B). This finding suggests that families are not systematically sorting into municipalities on the basis of local fluoride levels. In other words, migration behavior during childhood appears to be largely orthogonal to initial fluoride exposure, alleviating concerns that selective mobility drives our main results.

Figure A4: Correlation between Fluoride Exposure and Attrition Status

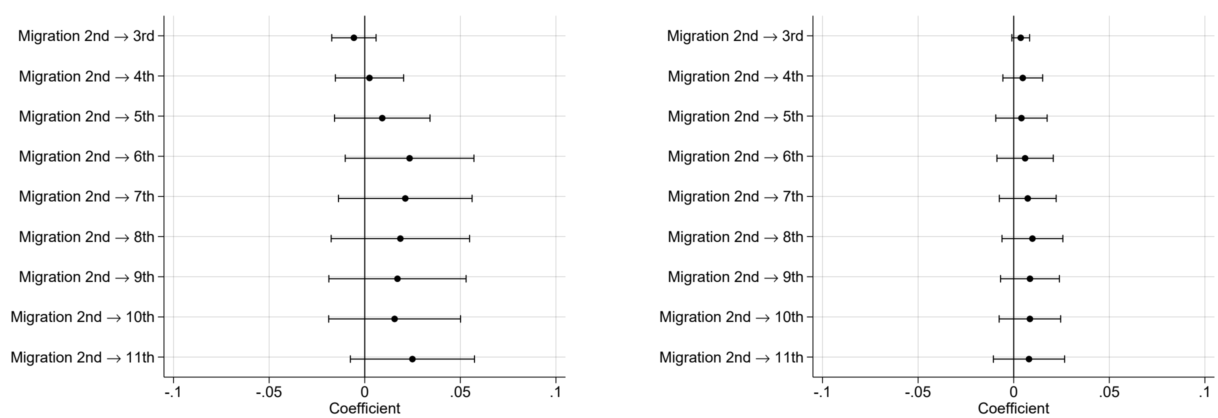


Notes: This figure reports the point estimates and 95% confidence intervals of β from regressions based on Eq. (4), with replacing the outcome with attrition indicator at each survey round. Standard errors are clustered at the municipality level, based on the location where the surveyed children resided at age 12. All models control for municipality-level characteristics as of 2005 and include province fixed effects.

Figure A5: Correlation between Fluoride Exposure and Migration Status

(A) Based on Municipality Code

(B) Based on Prefecture Code



Notes: This figure reports the point estimates and 95% confidence intervals of β from regressions based on Eq. (7). Standard errors are clustered at the province level, based on the location where the surveyed children resided at age 2. All models control for municipality-level characteristics as of 2005 and include province fixed effects at age 2.

G Details of Robustness Check

G.1 Other Contaminants

This appendix examines whether fluoride concentrations in drinking water are correlated with other potentially harmful substances, and whether our regression results remain robust when these additional contaminants are included as controls.

Table A8 summarizes contaminant levels in the Japanese water supply (DWQA 2003–2012), and Figure A6 shows their correlation matrix. Our focus is on the extent to which fluoride levels correlate with other potential confounders, such as arsenic, lead, and nitrates. Overall, correlations with fluoride are small, though a few substances exhibit moderate correlations (above 0.1 in magnitude), which we examine in more detail.

- Arsenic in drinking water is a recognized health risk. Exposure to several hundred micrograms per liter can cause cancers (skin, bladder, lung, and potentially kidney, liver, and prostate) and chronic poisoning symptoms such as hyperpigmentation and palmar–plantar hyperkeratoses (Brown and Ross, 2002). Research also links arsenic exposure to adverse neonatal outcomes (Bloom et al., 2014; Howe et al., 2020). In Japan, arsenic levels are strictly regulated at 0.01 mg/L, with all water plants below this threshold and a mean concentration of just 0.0007 mg/L (Table A8). Thus, despite a correlation of 0.11 with fluoride, the associated health risk is negligible.

- Sodium is salt. The WHO's position is that sodium is not to be considered a health concern in drinking water (WHO). Japan has set a threshold value for sodium of 200 mg/L,[34] because excess levels may change the taste of water(Aggeborn and Öhman, 2021). The 2010 Dietary Guidelines for Americans recommend that children consume less than 2,300 mg of sodium per day to avoid high blood pressure.[35] This implies that a person would need to drink 11.5 liters of water per day, at the 200 mg/L threshold, to reach this limit. As shown in Table A8, the mean sodium concentration in Japanese drinking water is 10.72 mg/L. Therefore, despite its moderate correlation (r = 0.25) with fluoride concentration, the sodium levels observed in our water data are unlikely to pose any health risk.

We also estimate our regressions controlling for these additional contaminants. As

[34] https://www.env.go.jp/water/water_supply/kijun/kijunchi.html (in Japanese; Accessed on July 30th, 2025)

[35] https://www.cdc.gov/vitalsigns/pdf/2014-09-vitalsigns.pdf (Accessed on July 30th, 2025)

shown in Tables A9 – A11, our main results remain robust when these substances are included as covariates.

Table A8: Summary Statistics of Substances in Drinking Water (Water Plant Level Observation)

	Mean	Std. Dev.	p5	p95	Limit
Fluoride	0.0713	0.0654	0.025	0.18	0.8
Arsenic	0.0007	0.0008	0.0005	0.002	0.01
Cadmium (*10)	0.0039	0.0027	0.0015	0.005	0.1
Copper	0.0145	0.0196	0.005	0.05	1
Iron	0.0155	0.0144	0.005	0.04	0.3
Lead	0.0007	0.0007	0.0005	0.002	0.01
Mercury (*100)	0.0026	0.0020	0.0025	0.0025	0.05
Nitrates	1.1028	1.1769	0.08	3.5	10
Sodium	10.72	9.0206	0.005	26.7	200
Zinc	0.0149	0.0219	0.002	0.05	1

Figure A6: Correlation between Substances in Drinking Water

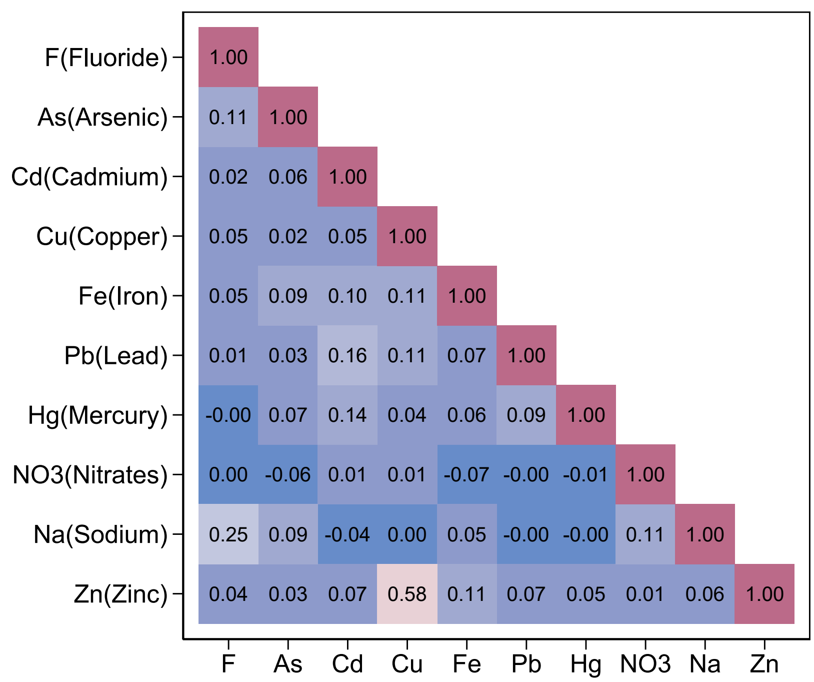


Table A9: Effect of Average Childhood Fluoride Exposure on Dental Health —Other Contaminants Controlled —

Panel A: Outpatient Dummy	(1) All	(2) Male	(3) Female			
Dep. Var.	Outpatient(Dental)$_{i,12}$					
$\overline{Fluoride_i}$ (0.1mg/L)	-0.0177**	-0.00825	-0.0258**			
	(0.00847)	(0.0120)	(0.0107)			
Data	LSN21 (12th)					
Other Contaminants Control	Yes	Yes	Yes			
Mean. Dep. Var	0.249	0.258	0.240			
Observations	29,839	15,426	14,413			
Panel B: Cost and Visit Interval	(1) All	(2) Male	(3) Female	(4) All	(5) Male	(6) Female
Dep. Var.	Log of Monthly Spending in JPY (Dental-Related)			Visit Interval in Day (Dental Clinics)		
$Fluoride_{my}$ (0.1mg/L)	-0.0263	0.00912	-0.0571*	1.648	0.00778	2.888**
	(0.0196)	(0.0197)	(0.0310)	(1.165)	(1.329)	(1.432)
Data	Medical Claim (SMCA)			Patient Survey (PS)		
Other Contaminants Control	Yes	Yes	Yes	Yes	Yes	Yes
Mean Dep. Var.	7781	7773	7790	18.26	18.18	18.33
Observations	12987	6559	6428	6250	3085	3165

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.
Panel A: In all models, we control for municipality-level characteristics as of 2005 and the province fixed effect. Outpatient(Dental)$_{i,12}$ represents a binary indicator for whether the child had dental cavities that required a visit to a hospital or clinic for medical care in the past year, as reported in the LSN21's 12th round of the survey, and $\overline{Fluoride_i}$ denotes the average exposure to fluoride in the tap water of child i during childhood (between ages 2 and 11). Standard errors are clustered at the province where the surveyed children lived when they were 12 years old.

Table A10: Effects of Average Childhood Fluoride Exposure on Self-Esteem During Adolescence —Other Contaminants Controlled —

	(1) All	(2) Male	(3) Female
Dep. Var.	Self-Esteem (standardized)		
$\overline{Fluoride_i}$ (0.1mg/L)	0.0263	-0.0000631	0.0571**
	(0.0179)	(0.0259)	(0.0226)
Data	LSN21 (16th-21st)		
Other Contaminants Control	Yes	Yes	Yes
Observations	131826	66297	65529

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors are clustered at the province where the surveyed children lived when they were 12 years old. In all models, we control for municipality-level characteristics as of 2005, the province fixed effect, and the survey-round fixed effect. $\overline{Fluoride_i}$ denotes the average exposure to fluoride in the tap water of child i during childhood (between ages 2 and 11) based on the municipality where the child lived at each age.

Table A11: Effects of Average Childhood Fluoride Exposure on Academic Achievement During Adolescence —Other Contaminants Controlled —

	(1)All	(2)Male	(3)Female	(4)All	(5)Male	(6)Female
Dep. Var.	High School Quality Score			Attending College		
$\overline{Fluoride_i}$ (0.1mg/L)	0.300	0.426	0.180	0.0235**	0.0228	0.0239
	(0.380)	(0.431)	(0.435)	(0.0116)	(0.0216)	(0.0148)
Data	LSN21 (16th)			LSN21 (19th)		
Mean. Dep. Var.	53.89	53.85	53.92	0.602	0.576	0.630
Observations	21451	10853	10598	22298	11167	11131

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors are clustered at the province where the surveyed children lived when they were 12 years old. In all models, we control for municipality-level characteristics as of 2005 and the province fixed effect. $\overline{Fluoride_i}$ denotes the average exposure to fluoride in the tap water of child i during childhood (between ages 2 and 11).

G.2 Alternative Specifications

First, we include individual-level covariates. Second, while the main specification includes province fixed effects based on the child's residence at age 12, we also estimate models using province fixed effects at age 2, as well as a specification that includes province fixed effects at both ages 2 and 12 simultaneously. Third, we estimate a version that replaces province fixed effects with municipality fixed effects. Since fluoride exposure is aggregated at the municipality level in each survey round, this specification identifies within-individual variation over time—such as changes in water sources or household migration. while this approach exploits more plausibly exogenous variation in exposure, the identifying variation becomes limited, resulting in less precise estimates. Finally, we assess the robustness of our results by excluding specific subsamples. In one specification, we exclude Tokyo and Osaka—large urban areas with greater access to dental care (including orthodontics) and more extensive educational opportunities. In another, we exclude Okinawa, the only province in Japan where a large-scale artificial fluoridation program was implemented in the past. As a result, residents in Okinawa may be more informed about the potential benefits and risks of fluoride, which could influence their behavior or awareness in ways that differ from other regions.

Overall, Figures A7–A10 show that the results are robust to these alternative specifications. Even when controlling for municipality fixed effects (fifth and sixth rows), the qualitative patterns remain unchanged, although the point estimates become less precise.

G.3 Different Levels of Clustering

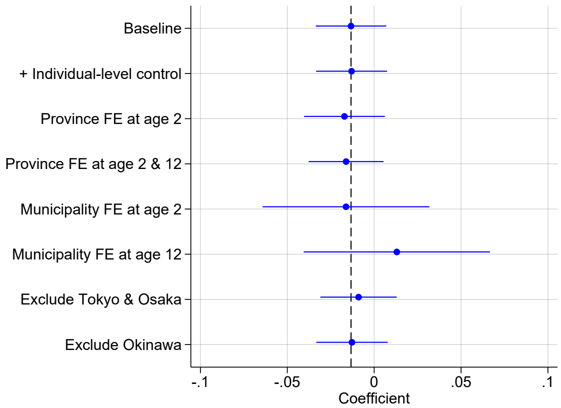
We consider several alternative clustering schemes to ensure that our inference is not sensitive to the choice of clustering unit. In the baseline specification, standard errors are clustered at the province level, motivated by the fact that inter-municipal water supply associations (IWSAs) operate within provincial boundaries. As a robustness check, we also implement clustering at the municipality level, which provides the most granular unit of administration. In addition, we construct clusters at the level of IWSAs. IWSAs are administrative associations jointly managing water supply systems across multiple municipalities, and thus represent a natural unit of correlated exposure. For most municipalities, membership in an IWSA is uniquely defined; that is, municipalities belong to one IWSA. However, in three municipalities that participate in more than one IWSA, the assignment of a cluster is not well defined because they could be grouped into multiple associations. For these cases, we conservatively cluster at the municipality level (i.e., use the municipality identifier as the clustering unit). Excluding these three municipalities from the analysis does not materially change our estimates (Results available upon request).

For outcomes available in the LSN21 longitudinal survey, we additionally see how cluster at the individual level change our qualitative results. Note that this clustering scheme is not feasible for analysis using SMCA or PS because these data are repeated cross-section. Finally, to account for potential spatial correlation in treatment and outcomes beyond administrative boundaries, we estimate spatially correlated standard errors following Conley (1999), varying the cutoff distance at 10, 30, and 50 km.

Across all these clustering choices, the qualitative pattern of results remains unchanged.

Figure A7: Robustness Analysis (Outpatient(Dental)$_{i,12}$)

(A) Male



(B) Female

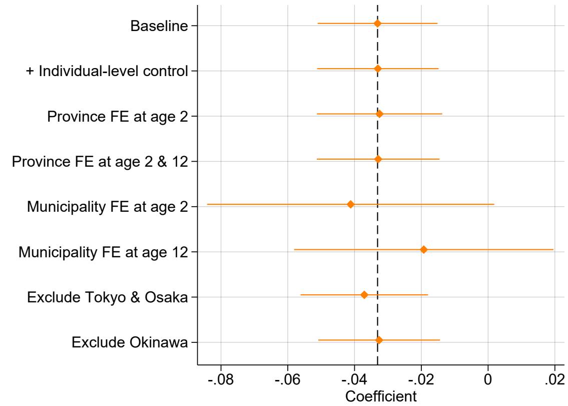
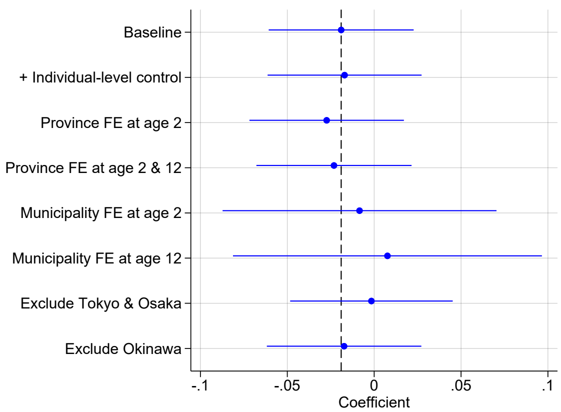


Figure A8: Robustness Analysis (Self-Esteem)

(A) Male



(B) Female

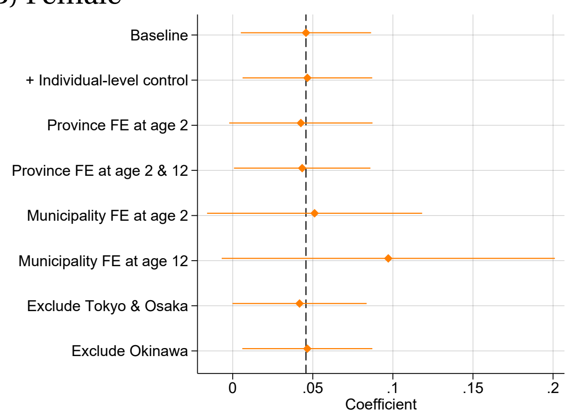


Figure A9: Robustness Analysis (Quality of High School)

(A) Male (B) Female

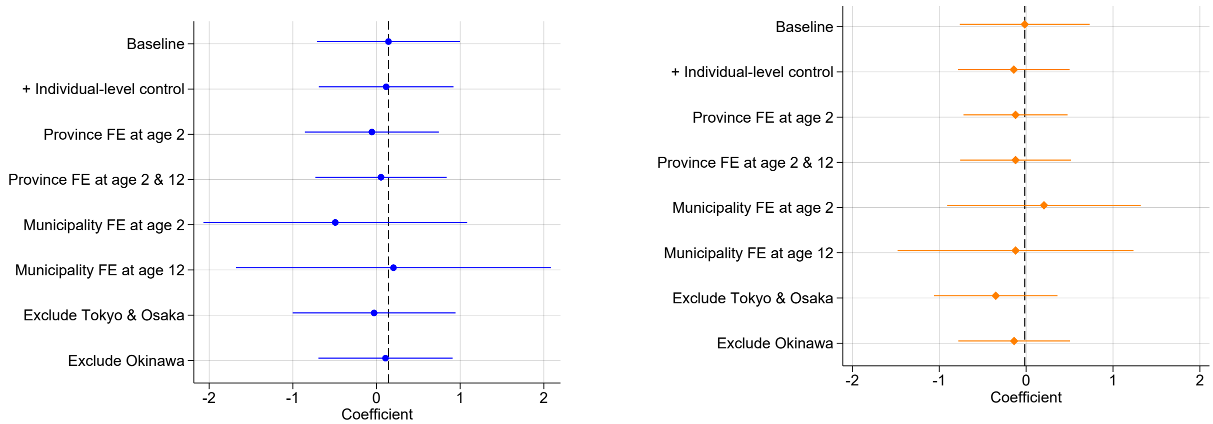


Figure A10: Robustness Analysis (College Attendance)

(A) Male (B) Female

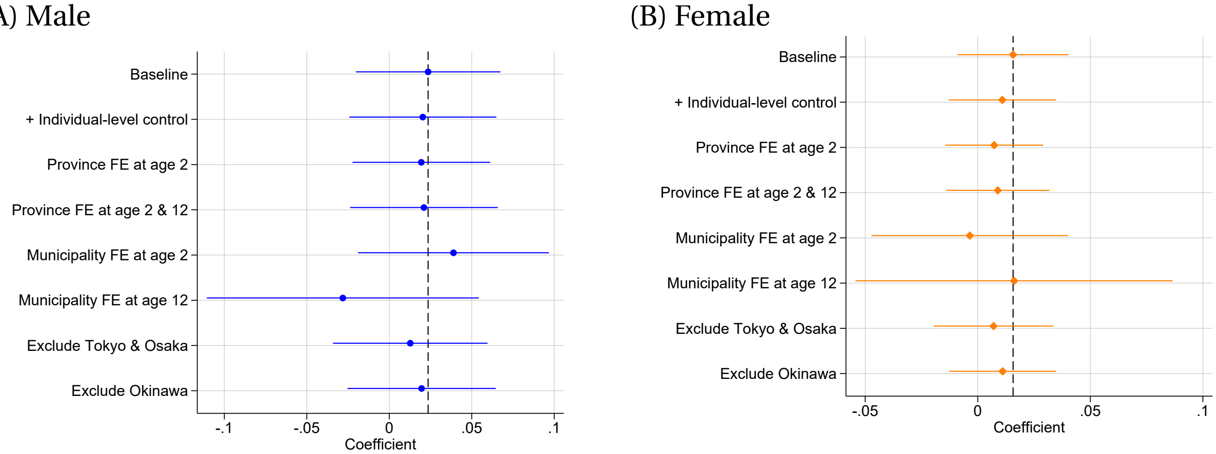


Table A12: Alternative Unit of Cluster —Dental Health Outcomes —

Dep. Var.	Outpatient Visit		Log of Monthly Spending (in JPY)		Visit Interval (in Days)	
Sample	(1) Male	(2) Female	(3) Male	(4) Female	(5) Male	(6) Female
	-0.0133	-0.0331	0.00330	-0.0579	1.186	3.008
Baseline (Province)	(0.0101)	(0.00893)***	(0.0185)	(0.0251)**	(1.289)	(1.392)**
Municipality	(0.0104)	(0.00998)***	(0.0185)	(0.0232)**	(1.431)	(1.217)**
IWSA	(0.0104)	(0.00997)***	(0.0186)	(0.0231)**	(1.426)	(1.221)**
Individual	(0.0111)	(0.0101)***	NA	NA	NA	NA
Conley (10km)	(0.0113)	(0.00941)***	(0.0197)	(0.0231)**	(1.599)	(1.219)**
Conley (30km)	(0.0116)	(0.00947)***	(0.0187)	(0.0229)**	(1.642)	(1.316)**
Conley (50km)	(0.0124)	(0.00937)***	(0.0202)	(0.0231) **	(1.722)	(1.219)**
Data	LSN21 (12th)		SMCA		PS	
Observations	15,426	14,413	6,601	6,474	3,267	3,286

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. IWSA denotes an inter-municipal water supply authority, a cooperative organization formed by multiple municipalities to jointly manage water sources. The column labeled “IWSA” treats all municipalities belonging to the same authority as a single unit. The last three rows report spatially clustered standard errors following Conley (1999), using distance cutoffs of 10, 30, and 50 km, respectively. Columns (1) and (2): Outcome is a binary indicator for whether the child had dental cavities requiring a hospital or clinic visit in the past year, as reported in the 12th round of LSN21. Controls include municipality-level characteristics measured in 2005 and province fixed effects (measured at the 12th round of LSN21). Estimates are based on Equation (1), with clustering units varied across columns. Columns (3) and (4): Outcome is the logarithm of monthly spending on dental care, sourced from the Statistics of Medical Care Activities (a random sample of medical and dental claims). Controls include municipality-level characteristics, patient characteristics (age, type of insurance coverage, and an indicator for first versus follow-up consultation), and province fixed effects. The sample is restricted to individuals under age 18. Columns (5) and (6): Outcome is the visit interval (in days) since the previous dental visit, sourced from the Patient Survey. Controls include municipality-level characteristics, patient characteristics (age and type of insurance coverage), and province fixed effects. The sample is restricted to individuals under age 18.

Table A13: Alternative Unit of Cluster —Skill Outcomes —

Dep. Var.	Self-Esteem		Quality of High School		College Attendance	
Sample	(1) Male	(2) Female	(3) Male	(4) Female	(5) Male	(6) Female
	-0.0190	0.0457	0.136	-0.0201	0.0236	0.0157
Baseline (Province)	(0.0207)	(0.0202)**	(0.424)	(0.371)	(0.0218)	(0.0122)
Municipality	(0.0209)	(0.0230)**	(0.309)	(0.289)	(0.0157)	(0.0128))
IWSA	(0.0209)	(0.0231)**	(0.310)	(0.289)	(0.0156)	(0.0128)
Individual	(0.0217)	(0.0232)**	(0.279)	(0.251)	(0.0144)	(0.0132)
Conley (10km)	(0.0192)	(0.0198)**	(0.359)	(0.294)	(0.0157)	(0.0121)
Conley (30km)	(0.0183)	(0.0200)**	(0.354)	(0.301)	(0.0158)	(0.0106))
Conley (50km)	(0.0182)	(0.0201)**	(0.380)	(0.309)	(0.0176)	(0.0123)
Data	LSN21 (16th-21st)		LSN21 (16th)		LSN21 (19th)	
Observations	66,297	65,529	10,853	10,598	11,167	11,131

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. IWSA indicates inter-municipal water supply authority, which is a cooperative organization formed by multiple municipalities to jointly manage water sources. The column labeled “IWSA” treats all municipalities belonging to the same inter-municipal water supply authority as a single unit. The last three rows present spatially clustered standard errors following Conley (1999), using distance cutoffs of 10, 30, and 50 km, respectively.

H Additional Information about the Water Supply Service and Fluoridation in Japan

Water Supply Act (WSA) The purpose of the Water Supply Act (WSA) is to ensure the appropriate and efficient construction and operation of water supply services, promote the systematic development of water supply infrastructure, and secure the provision of safe, sufficient, and affordable water. By safeguarding and advancing water supply systems, the Act aims to contribute to public health and the improvement of living conditions for local residents. Henceforth, we refer to Japanese Law Translation (2023) for the English translation of the Act.

Under the WSA, four categories of water supply systems are defined: (1) Wholesale Water Supply Services, (2) Water Supply Services, (3) Private Water Supply Systems, and (4) Tank Storage Water Supply Systems. Figure A11 summarizes the relationship among these systems alongside their Japanese designations.

- **Wholesale Water Supply Services**
  These refer to public services that supply water to water utilities for use in their own water supply operations. They function upstream in the supply chain, providing bulk water to municipalities or other entities.

- **Water Supply Services**
  These are public systems that provide water in response to general community demand. Within this category, two subtypes are recognized based on the population served, as discussed in Section 2.1: - *Public Water Supply Services*, which serve more than 5,000 people, typically through large-scale municipal systems with extensive piped infrastructure. - *Small-Scale Water Supply Services*, which serve communities of 5,000 people or fewer.

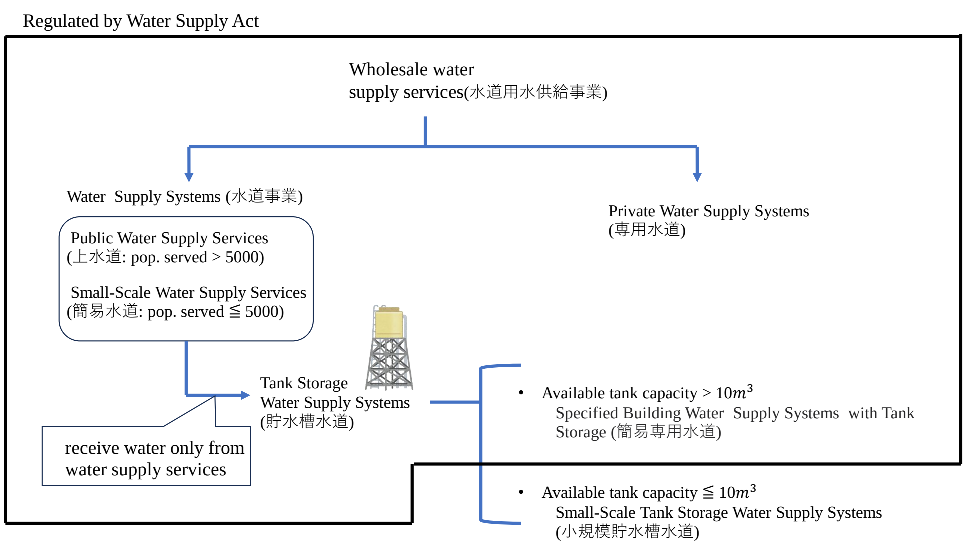
- **Private Water Supply Systems**
  These refer to non-public systems that satisfy either of the following conditions: (1) the system supplies drinking water for the daily needs of more than 100 people, or (2) it has a maximum daily supply volume of 20 m^3 or more.

- **Tank Storage Water Supply Systems**
  These are systems that are neither public nor private water supply systems, and whose water source is limited to water supplied from public systems. They are further classified into two types based on storage capacity: - *Specified Building Water Supply Systems with Tank Storage*, and - *Small-Scale Tank Storage Water Supply*

Systems. The former is regulated under the WSA, while the latter is governed by local ordinances independently enacted by municipal governments.

Initially, when the WSA was enacted in 1957, tank storage systems were not subject to regulation. However, with increasing urbanization and the widespread use of these systems, regulatory oversight was introduced in 1977 (Showa 52) for larger facilities, thereby bringing Specified Building Water Supply Systems with Tank Storage under the scope of the Act.

Figure A11: Flowchart of Water Supply Act



Communities with a History of Water Fluoridation Policy As described in Section 2.2, water fluoridation was implemented in a small number of municipalities in the past. The figure below highlights these municipalities, including those where fluoridation was introduced under U.S. military administration (Okinawa) or through local public health initiatives (Yamashina in Kyoto and Asai in Mie).

Figure A12: Municipalities with a History of Water Fluoridation in Japan