Effects of Prenatal Stress from Radiation Fear on Birth Outcomes: Insights from the Fukushima Accident

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January 9, 2025

Abstract

This study assesses the impact of prenatal radiation fear following the Fukushima nuclear accident on birth outcomes and child health over eight years. By integrating birth records with census and data from Google Trends, we analyze the quasi-experimental exposure of children to prenatal radiation fear. Our results indicate that prenatal stress significantly reduces birth weight and increases the risk of preterm births, with the most pronounced effects observed when exposure occurs during the first trimester. The adverse impacts intensify with higher levels of fear and are more acute among lower-income families and less-educated mothers. Additionally, while the negative effects are evident at birth and persist until age two, they abate by age five, suggesting that the influence of prenatal stress on physical health is temporary. This study enhances our understanding of the maternal stress impacts from intangible risks, emphasizing the need for targeted health interventions during pregnancy.

Keywords: Radiation fear; intangible risk factors; prenatal stress; birth outcomes; fetal origin hypothesis

JEL Classification: I14, I31, J13, H8

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1 Introduction

Health at birth is a crucial determinant of human capital development, significantly influencing outcomes throughout life, from educational attainment in adolescence to income levels in adulthood (Almond et al., 2005; Almond and Currie, 2011; Black et al., 2007). Numerous studies have investigated the determinants of birth outcomes, with a focus on the effects of prenatal stress (Currie, 2011). Consistently, research shows that prenatal stress negatively impacts birth outcomes, with stressors that include intrinsic factors such as pregnancy-specific anxiety, maternity blues, and stressful life events like unemployment, divorce, or the death of a loved one, as well as extrinsic factors such as natural disasters and terrorist attacks (Black et al., 2016; Camacho, 2008; Currie et al., 2020; Currie and Rossin-Slater, 2013; Persson and Rossin-Slater, 2018; Torche, 2011).

A primary challenge in studying the relationship between prenatal stress and birth outcomes is endogeneity, which arises from the influence of multiple unobservable confounding factors correlated with prenatal stress. This issue is particularly pronounced with intrinsic stressors, as traditional regression analyses often fail to distinguish if the effects are due to socioeconomic repercussions or the stress itself (Black et al., 2016). To overcome these issues, studies have increasingly utilized extrinsic stressors like natural disasters as alternatives (Currie and Rossin-Slater, 2013; Torche, 2011). However, these extrinsic stressors also present complications; they cause acute, specific damage, and the affected mothers are often direct victims (Currie and Rossin-Slater, 2013; De Oliveira et al., 2021; Torche, 2011). Disentangling the effects of prenatal stress from the direct physical and socioeconomic impacts of extrinsic stressors is therefore complex. Moreover, the reliability of survey data on stressors may be compromised by issues such as confirmation bias, potentially leading to either underestimation or overestimation of the intergenerational health impacts of prenatal stress.

This study seeks to address these challenges by introducing a novel stressor—ionizing radiation exposure, which has been implicated in the development of subclinical conditions like thyroid dysfunction and carotid atherosclerosis (Surks et al., 2004). We investigated the impact of prenatal stress, induced by radiation fear following the Fukushima Nuclear Power Plant (NPP) accident in Japan, on fetal health at birth and up to eight years later. The exogenous nature of the Fukushima accident reduces the selection bias often associated with intrinsic stressors. Furthermore, the consequences of subclinical radiation exposure are intangible, uncertain, and associated with ambiguous loss (Rahu, 2003; UNSCEAR, 2008), which engender widespread fear even among individuals not directly at risk. Consequently, radiation fear can serve as a potent proxy for prenatal stress, effectively isolating its influence from other confounding factors.

Previous studies have predominantly focused on the direct impacts of subclinical radiation exposure from events like the Chernobyl accident on intergenerational health outcomes, rather than the fear of such exposure. For instance, Almond et al. (2009) reported lower cognitive performance among Swedish adolescents born in areas contaminated following the Chernobyl accident but found no effect on birth weight. Heiervang et al. (2010) reached a similar conclusion in Norway. Cwikel et al. (2020) noted reduced fertility among women exposed to the Chernobyl radiation. Among others, Huizink et al. (2007) found lifelong depressive symptoms in Finnish adults born to mothers who experienced anxiety due to the Chernobyl accident; however, this study did not clearly distinguish between the impacts of actual exposure and prenatal fear. Research related to the Fukushima accident also focused primary on direct radiation effects rather than the fear of exposure. For example, Leppold et al. (2017) studied birth records from a hospital close to the accident site and found no significant changes in birth weight post-accident. Fujimori et al. (2014) surveyed mothers in Fukushima Prefecture, finding abortion and stillbirth rates similar to the national average. However, these findings were limited due to the small sample size and geographic focus on an area severely impacted by the Great East Japan Earthquake.

Our study fills existing gaps in research by providing novel insights into the causal relationship between radiation fear and offspring health, utilizing comprehensive population data from Japan. We constructed a dataset from Japan's universal birth records linked to concurrent censuses, focusing specifically on newborns whose estimated due dates fell within 280 days of the Fukushima accident. To isolate the effect of radiation fear, we excluded mothers from areas devastated by the tsunami or contaminated by fallout. We conducted our analysis using three distinct cohorts: the prenatal cohort, consisting of newborns in utero at the time of the Fukushima accident; the postnatal cohort, comprising those whose due dates were just before the accident; and a placebo cohort, 'exposed' to a hypothetical accident. We assessed health differences attributed to radiation fear by comparing the prenatal cohort against the postnatal and placebo cohorts. Additionally, we measured variations in health outcomes relative to levels of radiation fear, quantified using Google Trend-based search popularity index. We also conducted a within-mother analysis using a difference-in-differences-like approach, comparing health outcomes between newborns in the targeted cohorts and their older siblings.

The results revealed that prenatal radiation fear significantly increased the likelihood of preterm birth by 16% and reduced birth weight by 22–26 grams. These effects were particularly pronounced at the lower end of the birth weight spectrum, suggesting that high-risk newborns were most affected. Notably, the impact of radiation fear was transient; by age five, the prenatal cohort's health was

comparable to or better than that of the two comparison cohorts. The most substantial effects were observed in fetuses exposed during the first trimester, likely due to their prolonged exposure to radiation fear. The adverse outcomes were less pronounced among families where mothers were well-educated or household incomes were in the top quartile, underscoring the protective role of socioeconomic status and the capacity to process information in mitigating stress effects. Furthermore, our findings indicated minimal changes in maternal health behaviors and nutrient intake, suggesting that prenatal stress, rather than changes in health practices, was the primary driver of the observed adverse birth outcomes.

This study sheds new light on the relationship between prenatal stress and fetal health, contributing valuable insights to the field of nuclear power-related research. Recent events have escalated public concerns about nuclear safety, including the 2021 leak at a Chinese NPP, ongoing threats to nuclear facilities during the Ukraine war, and the decision to release treated Fukushima cooling water into the ocean (Cohen, 2021; Kirby, 2022; Murakami, 2022). Understanding the hidden costs of these nuclear risks is crucial. Our research also underscores the significant impact of intangible and uncertain risks—not only those associated with nuclear power but also other global concerns such as air pollution and pandemics (Goyal and Selix, 2021). Specifically, our findings offer a preliminary evaluation of the effects of prenatal anxiety during the early stages of the COVID-19 pandemic. While the complete ramifications of such prenatal stress will require years of further study, our results provide an important early indicator of potential long-term impacts.

2 The Fukushima Nuclear Power Plant Accident

On March 11, 2011, a catastrophic 9.0-magnitude earthquake struck Japan, triggering a devastating tsunami that would lead to the most severe and enduring consequence of this natural disaster: the Fukushima Nuclear Power Plant (NPP) accident. When the tsunami overwhelmed the facility's defenses, it destroyed all power sources—including emergency diesel generators, batteries, and power supply panels—resulting in a complete loss of core cooling capabilities.[1] The ensuing crisis culminated in three hydrogen explosions between March 12 and March 15, releasing radioactive materials such as cesium-137 and iodine-131 into the atmosphere.[2] The government responded by issuing emergency evacuation orders to residents within 3-20 km of the plant, ensuring most were

[1] Appendix C provides a comprehensive introduction to nuclear energy program in Japan.

[2] Cesium-137 has a half-life of 30 years (the amount of time for half the atoms to disintegrate). The half-life of iodine-131 is 8 days.

evacuated before the largest atmospheric release on March 15 (Hasegawa et al., 2015).[3] The incident's severity led to its classification as a level 7 event on the International Nuclear Incident Scale, making it only the second accident after Chernobyl to receive this highest designation.

2.1 Radiation Exposure and Health Impact Assessment

According to Japanese authorities, the majority of radioactive material remained contained within the reactor buildings' water systems. The atmospheric release was estimated at approximately 10% of that released during the Chernobyl accident (Von Hippel, 2011). In Fukushima Prefecture, the effective radiation dose during the first year post-accident was measured at 2.1 millisieverts, exceeding the International Commission on Radiological Protection's recommended maximum of 1.0 millisievert. The predicted lifetime dose after the acute phase was estimated at 2.0 millisieverts (Hasegawa et al., 2015).

To minimize health risks, authorities immediately suspended shipments of dairy and agricultural products from Fukushima and three adjacent prefectures, while implementing regular radiation screening of foodstuffs. These preventive measures proved effective, particularly in reducing the risk of thyroid cancer in children from iodine exposure. Subsequent research has found minimal evidence linking post-accident thyroid cancer diagnoses to radiation exposure (Takamura et al., 2016), and studies confirmed that children's internal radiation exposure remained minimal within the first year (Tsubokura et al., 2013).

2.2 Psychological Impact and the 'Epidemic of Fear'

While the direct health impacts from radiation exposure were limited, the psychological consequences of radiation fear proved far more pervasive and significant (Tateno and Yokoyama, 2013). Multiple survey-based studies documented elevated anxiety levels not only among local residents (Iwasaki et al., 2017; Nakayama et al., 2019; Yoshida et al., 2016) but throughout the Japanese population (Midorikawa et al., 2016; Rubin et al., 2012; Shinoda et al., 2014; Takebayashi et al., 2017; Tateno and Yokoyama, 2013). This widespread fear stemmed largely from the government's delayed risk communication, which left citizens uncertain about appropriate preventive measures (Takebayashi et al., 2017). The invisible nature of radiation exposure, combined with media misinformation and rumors—amplified by internet circulation—led to widespread public mistrust in government

[3] In this study, the date of the accident is March 15, 2021, because the explosion on that day was the most severe and released the largest number of radioactive materials.

statements (Harada et al., 2015; Kitada, 2013; Maeda et al., 2018).

Mothers of young children experienced particularly acute anxiety, resulting in an unusually high rate of thyroid cancer screening for children—a phenomenon termed the 'epidemic of fear' (Midorikawa et al., 2016; Normile, 2016). Expecting mothers showed especially concerning levels of distress, with 28% exhibiting depressive symptoms—significantly higher than the general population (Goto et al., 2015). Ultimately, comprehensive analyses of the Fukushima accident's impact have concluded that the psychological consequences of radiation fear, rather than direct physical harm from radiation exposure, constituted the most severe and persistent challenge (Hasegawa et al., 2015; Von Hippel, 2011).

I'll refine the language and improve the flow while maintaining all content and citations. Let me focus on clarity, logical progression, and completeness:

3 Data

Our study integrates data from three comprehensive Japanese administrative sources: universal birth records and national census data from 2010 and 2015. By linking birth records with census data, we constructed a rich dataset capturing both newborn outcomes and household characteristics. As shown in Figure 1, our study period extends from March 2010 through December 2011.

Figure 1 here

The linkage methodology comprised two distinct phases, dictated by the October timing of census administration. For pre-October 2010 births, we achieved direct linkage with the 2010 census using multiple identifiers: household residence location, newborn characteristics (birth year, month, and sex), and parental birth dates. This process successfully matched approximately 75% of records.

For births occurring after October 2010, we developed an alternative approach since these births post-dated the 2010 census. First, we identified households in the 2015 census with children born between October 2010 and April 2012.[4] We then traced these households back to their 2010 census records using household residence information and birth dates of parents and any existing siblings. This retrospective matching enabled us to extract newborn birth dates from the 2015 census—information crucial for subsequent linkage with birth records using our established matching criteria. Through this method, we achieved a 56% linkage rate for the post-October 2010 period.

[4]This time range was extended to account for the prenatal cohort (Figure 1) defined by expected due dates ranging from March 2011 to December 2011. Actual birth dates recorded in the 2015 census may extend beyond December 2011.

We excluded single-parent households due to consistently low linkage rates,[5] and restricted our analysis to singleton births since multiple births typically present different birth weight patterns that could confound our results. Our initial linked dataset encompassed 1,163,475 newborns.

3.1 Sample Restrictions

We implemented two critical geographic exclusions to isolate the effects of radiation fear. First, recognizing that the tsunami caused the majority of immediate casualties and destruction—and that natural disasters can independently affect birth outcomes through prenatal stress (Currie and Rossin-Slater, 2013; Torche, 2011)—we excluded data from tsunami-affected regions (Ishiwatari, 2011).[6] These exclusions are detailed in Appendix Figure A1.

Second, to address potential radiation exposure effects on fetal development, we excluded data from regions where annual cumulative radiation exceeded 1.0 millisievert[7] between March 2011 and April 2012 (Appendix Figure A2). This threshold was calculated using monthly radioactive fallout data from the Japan Nuclear Regulation Authority,[8] combining the highest monthly doses of cesium-137 and cesium-134[9] to estimate annual exposure levels. The geographic distribution of excluded areas is presented in Appendix Figure A3. After implementing these geographic restrictions, our final analytical sample contained 954,172 parent-newborn pairs.

3.2 Outcome Measures

3.2.1 Birth Outcomes

We examined birth outcomes through two primary measures. The first was preterm birth, defined as delivery before 37 weeks gestation. The second was birth weight, which we analyzed both as a continuous measure (in grams) and through three clinically significant thresholds: low birth weight (LBW, <2500 grams), very low birth weight (VLBW, <1500 grams), and extremely low birth weight (ELBW, <1000 grams). LBW serves as a critical indicator warranting neonatal intensive care unit admission until stable discharge is possible. While LBW infants typically achieve normal growth

[5]According to the 2010 census, only 1.6% of Japan's total 51,842,307 households were single-parent households, totaling 844,661. (Source: Statistics Bureau of Japan; available at https://www.stat.go.jp/data/kokusei/2020/kekka.html , accessed on February 5, 2023).

[6]We exclude 43 municipalities where the death toll from the tsunami exceeds zero.

[7]The International Commission on Radiological Protection advises a maximum annual individual exposure of 1.0 millisievert, which the Ministry of the Environment adopted as a standard following the accident.

[8]The monthly radioactive fallout records are available from https://radioactivity.nsr.go.jp/ja/list/195/list-1.html.

[9]We do not account for iodine-131 because it has an 8-day half-life that is not detectable during most of the period. Instead, we account for cesium-134, which is a shorter-lived relative of cesium-137 that contaminates land for prolonged periods.

trajectories absent other complications (Euser et al., 2008), VLBW and ELBW births carry substantially higher risks of persistent cognitive and physical challenges (McCormick, 1985).

3.2.2 Longitudinal Health Outcomes

We tracked children's health outcomes at ages two, five, and eight through the 2013–2019 Comprehensive Survey of Living Conditions (CSLC), a nationally representative triennial survey sampling from the most recent census.[10] The 2013 CSLC was linked to the 2010 census, while the 2016 and 2019 surveys connected to the 2015 census. These surveys were subsequently linked to our primary dataset (detailed methodology in Appendix B.I and B.II).[11] Our longitudinal tracking yielded samples of 3,755 children at age two, 2,864 at age five, and 2,363 at age eight.

The CSLC provided detailed health information through reported physical complaints and medical treatment patterns. We constructed binary indicators (1=present, 0=absent) for overall physical complaints and specific conditions associated with prenatal stress: respiratory, digestive, and skin complaints (Van De Loo et al., 2016; Zijlmans et al., 2017). Parallel indicators captured whether medical treatment was sought for each condition.

3.3 Measuring Radiation Fear

Figure 2 here

To overcome measurement errors and external validity concerns present in previous studies, we developed a novel approach to quantifying radiation fear.[12] We constructed a standardized search popularity index encompassing all Japanese nuclear power plants (NPPs) except Fukushima. Using Google Trends data, we measured search popularity for each NPP during the month following the accident, comparing it with the same period in the previous year. As illustrated in Panel A of Figure 2, our analysis included 15 NPPs distributed across Japan, excluding Fukushima.

We collected these indices at the prefectural level, normalizing them against search popularity for 'Uniqlo'—a benchmark selected for its high national recognition and search pattern stability unaffected

[10]The CSLC includes four questionnaires assessing household, health, income/savings, and long-term care. The dataset is widely used. In this study, we use the household and health questionnaires, which are administered to over 600,000 respondents from over 300,000 households in each wave and assessed each household member's demographic, socioeconomic, and health status.

[11]We link CSLC to Census using information on the birth year, month, and gender of the (1) household heads, (2) the spouse of the household heads (if any), (3) the oldest child of the household heads (if any), and (4) the oldest parents of the household heads (if any), as well as (5) household residency.

[12]Ideally, radiation fear should be directly assessed at an individual level. However, we were unable to do so because our data lacked essential information.

by the Fukushima accident. By excluding Fukushima-specific searches, we minimized confounding effects from localized accident-related search activity, thereby obtaining a cleaner measure of general radiation concern. Post-accident increases in search activity served as indicators of heightened public anxiety about nuclear safety. We aggregated these measurements into a Search Popularity Index (SPI) for each prefecture p:

$$\text{SPI}_{tp} = \sum_{i=1}^{15} \frac{\text{NNP}_{itp}}{\text{UNIQLO}_{tp}} \tag{1}$$

where i denotes individual NPPs, and t distinguishes between pre-accident ($t = 0$) and post-accident ($t = 1$) periods. The indices were normalized to ensure comparability across time periods.

3.4 Control Variables

Our analysis incorporated an extensive set of background characteristics to account for potential confounding factors. Parental variables included age at conception and educational attainment (less than high school, vocational school, or university and above). Socioeconomic controls encompassed fathers' occupational categories (professionals, clerks, service industry workers, agricultural workers, craft workers, and those not working)[13] and household annual income quartiles (measured in million JPY).

We also controlled for earthquake-related factors by including seismic intensity (measured as the median intensity reported by each municipality during the earthquake, detailed in Appendix Figure A5) and dwelling characteristics. These included building type (house or apartment), floor level of residence (5th floor or lower, 6th-10th floor, or 11th floor and higher), and duration of residence (less than one year, one to five years, or more than five years). Additionally, we accounted for neonatal characteristics including gender and birth order (first, second, or third child).

4 SPI as a Measurement of Radiation Fear

To quantify public anxiety regarding radiation and nuclear power, we developed the SPI using Google Trends data. While the literature offers limited precedent for such an index, we conducted multiple analyses to validate SPI as a reliable measure of radiation fear.

[13]Given that expectant mothers in Japan are highly likely to leave the labor market, their occupation is not considered informative for the study and is therefore omitted from the analysis.

4.1 Geographic Patterns in Radiation Fear

Figure 3 demonstrates the relationship between SPI values and distance from the Fukushima Nuclear Power Plant (NPP). We visualize this relationship by prefecture, using a color-coding scheme to represent NPP operational status after the accident: blue indicates prefectures without NPPs, orange denotes those with operating NPPs, and green shows those with non-operating NPPs. Pre-accident SPI values, shown in gray, establish a baseline for comparison. The data reveals several key patterns. First, we observe a negative correlation ($\rho = -0.265$) between distance from Fukushima and post-accident SPI values, indicating that closer proximity to Fukushima corresponds with heightened anxiety about radiation and nuclear power. Second, prefectures hosting NPPs consistently show elevated SPI values compared to those without, regardless of operational status, suggesting increased sensitivity to radiation-related concerns in areas with nuclear facilities. Third, pre-accident SPI values remain minimal across all prefectures, demonstrating negligible public interest in NPPs before the Fukushima accident. This stark contrast with post-accident values underscores the dramatic surge in public concern about nuclear safety following the incident. Panel B of Figure 2 provides additional geographic detail, mapping the magnitude of SPI changes before and after the Fukushima accident.

4.2 Regression Analysis of SPI Determinants

To systematically analyze the factors influencing changes in SPI, we developed the following regression model:

$$\begin{aligned} \text{SPI}_{tp} = \alpha &+ \beta_1 \text{Post}_t + \beta_2 \text{Distance}_p + \beta_3 \text{Distance}_p^2 + \beta_4 \text{NPP}_p \\ &+ \beta_5 (\text{Post}_t \times \text{Distance}_p) + \beta_6 (\text{Post}_t \times \text{Distance}_p^2) \\ &+ \beta_7 (\text{Post}_t \times \text{NPP}_p) + \gamma_p + \varepsilon tp \end{aligned} \tag{2}$$

In this model, SPI_{tp} represents the SPI value for prefecture p at time t. The indicator variable Post_t captures the post-accident period, controlling for overall SPI trends. We include Distance_p as a quadratic polynomial measuring distance from the Fukushima NPP, allowing for nonlinear relationships with radiation anxiety. The presence of NPPs in a prefecture is indicated by NPP_p. To capture how these factors' influences changed after the accident, we incorporate interaction terms between the post-accident period and both distance and NPP presence. Prefecture fixed effects γ_p control for unobserved prefecture-specific characteristics, ensuring our model isolates accident-related

SPI variations.

Figure 4 presents the results from Equation (2), illustrating how SPI changes after the accident varied by distance from Fukushima and NPP presence. All estimates across both panels show statistical significance and positive values, demonstrating that radiation concerns increased throughout Japan. This widespread effect highlights the Fukushima accident's profound impact on public perception and reveals extensive radiation fears, even in areas facing minimal direct risk.

The left panel reveals a clear spatial pattern: SPI values increase as distance from Fukushima decreases, indicating more intense radiation concerns in areas closer to the accident site. The right panel demonstrates consistently higher SPI values in prefectures with NPPs compared to those without, suggesting that the presence of nuclear facilities amplified local anxiety about radiation risks. Together, these findings document the pervasive nature of radiation fear following the Fukushima accident, with particularly pronounced effects in areas near either Fukushima or existing nuclear facilities.

5 Empirical Strategy

To examine how prenatal radiation fear affects health outcomes at birth and beyond, we employ a simplified model:

$$y_i = \theta \text{Accident}_i + \mathbf{x}_i' \boldsymbol{\tau} + u_i, \tag{3}$$

where y_i represents the health outcome for parent-newborn pair i, Accident_i indicates exposure to prenatal radiation fear from the Fukushima accident, $\mathbf{x}_i$ comprises observable determinants of y_i, and u_i denotes the error term. Identifying θ requires addressing both non-random exposure assignment and potential correlation between u_i and radiation fear. Following prior studies (Currie et al., 2020; Persson and Rossin-Slater, 2018), we approximate a randomized design by constructing comparison groups, comparing outcomes between newborns exposed to radiation fear prenatally versus postnatally, as well as against a cohort exposed to a hypothetical accident.

5.1 Cohort Construction and Sample Definition

Our analysis focuses on two distinct samples (see Figure **??**):

$$S_1 = \{i : 1[c \leq \text{Accident} < e_d]_i = 1 \mid 1[e_d \leq \text{Accident} \leq e_d + 280]_i = 1\}, \tag{4}$$

$$S_2 = \{i : 1[c \leq \text{Accident} < e_d]_i = 1 \mid 1[c \leq \text{Placebo} < e_d]_i = 1\}, \tag{5}$$

where c denotes conception date (calculated as birth date minus gestational age in days), and e_d represents expected due date (defined as $c + 280$ days or 40 weeks).[14] Within these samples, $1[c \leq \text{Accident} < e_d]_i = 1$ identifies the prenatal cohort whose pregnancies coincided with the Fukushima accident. $1[e_d \leq \text{Accident} \leq e_d + 280]_i = 1$ denotes the postnatal cohort comprising newborns whose expected due dates fell within 280 days before the accident. $1[c \leq \text{Placebo} < e_d]_i = 1$ identifies the placebo cohort, which matches the prenatal cohort's pregnancy timeline but uses a hypothetical accident date. The postnatal cohort, with due dates preceding the Fukushima accident, naturally avoids prenatal stress effects and serves as our primary comparison group. The placebo cohort provides an additional comparison that controls for potential seasonal influences on health outcomes.

5.2 The Baseline Estimation

For each newborn $i \in S_{j=1,2}$ born in municipality m and conceived in month c, we estimate:

$$y_{imc} = \alpha_0 + \alpha_1 1[c \leq \text{Accident} < e_d]_{imc} + \lambda_m + \lambda_c + \mathbf{x}_i'\boldsymbol{\tau} + \epsilon_{imc}, \tag{6}$$

where the indicator variable $1[c \leq \text{Accident} < e_d]imc$ equals one for the prenatal group and zero otherwise, allowing α_1 to capture prenatal radiation fear's impact on fetal health. We include municipality fixed effects (λ_m) and conception-month fixed effects (λ_c) to account for geographical and seasonal variations in health outcomes (Buckles and Hungerman, 2013).[15] The vector $\mathbf{x}_i$ encompasses previously defined covariates. We cluster robust standard errors by parents' municipality of residence and newborns' conception month.

To understand how exposure timing affects outcomes, we replace the prenatal indicator in Equation (6) with trimester-specific indicators. This modification helps determine whether exposure during

[14] We did not use the actual birth dates because these are endogenous. Torche (2011) shows that maternal stress may reduce gestational age and increase the likelihood of stillbirth, which may induce sample selection.

[15] Due to small sample sizes, we use prefecture fixed effects instead of municipality fixed effects when estimating health effects at ages two, five, and eight.

specific trimesters differentially affects health outcomes. We also explore socioeconomic variations by interacting the prenatal indicator with maternal education and household income quartile, as parental resources may influence their ability to mitigate maternal stress effects.

5.3 Fear Level Analysis

To investigate potential 'dose-response' relationships between radiation fear intensity and health outcomes, we estimate:

$$\begin{aligned} y_{imc} = \beta_0 + \beta_1 1[c \leq \text{Accident} < e_d]_{imc} \\ + \beta_2 (1[c \leq \text{Accident} < e_d]_{imc} \times \text{SPI}_{pt}) + \lambda_m + \lambda_c + \mathbf{x}_i' \boldsymbol{\tau} + \epsilon_{imc}. \end{aligned} \tag{7}$$

The interaction between the prenatal indicator and Search Pattern Index (SPI) examines whether higher levels of radiation fear, measured through search activity intensity, amplify health effects. A significant β_2 would indicate that increased public anxiety about radiation exacerbates the negative health effects of prenatal stress. All other variables retain their previous definitions.

5.4 Within-Parent Analysis

To enhance our estimation's robustness, we conduct a within-parent analysis using a difference-in-differences approach. This analysis examines higher-parity newborns and their immediate older siblings, identified through vital statistics records. By constructing a panel dataset of households with multiple children, we compare health differences between the prenatal-postnatal and prenatal-placebo cohorts against those of their older siblings. This approach effectively controls for unobserved fixed parental characteristics that might confound prenatal stress effects. We estimate:

$$\begin{aligned} y_{imc} = \gamma_0 + \gamma_1 1[c \leq \text{Accident} < e_d]_{imc} \\ + \gamma_2 (1[c \leq \text{Accident} < e_d]_{imc} \times \text{Sibling}_{imc}) + \lambda_h + \lambda_m + \lambda_c + \mathbf{z}_i' \boldsymbol{\tau} + \epsilon_{imc}, \end{aligned} \tag{8}$$

where Sibling_{imc} indicates focal newborns (value of one) versus their older siblings (value of zero). The term λ_h represents parental fixed effects, and $\mathbf{z}_i$ includes sibling-varying covariates such as gender, birth order, and household head occupation from birth records. The interaction between prenatal and sibling indicators reveals whether prenatal stress effects persist after accounting for fixed parental characteristics.

5.5 Validity Tests

Our identification strategy rests on the assumption that the Fukushima accident's timing was exogenous to newborns in our sample. While we cannot directly test this assumption, the accident's nature as an unforeseen consequence of an unexpected earthquake supports its plausibility.

Figure 5 here

We conducted several analyses to validate this assumption. First, we examined potential selection bias by analyzing differences in abortion, miscarriage, and stillbirth rates due to prenatal radiation fear. Universal stillbirth records showed no significant intergroup differences in abortion rates (detailed in Appendix Table D1), and we found no differences in stillbirth rates or sex ratios at birth, suggesting minimal selection issues. Second, we investigated potential confounding factors, such as the government's post-accident energy-saving demands. By estimating Equation (6) separately for regions subject to these demands and those exempt, we found no meaningful differences in effect magnitude (reported in Appendix Table D2), supporting our model's robustness against such confounding events. Finally, we conducted an event study analyzing periodic trends by replacing the prenatal indicator in Equation (6) with an indicator for the number of months between conception and the accident. As illustrated in Figure 5, this analysis revealed no significant periodic variations in birth weight for the postnatal group conceived 11-18 months before the accident. These tests collectively support both the exogeneity of the accident's timing and our model's reliability in estimating prenatal radiation fear impacts.

6 Results

6.1 Summary Statistics

Table 1 presents summary statistics for the prenatal, postnatal, and placebo cohorts in columns (1)–(3), with intergroup comparison t-tests reported in columns (4)–(5).

Table 1 here

The analysis reveals two key findings. First, Panel A documents significantly adverse birth outcomes in the prenatal cohort. Preterm births occurred at a higher rate of 4.5% compared to 4.1% and 4.2% in the postnatal and placebo cohorts, respectively. Similarly, the average birth weight in the prenatal

cohort was significantly lower at 3024 grams, compared to 3036 grams in the postnatal cohort and 3032 grams in the placebo cohort. Second, Panel B demonstrates a stark difference in radiation fear as measured by the SPI. The prenatal cohort's SPI of 0.679 was approximately 62 times higher than the postnatal (0.011) and placebo (0.010) cohorts, indicating a dramatic surge in radiation-related concerns following the accident.

The remaining panels reveal more modest intergroup variations. Panels C through E examine newborn, parental, and residential characteristics, respectively. While the proportion of male newborns remains consistent across groups, we observe some demographic differences in birth order and parental characteristics. Parental age and education levels show minor variations, as do occupational patterns and household income distributions. These differences, while statistically detectable, do not suggest fundamental socioeconomic disparities between cohorts. Similarly, residential patterns show moderate variations, with the prenatal cohort reporting somewhat shorter residency durations. However, these differences do not indicate substantial disparities in living conditions or residential stability across the cohorts.

Table 2 presents a longitudinal analysis of health outcomes at ages two, five, and eight across the prenatal, postnatal, and placebo cohorts. The results reveal a dynamic pattern of health differences that evolves over time.

Table 2 here

At age two, the prenatal cohort exhibits notably poorer health outcomes, with 25.7% reporting health complaints compared to 22.5% and 22.6% in the postnatal and placebo cohorts, respectively. This cohort also required more frequent medical treatments, particularly for respiratory conditions. However, these health disparities show a marked shift by age five, with the prenatal cohort unexpectedly reporting fewer symptoms than both comparison groups and showing no significant differences in treatment frequency. This trend continues through age eight, where although all cohorts demonstrate lower frequencies of symptoms and treatments overall, the prenatal cohort maintains relatively fewer reported symptoms and lower treatment needs. This pattern suggests a possible compensatory health trajectory or adaptation effect as children age.

6.2 Prenatal Stress and Birth Outcomes

Table 3 presents the results from Equation (6), with Panel A comparing the prenatal cohort to the postnatal cohort and Panel B to the placebo cohort. Both comparisons reveal consistent adverse

effects on birth outcomes in the prenatal cohort.

Table 3 here

The prenatal cohort experienced a 16% increase in preterm births, representing increases of 0.67 and 0.68 percentage points compared to the postnatal and placebo cohorts, respectively. Birth weights decreased by 26 grams compared to the postnatal cohort and 22 grams compared to the placebo cohort, representing approximately a 1% reduction from mean birth weights. The analysis also reveals a gradient in low birth weight impacts: the prenatal cohort showed increases of 0.5, 0.2, and 0.1 percentage points in the rates of LBW, VLBW, and ELBW respectively compared to both comparison groups. These changes represent proportional increases of 7%, 48%, and 74% from the mean rates.

These findings align with existing literature on prenatal stress while revealing distinctive patterns. The observed birth weight reduction of 22–26 grams, though less severe than impacts documented following natural disasters or terrorist attacks (Camacho, 2008; De Oliveira et al., 2021; Torche, 2011), exceeds those associated with family disruptions (Black et al., 2016; Persson and Rossin-Slater, 2018). This intermediate effect magnitude may reflect the unique nature of radiation fear: while lacking the immediate shock of tangible disasters, it potentially generates persistent anxiety that chronically affects fetal development. Particularly noteworthy is the disproportionate impact on vulnerable newborns. The stark 74% increase in ELBW incidence, compared to the more modest 7% rise in LBW, suggests that prenatal radiation fear most severely affects already-vulnerable fetuses. Given that these infants face elevated risks of birth complications and long-term health challenges (Lawn et al., 2014; Werner, 1989), these findings point to potentially significant and lasting impacts on human capital development.

6.3 Health Impact by Fear Level

Table 4 presents estimates from Equation (7), examining how the intensity of radiation fear, measured by the SPI, modulates the impact of prenatal radiation exposure on birth outcomes. The analysis reveals two key findings.

Table 4 here

First, higher levels of radiation fear significantly amplify adverse birth outcomes. This dose-response relationship is consistent across both comparison groups—prenatal versus postnatal cohorts (Panel A) and prenatal versus placebo cohorts (Panel B). The magnitude of this effect is substantial: for

each unit increase in SPI, birth weight decreases by approximately 40 grams when compared to the postnatal cohort and 36 grams when compared to the placebo cohort. We observe similar intensifying patterns for other adverse outcomes, including higher rates of VLBW and ELBW, with the negative effects becoming more pronounced as fear levels rise.

Second, and notably, the prenatal indicator coefficients reveal significant adverse health impacts even in regions with minimal radiation fear. This finding has important implications for understanding the broader impact of nuclear accidents: it suggests that anxiety about radiation and nuclear power affected fetal health throughout Japan, not just in areas where fear was most intense. Even newborns in regions with relatively low SPI values showed worse outcomes compared to both comparison cohorts, indicating a widespread effect of the accident on public health.

6.4 Within-Parent Analysis

Table 5 examines the impact of prenatal radiation fear on birth outcomes using within-parent comparisons, contrasting affected newborns with their older siblings to control for fixed parental characteristics. Although this approach typically yields more conservative estimates than baseline comparisons (Currie and Schwandt, 2013), our analysis reveals persistent and significant effects of prenatal radiation fear.

Table 5 here

Panel A demonstrates several significant adverse outcomes. Preterm births increased by 0.25 percentage points, representing a 6% rise from the mean rate. Birth weight showed a decrease of 9 grams, and we observed a notable increase in the incidence of low birth weight (LBW). While the effects on very low birth weight (VLBW) and extremely low birth weight (ELBW) were not statistically significant, the overall pattern suggests meaningful impacts on fetal development.

Panel B corroborates these findings with similar patterns: birth weight decreased by 7 grams, and preterm births increased by 0.36 percentage points—equivalent to a 9% increase from the mean rate. The consistency of these results across both panels, even when controlling for parental fixed characteristics, reinforces our baseline estimates and underscores the substantial impact of prenatal radiation fear on fetal development.

6.5 Timing of the Exposure

Figure 6 illustrates how the impact of prenatal radiation fear on birth outcomes varies across pregnancy trimesters, comparing the prenatal cohort against both postnatal and placebo cohorts. The analysis reveals a clear pattern: adverse effects are most pronounced during the first trimester and progressively diminish in later stages of pregnancy.

Figure 6 here

The magnitude of these trimester-specific effects is substantial. First-trimester exposure to radiation fear results in birth weight reductions of 39 grams compared to the postnatal group and 32 grams relative to the placebo group. These effects attenuate significantly by the third trimester, where birth weight reductions measure only 7 to 9 grams. This temporal pattern aligns with Figure 4, which shows that women in their second to fourth months of pregnancy exhibited the strongest reactions to radiation fear, as evidenced by considerable declines in birth weight.

Our findings contribute to an ongoing debate in the literature about the timing of prenatal stress effects. While some studies document stronger effects in the first trimester (Camacho, 2008; Huizink et al., 2007; Quintana-Domeque and Ródenas-Serrano, 2017; Torche, 2011), others find more pronounced impacts in the third trimester (Currie et al., 2020; Henrichs et al., 2010), particularly in cases involving direct physical injury. Still others report relatively uniform effects across trimesters (Currie and Rossin-Slater, 2013; Persson and Rossin-Slater, 2018). Our results, showing the strongest effects in the first trimester, suggest a cumulative impact of prolonged stress exposure following the accident (Maeda et al., 2018). This pattern aligns with the "placental-clock hypothesis," which suggests that early prenatal stress can lead to shortened gestational periods and adverse birth outcomes (Torche, 2011). The consistent pattern we observe in both low birth weight and preterm birth rates across trimesters provides additional support for this hypothesis.

The minimal third-trimester impact has important implications for understanding the mechanisms at work. If nutritional factors, such as reduced food intake due to contamination concerns, were driving these outcomes, we would expect to see more pronounced effects during the third trimester when fetal growth is most rapid. The absence of such a pattern suggests that the observed birth outcome disparities primarily stem from maternal stress due to radiation fear rather than direct nutritional deficiencies.

6.6 Differential Impact by Parents' Socioeconomic Characteristics

Figure 7 reveals a clear educational gradient in how prenatal radiation fear affects birth outcomes. The analysis demonstrates that maternal education substantially moderates the severity of adverse birth outcomes, with less-educated mothers experiencing more pronounced effects.

Figure 7 here

The magnitude of these educational disparities is substantial. Newborns of mothers with only a high school education show the most severe impacts, experiencing birth weight reductions of 32–39 grams. In contrast, newborns of mothers with university degrees or higher education show more moderate effects, with birth weight decreases of only 10–14 grams. This educational gradient extends beyond birth weight, as high school-educated mothers also face elevated risks of low birth weight, very low birth weight, extremely low birth weight, and preterm births.

These findings suggest that maternal education serves as a crucial buffer against prenatal stress. The observed gradient likely reflects broader socioeconomic disparities that affect mothers' ability to manage environmental stressors effectively. Less-educated mothers may face multiple disadvantages: limited access to quality healthcare, reduced availability of nutritious food, and fewer resources for accessing and interpreting information about radiation risks (Nakayama et al., 2019). This interpretation aligns with established research demonstrating that socioeconomic status significantly influences offspring health outcomes by affecting mothers' capacity to protect their pregnancies from stress-related complications (Aizer et al., 2016).

Figure 8 documents how household income modulates the impact of prenatal radiation fear on birth outcomes, revealing a clear socioeconomic gradient in the severity of effects. The analysis demonstrates that lower-income households experience disproportionately adverse impacts.

Figure 8 here

The magnitude of these income-based disparities is striking. Households in the lowest income quartile (Q1) experience birth weight reductions of 33 to 36 grams, while those in the highest income quartile (Q4) show substantially smaller decreases of only 9 to 16 grams. This income gradient extends to other birth outcomes as well, with lower-income quartiles consistently showing more pronounced effects, particularly in preterm birth rates.

These findings suggest that financial resources serve as an important buffer against prenatal radiation stress. Higher household income likely facilitates better access to healthcare services and social

support systems, helping to mitigate the adverse effects of environmental stressors. This pattern aligns with existing literature on socioeconomic disparities in health outcomes, specifically supporting research by De Oliveira et al. (2021) that demonstrates how economic stability can protect against the negative impacts of prenatal stress.

6.7 Health at Age Two, Five, and Eight

Table 6 examines how prenatal radiation fear affects children's health outcomes across three developmental stages: ages two, five, and eight. The analysis focuses on two key metrics presented in Panels A and B: physical health complaints and medical treatment requirements.

Figure 6 here

In Panel A, the data reveals a dynamic pattern of health impacts across age groups. At age two, children with prenatal exposure to radiation fear showed significantly more physical complaints compared to both postnatal and placebo groups, with a 5.4 percentage point increase (representing a 24% rise from the mean). However, this pattern notably reversed by age five, when the prenatal cohort exhibited fewer complaints—specifically, a 5.4–6.1 percentage point decrease in overall physical complaints, equivalent to a 27% reduction from the mean. This decrease was particularly evident in respiratory and digestive complaints. By age eight, these differences had largely dissipated, with most results showing statistical insignificance.

Panel B provides an important complementary finding: despite the early variations in physical complaints, there was no corresponding increase in medical treatments as children aged. This suggests that the health impacts of prenatal stress were temporary rather than chronic in nature. These findings expand our understanding of how prenatal stress affects child development, complementing existing research that has documented significant impacts on mental health and cognitive development (Aizer et al., 2016; Huizink et al., 2007; Persson and Rossin-Slater, 2018). Our results indicate that while prenatal exposure to radiation fear can trigger immediate physical health manifestations in early childhood, these effects tend to diminish over time. This pattern may reflect the mitigating influence of enhanced parental care and intervention, underscoring the crucial role of early childhood care in addressing the health consequences of prenatal stress exposure.

6.8 Alternative Channels and Robustness Checks

We investigate potential mechanisms linking radiation fear to birth outcomes using data from the National Health and Nutrition Survey.[16] This analysis examines changes in expectant mothers' health behaviors, mental health, and nutritional intake following the accident.[17] The analysis reveals that maternal stress appears to be the primary mechanism through which radiation fear affected birth outcomes. As detailed in Appendix Table E1, expectant mothers showed no significant changes in key health behaviors—including smoking, alcohol consumption, sleep patterns, physical activity, and medication use—following the accident. However, they experienced a marginally significant increase in reported stress levels of 9.7 percentage points, equivalent to a 23% increase from the sample mean. Supporting these findings, Appendix Table E2 shows no significant changes in mothers' nutrient intake, including total energy, protein, fat, calcium, iron, and folic acid consumption. To validate these findings, we conducted several robustness checks. First, we re-evaluated the impacts using an extended dataset that employed monthly mean fallout rather than peak levels for calculating annual cumulative radiation. This approach, which included more data points, confirmed our initial findings (Appendix Figure F1 and Table F1). Second, we performed sensitivity tests using alternative fear levels based on wind direction search popularity. These tests revealed consistent impacts, indicating widespread national radiation fear that increased moderately with fear levels (Appendix Figures F2–F3 and Table F2).

7 Conclusion

Research examining the intergenerational health impacts of prenatal stress faces the challenge of disentangling stress effects from broader impacts of stressful events. This study leverages a unique stressor—subclinical radiation exposure from the Fukushima accident—to address this challenge. Unlike typical stressors, subclinical radiation exposure is intangible, uncertain, and ambiguous, affecting mothers regardless of direct exposure risk. This characteristic makes it particularly suitable for isolating maternal stress impacts, allowing us to investigate how prenatal radiation fear affects health outcomes from birth through age eight.

[16] The survey, conducted triennially, samples approximately 10,000 individuals per survey year and collects comprehensive data on health behaviors, dietary patterns, and biomarkers.

[17] Our analysis employs the 2007, 2010, 2013, and 2016 survey waves using a triple difference approach. We estimate: $Y_{iat} = \alpha + \beta_1 Preg_{iat} + \beta_2 HighFear_a + \beta_3 Post_t + \beta_4(Preg_{iat} \times HighFear_a) + \beta_5(Preg_{iat} \times Post_t) + \beta_6(HighFear_a \times Post_t) + \beta_7(Preg_{iat} \times HighFear_a \times Post_t) + \gamma X_{iat} + \epsilon_{iat}$ where i denotes individual women, a denotes area, and t denotes time. Y_{iat} represents the vector of outcome variables including health behaviors, mental health, and nutrient intake. $Preg_{iat}$ indicates pregnancy status, $HighFear_a$ indicates residence in a high-fear area, and $Post_t$ indicates post-accident survey years. X_{iat} represents individual characteristics. The coefficient β_7 captures outcome changes among pregnant women in high-fear areas after the accident.

Our methodology combined multiple innovative approaches. We constructed a comprehensive dataset linking Japanese universal birth records with census data, providing detailed information on birth outcomes, parental characteristics, and residential locations. The analysis compared three distinct cohorts: infants in utero during the accident (prenatal), those due shortly before (postnatal), and a placebo group simulating exposure to a hypothetical accident. To measure radiation fear, we developed an index based on Google Trends search popularity. Additionally, we employed within-mother analysis using a difference-in-differences approach to compare outcomes between focal cohort newborns and their older siblings.

Our findings reveal several key patterns in the relationship between prenatal radiation fear and health outcomes. First, radiation fear adversely affects birth outcomes, particularly reducing birth weight and increasing preterm birth risks, with the most significant effects at the lower end of the birth weight spectrum. This suggests disproportionate impacts on the most vulnerable newborns. These negative outcomes intensify in prefectures with heightened nuclear power plant-related search activity, indicating that intense local fear corresponds with more severe effects. However, even in areas with minimal search activity—prefectures remote from Fukushima or without nearby NPPs—newborns still show significant effects, demonstrating the pervasive nature of radiation fear across Japan. These results remain robust after accounting for fixed parental characteristics.

The timing of exposure proves crucial, with first-trimester exposure being particularly detrimental, identifying early pregnancy as a critical period for stress vulnerability. Socioeconomic status emerges as a key moderator—children from higher-income households and those born to more educated mothers exhibit less susceptibility to prenatal stress effects, highlighting how social and economic resources can buffer environmental stressors during pregnancy. While physical health impacts persist through age two, manifesting as increased physical complaints, these effects largely dissipate by age five, suggesting both the transient nature of maternal stress impacts on physical health and the potential mitigating role of parental care.

Several limitations warrant consideration in future research. First, our dataset lacks information on mental health and cognitive function, preventing comprehensive assessment of longer-term consequences. Additionally, we lack detailed data on abnormal conditions and labor complications, limiting our understanding of the broader spectrum of affected birth outcomes. Another gap is the absence of analysis on how radiation fear might influence prenatal healthcare behaviors, such as prenatal checkup patterns, and potential parental compensatory responses. Future studies incorporating neonatal and maternal medical records could address these limitations by enabling more detailed examination of healthcare utilization and maternal behaviors during pregnancy.

The findings yield important policy implications, particularly for risk communication and management during crises. They reveal that welfare costs associated with intangible risks like radiation fear may be substantially underestimated, extending beyond direct physical impacts to affect vulnerable populations intergenerationally. These insights have broader relevance to other health crises, such as the COVID-19 pandemic, where infection fears may similarly impact maternal and infant health. The results emphasize the importance of transparent, timely information sharing to prevent undue stress and misinformation, especially for expectant mothers. Furthermore, the heightened vulnerability of those with lower human capital suggests the need for targeted interventions, such as risk management education and mental health resources, to prevent the intergenerational transmission of disadvantages.

Our study demonstrates how prenatal radiation fear from the Fukushima incident affects both immediate birth outcomes and subsequent child health, revealing patterns of vulnerability and resilience across different socioeconomic groups. These findings contribute to our understanding of how maternal stress impacts future generations and inform policy approaches for managing societal risks, particularly during crisis situations.

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Table 1: Descriptive Statistics

	Prenatal N=340,019 (1)	Postnatal N=447,964 (2)	Placebo N=496,407 (3)	Diff. I (4)=(1)-(2)	Diff. II (5)=(1)-(3)
Panel A: Birth Outcomes					
Preterm (< 37 weeks)	0.045	0.041	0.042	0.005***	0.004***
Birth weight (g)	3024.36	3036.34	3032.30	-11.97***	-7.94***
	(413.36)	(402.72)	(412.45)		
LBW (<2,500g)	0.081	0.076	0.078	0.005***	0.004***
VLBW (<1500g)	0.005	0.004	0.004	0.001***	0.001***
ELBW (<1000g)	0.002	0.001	0.001	0.001***	0.001***
Panel B: Radiation Fear					
SPI	0.679	0.011	0.010	0.668***	0.669***
	(0.328)	(0.026)	(0.026)		
Panel C: Parent Characteristics					
Male newborn	0.512	0.512	0.513	0.000	-0.001
Order of birth:					
First	0.383	0.464	0.466	-0.081***	-0.083***
Second	0.447	0.388	0.386	0.060***	0.062***
Third	0.149	0.129	0.127	0.020***	0.022***
Fourth	0.021	0.020	0.021	0.001***	0.000***
Panel D: Parent Characteristics					
Mother's age at conception	31.168	30.800	30.726	0.368***	0.443***
	(4.364)	(4.665)	(4.738)		
Father's age at conception	33.050	32.722	32.459	0.328***	0.591***
	(5.201)	(5.449)	(5.517)		
Mother's education:					
High school	0.029	0.030	0.032	-0.001***	-0.003***
Vocational school	0.288	0.301	0.304	-0.013***	-0.016***
University and above	0.361	0.353	0.347	0.008***	0.013***
Father's education:					
High school	0.044	0.048	0.051	-0.004***	-0.007***
Vocational school	0.327	0.333	0.334	-0.006***	-0.007***
University and above	0.140	0.142	0.140	-0.001*	0.000
Father's occupation:					
Professional	0.191	0.187	0.183	0.004***	0.008***
Clerk	0.123	0.121	0.119	0.002**	0.005***
Service	0.248	0.250	0.249	-0.003**	-0.001**
Agriculture	0.015	0.014	0.014	0.001	0.001
Craft	0.351	0.350	0.349	0.001	0.002
Household Income:					
Q1	2.999	3.016	3.020	-0.016*	-0.021*
	(0.846)	(0.837)	(0.834)		

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Table 1 – continued from previous page

	Prenatal N=340,019 (1)	Postnatal N=447,964 (2)	Placebo N=496,407 (3)	Diff. I (4)=(1)-(2)	Diff. II (5)=(1)-(3)
Q2	4.597	4.583	4.578	0.015*	0.019*
	(0.358)	(0.357)	(0.357)		
Q3	6.115	6.062	6.046	0.053***	0.069***
	(0.521)	(0.522)	(0.521)		
Q4	8.894	8.894	8.893	0.000	0.002
	(1.814)	(1.848)	(1.868)		
Panel E: Residence Characteristics					
Residence type: House	0.430	0.429	0.435	0.000	-0.005
Floor of Residence:					
F1-F5	0.848	0.846	0.845	0.001*	0.002*
F6-F10	0.089	0.091	0.091	-0.002*	-0.002*
F11+	0.060	0.059	0.060	0.001	0.000
Residence period:					
Less than one year	0.219	0.208	0.189	0.011**	0.030**
One-five years	0.511	0.505	0.512	0.006*	-0.001*
More than five years	0.251	0.257	0.267	-0.006*	-0.016**
Seismic Intensity	2.504	2.499	2.502	0.005	0.002
	(1.686)	(1.693)	(1.694)		

Notes: Standard deviations are in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 2: Health at Ages Two, Five, and Eight

	Prenatal (1)	Postnatal (2)	Placebo (3)	Diff. I (4)=(1)-(2)	Diff. II (5)=(1)-(3)
Panel A: Age Two					
Any complaint	0.257	0.225	0.226	0.032*	0.031*
Respiratory	0.179	0.167	0.167	0.012	0.012
Digestive	0.029	0.037	0.028	-0.009	0.000
Skin	0.056	0.060	0.051	-0.004	0.004
Any treatment	0.193	0.151	0.153	0.042**	0.040**
Respiratory	0.088	0.065	0.069	0.023*	0.020*
Digestive	0.003	0.004	0.003	-0.001	0.000
Skin	0.060	0.056	0.047	0.004	0.013
N	736	1,131	1,459		
Panel B: Age Five					
Any complaint	0.177	0.193	0.218	-0.016	-0.041**
Respiratory	0.116	0.129	0.134	-0.013	-0.018
Digestive	0.016	0.023	0.023	-0.007	-0.007
Skin	0.049	0.051	0.056	-0.003	-0.007
Any treatment	0.169	0.168	0.183	0.000	-0.015
Respiratory	0.073	0.081	0.084	-0.008	-0.011
Digestive	0.002	0.003	0.006	-0.001	-0.004
Skin	0.048	0.048	0.060	0.000	-0.012
N	1,317	975	486		
Panel C: Age Eight					
Any complaint	0.141	0.164	0.159	-0.023	-0.018
Respiratory	0.094	0.087	0.092	0.007	0.002
Digestive	0.008	0.023	0.012	-0.016*	-0.004
Skin	0.034	0.036	0.026	-0.001	0.008
Any treatment	0.164	0.192	0.187	-0.028	-0.023
Respiratory	0.069	0.077	0.095	-0.008	-0.025
Digestive	0.002	0.002	0.001	-0.001	0.001
Skin	0.051	0.043	0.043	0.008	0.007
N	1,082	813	391		

Notes: Statistical inference: * $p<0.1$, ** $p<0.05$, *** $p<0.01$

Table 3: Impacts of prenatal radiation fear on birth outcomes

	Preterm (1)	Birth Weight (2)	LBW (3)	VLBW (4)	ELBW (5)
A. Prenatal vs Postnatal					
	(0.0006)	(1.13)	(0.0007)	(0.0002)	(0.0001)
Prenatal	0.0067***	-26.27***	0.0055***	0.0019***	0.0010***
	(0.0006)	(1.13)	(0.0007)	(0.0002)	(0.0001)
Mean	0.0407	3036.34	0.0762	0.0039	0.0013
N	787,983	787,958	787,958	787,958	787,958
B. Prenatal vs Placebo					
Prenatal	0.0068***	-21.84***	0.0042***	0.0016***	0.0012***
	(0.0005)	(0.99)	(0.0007)	(0.0002)	(0.0001)
Mean	0.0415	3032.30	0.0779	0.0042	0.0012
N	836,434	836,398	836,398	836,398	836,398
% Change	16%	1%	7%	48%	74%

Notes: Each column in each panel represents a separate regression. "Prenatal" corresponds to the prenatal indicator $1[c \leq \text{Accident} < e_d]_i = 1$ in Equation (2). Panels A and B compare the prenatal cohort against the postnatal and placebo cohorts, respectively. All regressions controlled for municipality fixed effects, conception month fixed effects, mother's and father's age and education, father's occupation, household income, residential characteristics, and children's sex and order of birth. Standard errors are clustered by the parents' municipality of residence and the newborn's conception month. *** p<0.01, ** p<0.05, * p<0.1

Table 4: Impact on birth outcomes by level of radiation fear

	Preterm (1)	Birth Weight (2)	LBW (3)	VLBW (4)	ELBW (5)
A. Prenatal vs Postnatal					
Prenatal	0.0051***	-13.65***	0.0042**	0.0015***	0.0005
	(0.0016)	(3.26)	(0.0021)	(0.0005)	(0.0003)
Prenatal × SPI	0.0128	-40.31**	0.0111	0.0106***	0.0069***
	(0.0145)	(23.91)	(0.0191)	(0.0048)	(0.0029)
Mean	0.0407	3036.34	0.0762	0.0039	0.0013
N	787,983	787,958	787,958	787,958	787,958
B. Prenatal vs Placebo					
Prenatal	0.0073***	-12.91***	0.0044*	0.0013**	0.0005
	(0.0017)	(3.47)	(0.0023)	(0.0006)	(0.0003)
Prenatal × SPI	0.0142	-35.99	0.0086	0.0118***	0.0067***
	(0.0133)	(21.72)	(0.0176)	(0.0044)	(0.0027)
Mean	0.0415	3032.30	0.0779	0.0042	0.0012
N	836,434	836,398	836,398	836,398	836,398

Notes: "Prenatal × SPI" corresponds to the interaction term between prenatal indicator and SPI in Equation (3). Panels A and B compare the prenatal cohort against the postnatal and placebo cohorts, respectively. Standard errors are clustered by the parents' municipality of residence and the newborn's conception month. *** p<0.01, ** p<0.05, * p<0.1

Table 5: Impact on birth outcomes: within-parent estimates

	Preterm	Birth Weight	LBW	VLBW	ELBW
	(1)	(2)	(4)	(5)	(6)
A. Prenatal vs Postnatal					
Prenatal × Siblings	0.0025**	-9.33***	0.0048***	0.0007	0.0002
	(0.0012)	(2.00)	(0.0015)	(0.0004)	(0.0003)
Mean	0.0407	3036.96	0.0733	0.0042	0.0018
N	920,253	920,233	920,233	920,233	920,233
B. Prenatal vs Placebo					
Prenatal × Siblings	0.0036**	-9.20***	0.0060***	0.0009	0.0002
	(0.0016)	(2.61)	(0.0020)	(0.0006)	(0.0004)
Mean	0.0421	3034.72	0.0746	0.0046	0.0019
N	917,230	917,213	917,213	917,213	917,213

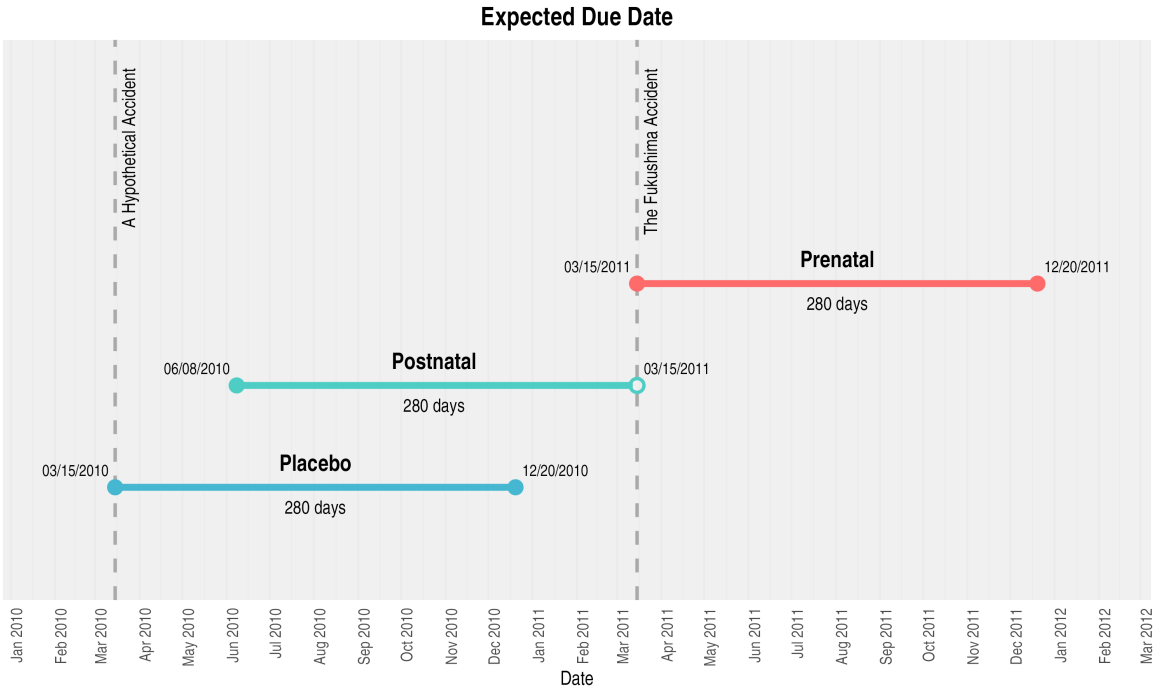
Notes: "Prenatal × Siblings" corresponds to the interaction term between prenatal indicator and SPI in Equation (3). Panels A and B compare the prenatal cohort against the postnatal and placebo cohorts, respectively. Standard errors are clustered by the parents' municipality of residence and the newborn's conception month. *** p<0.01, ** p<0.05, * p<0.1

Table 6: Impacts of prenatal radiation fear on health at age two, five, and eight

	Age 2				Age 5				Age 8			
	Any (1)	Resp. (2)	Dig. (3)	Skin (4)	Any (5)	Resp. (6)	Dig. (7)	Skin (8)	Any (9)	Resp. (10)	Dig. (11)	Skin (12)
Panel A: Complaints												
Pre vs Post	0.05**	0.04	0.00	-0.01	-0.05**	-0.04*	-0.02**	-0.01	-0.05	0.03	0.01	0.01
	(0.02)	(0.02)	(0.01)	(0.01)	(0.03)	(0.02)	(0.01)	(0.02)	(0.03)	(0.02)	(0.01)	(0.02)
Mean	0.23	0.17	0.04	0.06	0.19	0.13	0.02	0.05	0.16	0.09	0.02	0.04
Pre vs Plac	0.05***	0.03*	0.01	0.00	-0.06**	-0.03	-0.02*	-0.01	-0.06*	0.03	-0.02*	0.02
	(0.02)	(0.02)	(0.01)	(0.01)	(0.03)	(0.02)	(0.01)	(0.02)	(0.03)	(0.03)	(0.01)	(0.01)
Mean	0.23	0.17	0.03	0.05	0.22	0.13	0.02	0.06	0.19	0.08	0.00	0.04
Panel B: Medical Treatments												
Pre vs Post	0.02	0.02	0.00	-0.01	-0.01	-0.02	0.00	-0.01	-0.02	0.01	0.00	-0.01
	(0.02)	(0.02)	(0.00)	(0.02)	(0.02)	(0.02)	(0.00)	(0.02)	(0.03)	(0.02)	(0.00)	(0.02)
Mean	0.15	0.07	0.00	0.06	0.17	0.08	0.00	0.05	0.16	0.09	0.01	0.03
Pre vs Plac	0.03**	0.02	0.00	0.00	-0.03	-0.02	-0.01	-0.01	0.00	0.02	0.00	-0.01
	(0.02)	(0.01)	(0.00)	(0.01)	(0.03)	(0.02)	(0.00)	(0.02)	(0.03)	(0.02)	(0.00)	(0.02)
Mean	0.15	0.07	0.00	0.05	0.18	0.08	0.01	0.06	0.19	0.10	0.00	0.04

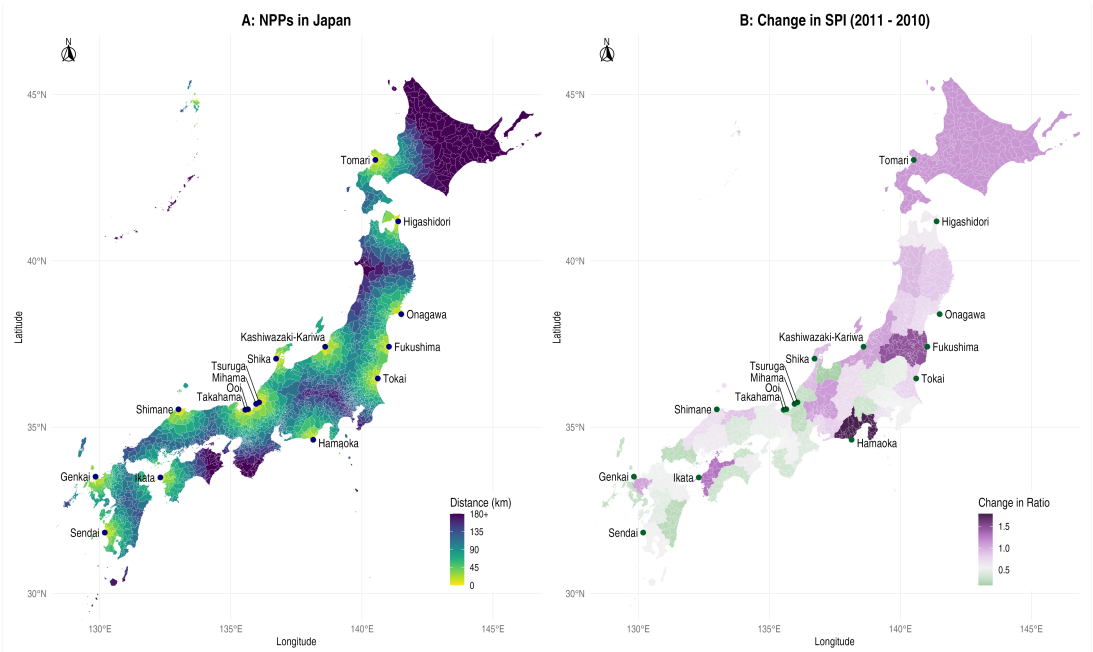
Notes: Each column in each panel represents a separate regression. Panels A and B present estimates on complaints and medical treatment received, respectively. "Pre vs Post" corresponds to the prenatal indicator in Equation (2) compare the prenatal cohort against the postnatal cohort. "Pre vs Plac" corresponds to the prenatal indicator in Equation (2) compare the prenatal cohort against the placebo cohort. All regressions controlled for municipality fixed effects, conception month fixed effects, mother's and father's age and education, father's occupation, residential characteristics, and children's sex and order of birth. All covariates were used when the children were two, five, and eight years old. Standard errors are clustered by the parents' municipality of residence and the newborn's conception month. *** p<0.01, ** p<0.05, * p<0.1

Figure 1: Expected due date and the prenatal, postnatal, and placebo cohorts



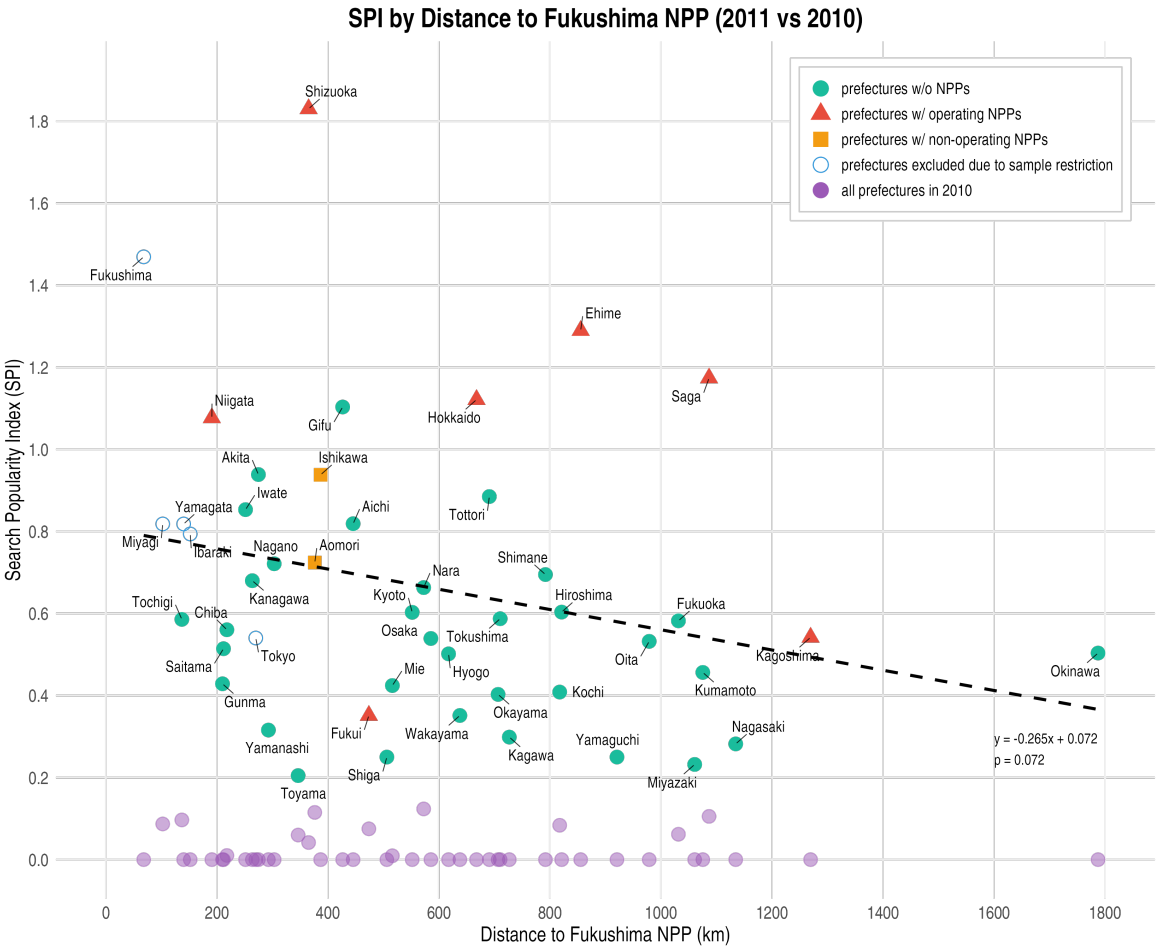
Notes: The figure illustrates the timeline used to define the prenatal, postnatal, and placebo cohorts with respect to the Fukushima accident and a hypothetical accident scenario. The date c represents the conception date, while e_d marks the expected due date. Timeframes shown in red indicate the period for the prenatal group, who were exposed to radiation fear during their gestation due to the Fukushima accident. Timeframes in blue highlight the comparison groups, including both the postnatal cohort and the placebo cohort.

Figure 2: Locations of NPP in Japan and changes in SPI post-Fukushima accident



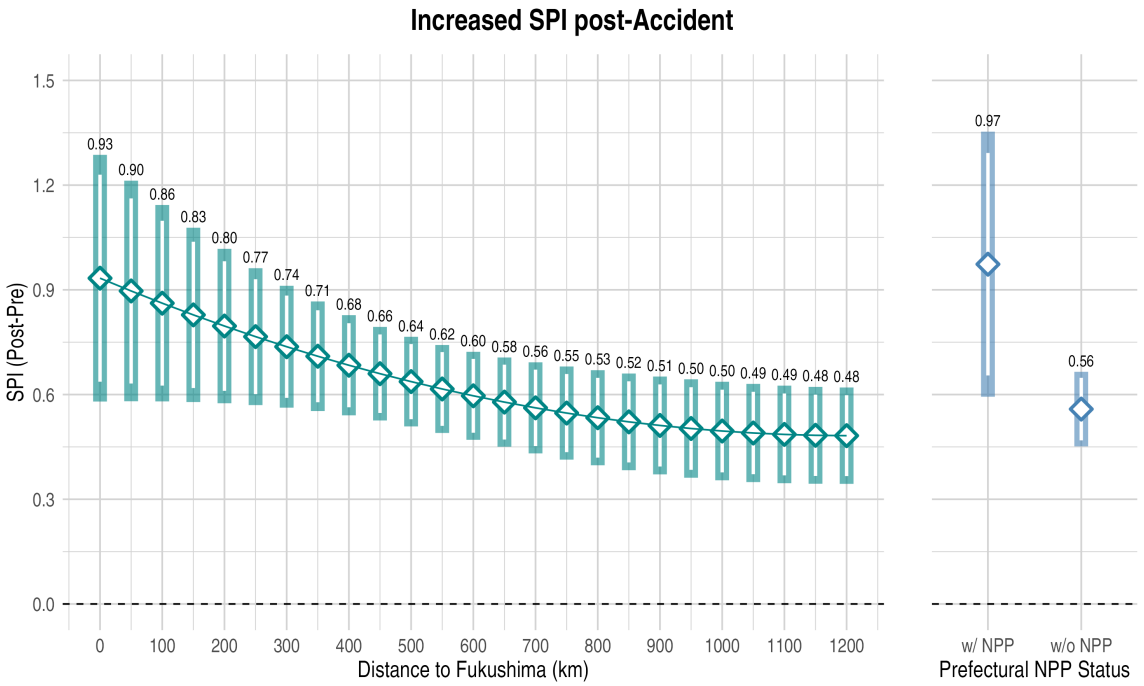
Notes: In Panel A, each circle represents the location of an NPP with its name labeled, such as Fukushima, Tokai, etc. The background gradient represents the distance in kilometers from each municipality to its nearest NPP. In Panel B, orange dots indicate NPPs included in the SPI calculation. The SPI, calculated from search terms related to each NPP relative to the baseline popularity of 'Uniqlo' within the same prefecture, excludes the Fukushima NPP to prevent confounding effects from direct impact-related searches. The color gradient transitions from purple to green, where purple shades indicate a greater increase in search activity, reflecting heightened public concern about radiation safety. Municipalities marked as "no data" were excluded from the analysis due to damage from the tsunami or having an annual radiation dose exceeding one millisievert. Further details about these municipalities are available in Appendix A.

Figure 3: SPI by distance from Fukushima and NPP status



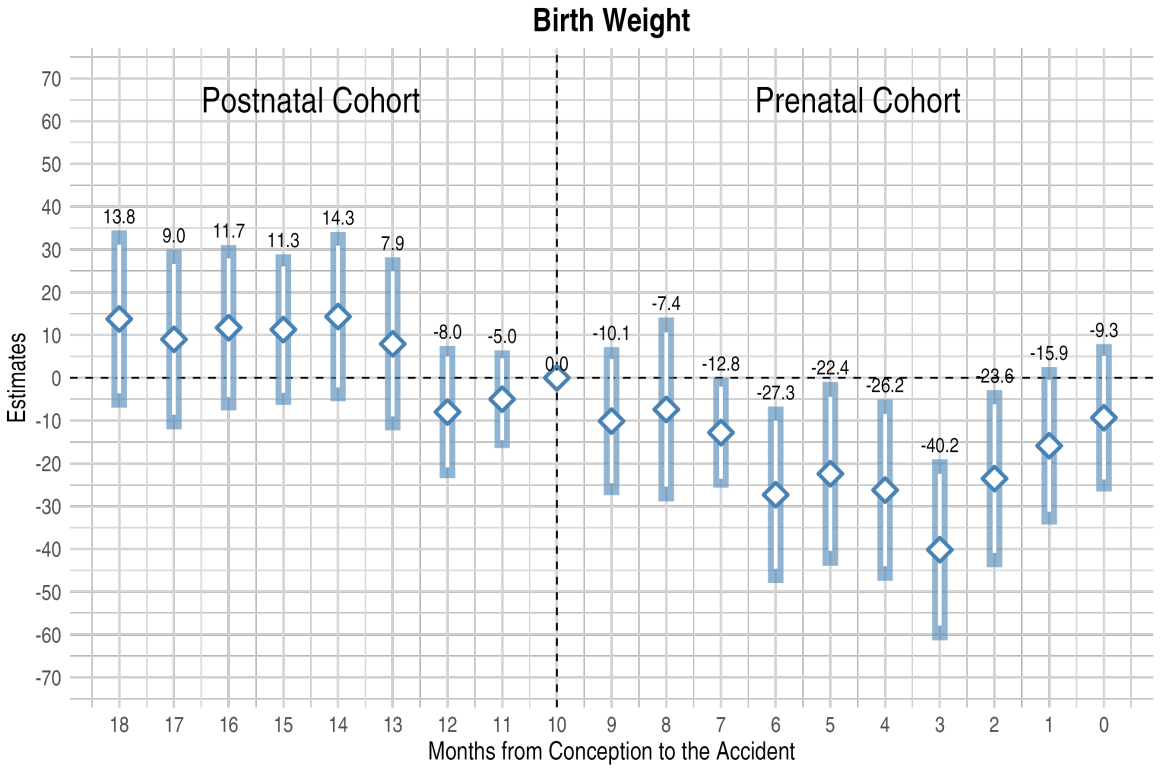
Notes: Each dot represents a prefecture, color-coded based on the operational status of NPPs within them: blue for prefectures without NPPs, orange for those with operating NPPs, and green for those with non-operating NPPs. Prefectures that were excluded from the analysis are shown in gray. The x-axis measures the distance from Fukushima NPP in kilometers, while the y-axis represents the SPI. A trend line, indicating a negative correlation ($\rho = -0.265$) between distance from Fukushima and SPI, suggests that closer proximity to Fukushima is associated with higher search popularity indices, reflecting greater public concern about radiation issues in these areas.

Figure 4: Increased SPI post-accident.



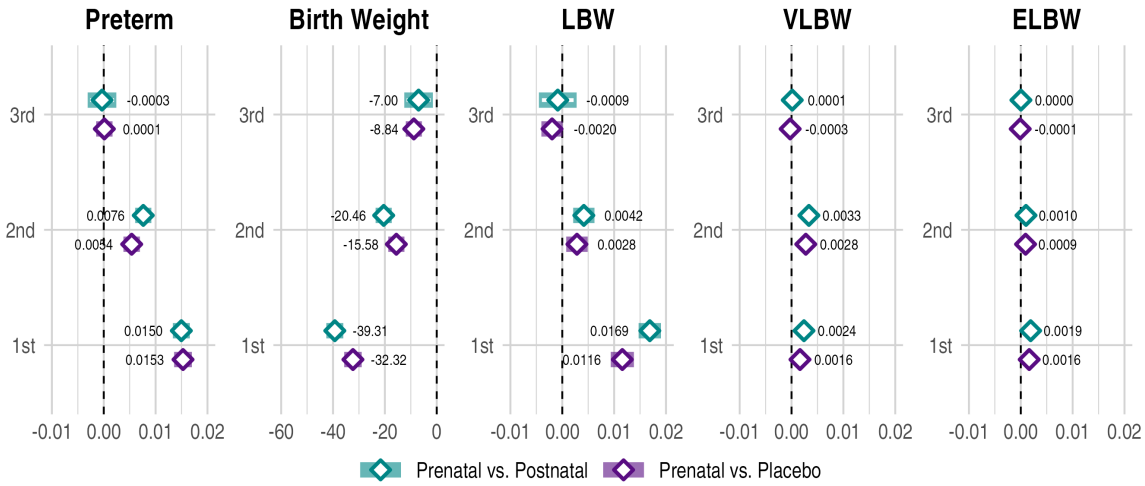
Notes: The figures plot the estimates with 95% confidence intervals from Equation (1), examining the post-accident changes in SPI based on distance from Fukushima NPP (left panel) and the presence of NPP by prefectural status (right panel

Figure 5: Event study on birth weight



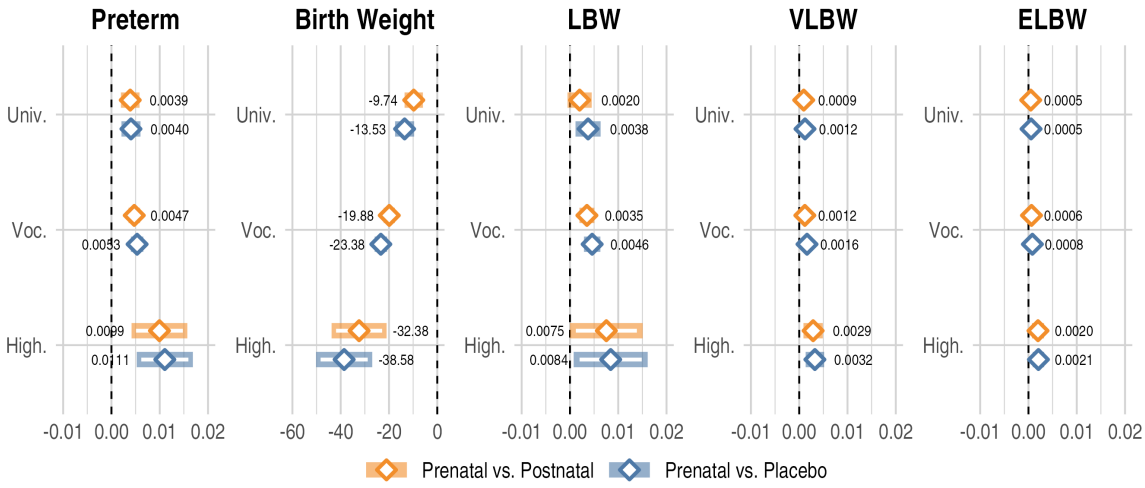
Notes: The figure shows the periodic trend in birth weights. It plots estimates with 95% confidences intervals derived from a regression where the prenatal indicator in equation (2) is replaced with an indicator of the number of months between conception and the accident, with 10-month serving as the reference. All regressions controlled for municipality fixed effects, conception month fixed effects, mother's and father's age and education, father's occupation, household income, residential characteristics, and children's sex and order of birth. Standard errors are clustered by the parents' municipality of residence and the newborns' conception month.

Figure 6: Trimester-specific impacts of prenatal radiation fear on birth outcomes



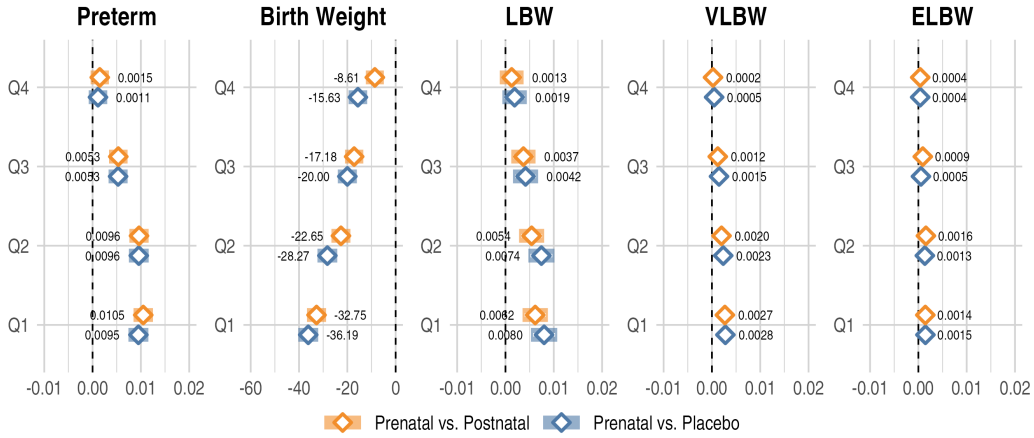
Notes: The figures display the estimates with 95% confidence intervals from a set of regressions where the prenatal indicator is replaced with specific indicators for exposure during the first, second, or third trimesters. Each graph corresponds to a distinct regression controlling for municipality fixed effects, parents' demographics (age and education), father's occupation, residential characteristics, and children's gender and birth order. Standard errors are clustered by the municipality of the parents and the conception month of the newborn. The trimesters are defined as follows: the first trimester within the first 91 days of conception; the second trimester between 92 and 182 days; and the third trimester from 183 days to the expected birth date. Each plot compares outcomes between cohorts exposed in different trimesters against the postnatal group, labeled as "1st Tri.", "2nd Tri.", and "3rd Tri." respectively.

Figure 7: Differential health impact of prenatal radiation fear by maternal educational level



Notes: The figures plot the estimates with 95% confidence intervals from a set of regressions where the prenatal indicator in equation (2) is interacted with mothers' education. Each figure represents a separate regression analysis. Each graph corresponds to a distinct regression controlling for municipality fixed effects, parents' age, father's occupation, household income, residential characteristics, and children's gender and birth order. Standard errors are clustered by the municipality of the parents and the conception month of the newborn. "H.S." for high school, "Voc." for vocational school, "Univ." for college or above.

Figure 8: Differential health impacts of prenatal radiation fear by household annual income



Notes: The figures plot the estimates with 95% confidence intervals from a set of regressions where the prenatal indicator in equation (2) is interacted with the quartile of household annual income. Each figure represents a separate regression analysis. Each graph corresponds to a distinct regression controlling for municipality fixed effects, parents' age and education, father's occupation, residential characteristics, and children's gender and birth order. Standard errors are clustered by the municipality of the parents and the conception month of the newborn. "Q1" for the lowest income quartile and "Q4" for the highest income quartile.