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Abstract

Identifying causal effects of prenatal psychological stress on birth outcomes is challenging because stressful events typically bundle psychological stress with material disruptions. The 2011 Fukushima nuclear accident provides a unique setting to overcome this challenge: while physical radiation exposure was geographically limited and well-documented, fear of radiation spread nationwide. We exploit this geographic separation to examine how maternal anxiety independently affects fetal development. Using universal Japanese birth records linked to census data, combined with a novel Google Trends-based measure of radiation-specific anxiety, we employ three complementary identification strategies: population-level comparisons of in-utero exposed versus unexposed cohorts, within-family sibling analysis controlling for time-invariant family characteristics, and dose-response estimation exploiting geographic variation in anxiety intensity. Prenatal exposure to the accident increased preterm births by 16% and reduced birth weights by 22-26 grams. Birth outcomes exhibit a clear dose-response relationship with anxiety intensity: each standard deviation increase in radiation-specific fear corresponds to 4-5 gram birth weight reductions and 7% increases in preterm births. Effects are concentrated among socioeconomically disadvantaged mothers and during first-trimester exposure. Our findings demonstrate that invisible threats generate measurable intergenerational health impacts through psychological stress pathways, with implications for disaster preparedness and risk communication during contemporary crises from pandemics to climate change.

Keywords: Prenatal Stress; Birth Outcomes; Nuclear Disasters; Google Trends; Fetal Origins

JEL Codes: Q54; J13; I14; I18

1. Introduction

How do invisible threats become biologically embedded in the next generation? A growing body of evidence suggests that prenatal stress during pregnancy can substantially affect birth outcomes (Almond & Currie, 2011; Currie, 2011; Dunkel Schetter, 2011). These effects at birth carry long-term consequences well established in the literature: health at birth predicts educational attainment in adolescence and income levels in adulthood (Almond & Currie, 2011; Black et al., 2007; Currie, 2011). Yet identifying the causal effects of psychological stress on fetal development remains challenging.

The identification challenge stems from the fact that stressful events typically involve both psychological impacts and material disruptions that directly affect maternal and fetal health. Traditional regression analyses struggle to distinguish whether birth outcome effects stem from maternal psychological stress or from the physical consequences of stressful events (Black et al., 2016). To address this problem, researchers have increasingly exploited natural disasters as sources of quasi-experimental variation (Currie & Rossin-Slater, 2013; Torche, 2011), but these studies face a persistent limitation: disasters typically bundle psychological trauma with physical damage and economic disruption in the same geographic areas, making it difficult to isolate the pure psychological stress mechanism.

The 2011 Fukushima nuclear accident provides a particularly well-suited natural experiment to address this identification challenge. The accident created a rare separation between physical and psychological impacts: while actual radiation exposure was geographically circumscribed and well-documented (Hasegawa et al., 2015; UNSCEAR, 2021), fear and anxiety about radiation spread nationwide through media coverage and social networks (Tateno & Yokoyama, 2013). This geographic divergence—physical damage concentrated in northeastern Japan but psychological impacts distributed across the entire country—enables us to isolate the effects of maternal anxiety from other disaster-related mechanisms that typically confound prenatal stress research.

The nationwide spread of radiation anxiety was amplified by the invisible nature of the threat itself. Unlike visible dangers that can be detected and avoided, subclinical radiation exposure cannot be sensed directly, its levels are difficult for individuals to assess, and its potential health consequences—especially for developing fetuses—remain uncertain and long-term (Goto et al., 2015; Normile, 2016). This invisibility and uncertainty made radiation anxiety particularly salient for pregnant women concerned about fetal vulnerability. Like other prenatal exposures that leave no visible external trace yet can significantly impact fetal development—such as maternal fasting during Ramadan (Almond & Mazumder, 2011), which operates through nutritional channels, or subclinical radiation exposure following Chernobyl (Almond, Edlund, & Palme, 2009)—radiation anxiety demonstrates how intangible stressors can produce tangible biological consequences, though in this case through purely psychological rather than physiological mechanisms.

To leverage Fukushima's unique geographic separation of physical and psychological impacts, we employ three complementary identification strategies to establish causality. First, we compare birth outcomes between pregnancies exposed to the accident in utero (with expected delivery dates after the accident) and pregnancies expected to deliver before the accident occurred. By excluding areas with direct tsunami damage or significant radiation exposure, we isolate psychological impacts from physical disaster effects. Second, we leverage within-family variation by comparing siblings born to the same parents where one was exposed in utero and the other was not. This design controls for all time-invariant maternal characteristics—including genetic predispositions, baseline health, socioeconomic status, and stress susceptibility—while accounting for natural birth-order effects (Currie & Schwandt, 2013). Third, we develop a novel measure of radiation anxiety using Google Trends data to test for dose-response relationships, examining whether birth outcomes deteriorate systematically with anxiety intensity across geographic areas.

This third strategy—our Google Trends-based search popularity index—addresses a critical limitation of standard disaster studies. While comparing exposed versus unexposed cohorts captures important effects, mothers experiencing any nuclear disaster timeline may be affected by multiple stress channels: radiation anxiety, aftershock fears, distressing media coverage, government mandates, and general crisis uncertainty (Currie & Rossin-Slater, 2013; He & Tanaka, 2023). Standard cohort comparisons cannot distinguish which stress mechanism drives observed effects.

The search popularity index provides more precise identification by directly capturing radiation-specific anxiety through prefecture-level search patterns for nuclear power plants. Building on established methods for using digital trace data to measure population-level health concerns (Eysenbach, 2009; Ayers et al., 2013; Bento et al., 2020), the approach offers four key advantages. First, it captures searches specifically related to nuclear power plants and radiation, rather than conflating multiple disaster-related stressors such as earthquakes, tsunamis, or economic disruption. Validation analyses (Table 1, Figure 1) confirm that the index correlates strongly with theoretically predicted risk factors—declining systematically with distance from Fukushima and elevated in prefectures with operating nuclear facilities—while exhibiting negligible pre-accident search activity. Second, it provides objective data free from recall bias (Nuti et al., 2014), recording information-seeking behavior as it occurs. Third, it varies continuously across geographic areas, enabling dose-response tests that binary exposure indicators cannot support (Bento et al., 2020). Fourth, it exhibits precise temporal patterns (Appendix Figure

B2), spiking immediately after the accident and gradually declining, validating its interpretation as event-driven anxiety.

Using these complementary identification strategies, our findings demonstrate that prenatal exposure to radiation anxiety significantly compromised birth outcomes, even in areas *without* direct physical impacts from the disaster. Population-level analyses show that accident exposure during pregnancy increased preterm birth by 16% and reduced birth weights by approximately 1% (22-26 grams). Within-family comparisons—which compare siblings born to the same mother—yield more conservative but still significant estimates: 6-9% increases in preterm births and 9-gram reductions in birth weight. Critically, these effects exhibit a clear dose-response relationship with our anxiety measure: each standard deviation (SD) increase in radiation-specific anxiety corresponds to 4–5-gram birth weight reductions and 7% increases in preterm birth rates. The severity gradient is particularly pronounced for the most vulnerable infants —low birth weight, very low birth weight, and extremely low birth weight categories show progressively larger proportional increases of 7%, 21-24%, and 31-50% respectively per SD of anxiety. The impacts are most pronounced during first-trimester exposure and show steep socioeconomic gradients, with substantially larger effects among mothers with less-education and lower household income.

This study advances the literature on fetal origins in three ways. First, we exploit the Fukushima setting's unique geographic separation of psychological from physical impacts to cleanly identify how maternal stress independently affects fetal development—a distinction rarely achievable in disaster research. Second, we introduce a scalable approach to measuring population-level stress using digital trace data, providing dose-sensitivity that standard binary exposure indicators cannot capture. Third, our multi-layered identification strategy—combining population comparisons, within-family variation, and dose-response analysis—provides robust causal evidence.

The heterogeneity analyses reveal systematic variation in stress responses across pregnancy stages and socioeconomic groups, with implications for understanding vulnerability mechanisms and targeting interventions during future crises involving invisible threats. Given that even modest birth weight reductions generate substantial lifetime economic costs through reduced earnings, increased healthcare utilization, and lower educational attainment (Almond et al., 2005), our findings suggest that psychological stress from invisible threats imposes significant welfare losses that extend well beyond immediate health impacts.

2. Background

2.1 Prenatal stress and birth outcomes

A substantial body of evidence demonstrates that prenatal stress can negatively impact birth outcomes and subsequent child development. Research has examined stress effects through various channels: pregnancy-specific anxiety, maternity blues, domestic violence, and stressful life events like unemployment or bereavement, as well as extrinsic stressors such as natural disasters and terrorist attacks (Black et al., 2016; Camacho, 2008; Currie et al., 2020; Currie & Rossin-Slater, 2013; Persson & Rossin-Slater, 2018; Quintana-Domeque & Ródenas-Serrano, 2017).

However, identifying the causal relationship between prenatal stress and birth outcomes presents significant challenges. A primary concern is endogeneity, which arises from multiple unobservable confounding factors correlated with prenatal stress. This issue is particularly pronounced when studying intrinsic stressors, as traditional regression analyses often fail to distinguish whether observed effects stem from the socioeconomic consequences of stressful events or from the stress itself (Black et al., 2016).

To address these challenges, researchers have increasingly turned to extrinsic stressors like natural disasters as sources of quasi-experimental variation (Almond & Mazumder, 2011; Currie & Rossin-Slater, 2013; de Oliveira et al., 2023; Torche, 2011). Yet these studies face their own limitations. Natural disasters and similar events typically cause acute, geographically concentrated damage, and affected mothers are often direct victims of both physical and economic impacts. This bundling of physical, economic, and psychological impacts in the same locations makes it difficult to isolate the pure effect of psychological stress from other consequences of the event.

2.2 The Fukushima setting

The Fukushima nuclear accident provides a unique opportunity to overcome this bundling problem. On March 11, 2011, a catastrophic 9.0-magnitude earthquake struck Japan, triggering a tsunami that led to the most severe nuclear accident since Chernobyl. The crisis culminated in three hydrogen explosions between March 12 and March 15,[5] releasing radioactive materials into the atmosphere. The incident's severity led to its classification as a level 7 event on the International Nuclear Event Scale, making it only the second accident after Chernobyl to receive this highest designation.[6]

Three key features of this setting enable us to isolate psychological stress from other disaster-related mechanisms. First, the physical impacts of radiation exposure were geographically limited. The atmospheric release was estimated at approximately 10% of that released during the

[5] We define the accident date as March 15, 2011, when the most severe explosion occurred, releasing the largest quantity of radioactive materials.
[6] Appendix C provides background on Japan's nuclear energy.

Chernobyl accident (Von Hippel, 2011), with the majority of radioactive material remaining contained within the reactor buildings' water systems. Government preventive measures, including food shipment suspensions and evacuation orders within a 20km radius, effectively limited direct exposure risks (Hasegawa et al., 2015). Research confirmed that internal radiation exposure in children was minimal within a year of the accident (World Health Organization, 2013). A decade later, the United Nations Scientific Committee on the Effects of Atomic Radiation concluded that no adverse health effects among Fukushima residents could be directly attributed to radiation exposure from the accident (UNSCEAR, 2021).[7]

Second, despite these limited physical risks, the accident generated widespread fear and anxiety throughout Japan, resulting in significant deterioration of mental well-being across the population (Rehdanz et al., 2015). This psychological impact stemmed largely from the government's delayed risk communication, which left citizens uncertain about appropriate preventive measures. The invisible nature of radiation exposure, combined with media misinformation and rumors escalated by internet circulation, amplified public anxiety and eroded trust in government statements (Tateno & Yokoyama, 2013).

Third, pregnant women and mothers of young children represent a particularly vulnerable group for studying these psychological effects. Studies indicate that 28% of pregnant women and young mothers exhibited depressive symptoms following the accident—significantly higher than the general population (Goto et al., 2015). This anxiety response was largely driven by the well-documented vulnerability of developing fetuses to radiation exposure. Mothers of young children

[7] The primary radioactive materials released were cesium-137 (half-life: 30 years) and iodine-131 (half-life: 8 days). Our radiation exposure calculations (Section 3.1) account for cesium-134 and cesium-137, which contaminate land for prolonged periods, but exclude iodine-131 due to its short half-life making it undetectable during most of our study period.

also experienced acute anxiety, resulting in an unusually high rate of thyroid cancer screening for children—a phenomenon termed the 'epidemic of fear' (Normile, 2016).

Together, these three features create a particularly suitable natural experiment for isolating psychological stress effects. The concentration of physical radiation exposure in northeastern Japan, combined with nationwide anxiety and heightened concern among pregnant women, allows us to identify how maternal stress during pregnancy affects birth outcomes by comparing regions with similar anxiety levels but different physical exposure risks.

3. Data and measurements

We constructed our dataset by linking universal Japanese birth records to national census data from 2010 and 2015. This linkage provides a rare combination of complete birth outcome data with detailed socioeconomic characteristics, typically unavailable in vital statistics. Japanese vital statistics are widely regarded as highly reliable, with near-complete birth registration and standardized measurement protocols for birth weight and gestational age across all medical facilities. We achieved linkage rates of 75% for births before 2010 and 60% for later births,[8] yielding a final sample of 1,163,475 singleton births from two-parent households.[9]

3.1 Sample restrictions

To isolate the effects of radiation fear from other disaster-related confounders, we excluded two geographic regions from our analysis. First, we excluded data from tsunami-affected regions

[8] The time range extends beyond December 2011 because the prenatal cohort (defined by expected due dates from March-December 2011; see Section 4) includes actual births recorded in 2015 that may occur after December 2011.

[9] Single-parent households comprised only 1.6% of Japan's 51 million households in the 2010 census (Statistics Bureau of Japan, https://www.stat.go.jp/data/kokusei/2010/kekka.html, accessed on February 5, 2023).

(Ishiwatari, 2011).[10] This exclusion was necessary because natural disasters can affect birth outcomes through channels other than psychological stress (Currie & Rossin-Slater, 2013; Torche, 2011), potentially confounding our estimates of radiation fear effects.

Second, to address potential direct radiation exposure effects on fetal development, we excluded regions where annual cumulative radiation exceeded 1.0 millisievert[11] between March 2011 and April 2012 (Appendix Figure A1). This threshold aligns with the International Commission on Radiological Protection's recommended maximum annual individual exposure, which the Japanese Ministry of the Environment adopted as a standard following the accident. To determine these regions, we analyzed monthly radioactive fallout data from the Japan Nuclear Regulation Authority,[12] combining the highest monthly doses of cesium-137 and cesium-134 to estimate annual exposure levels.[13] The geographic distribution of excluded areas is presented in Appendix Figures A2-A3.

These exclusions ensured that our analysis focuses on the psychological impact of radiation fear, rather than direct physical effects of the disaster. After implementing these restrictions, our final analytic sample contained 954,172 parent-newborn pairs.

3.2 Outcomes

We examined birth outcomes through two primary measures. The first was preterm birth, defined as delivery before 37 weeks of gestation. The second was birth weight, which we analyzed

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[10] We exclude 43 municipalities where tsunami-related deaths occurred.
[11] The International Commission on Radiological Protection recommends a maximum annual public exposure of 1.0 millisievert, which the Ministry of the Environment adopted as a standard following the accident.
[12] Monthly radioactive fallout data are available from the Japan Nuclear Regulation Authority: https://radioactivity.nsr.go.jp/ja/list/195/list-1.html (accessed on February 5, 2023).
[13] As noted in footnote 7, we exclude iodine-131 (8-day half-life) and include cesium-134 and cesium-137, which persist longer in the environment.

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 trajectories absent other complications (Euser et al., 2008), VLBW and ELBW births carry substantially higher risks of persistent cognitive and physical challenges (McCormick, 1985). These outcome measures are well-established indicators of fetal development that have been linked to long-term health and socioeconomic outcomes, making them relevant for assessing the impacts of radiation-related prenatal stress on fetal health.

3.3 Background characteristics

We controlled for various background characteristics of the parents and newborns, including parental ages at conception, parental education (less than high school, vocational school, university or above), fathers' occupations (professionals, clerks, service industry, agriculture industry, craft workers, and not working)[14], and quartile of household annual income (in million Japanese Yen). These socioeconomic measures are important because they may correlate with both exposure to radiation anxiety and birth outcomes, potentially confounding our estimates if omitted. We also controlled for covariates to address potential health impacts related to the earthquake and its aftershocks, incorporating seismic intensity (measured as the median reported by each municipality during the earthquake, see Appendix Figure A4) and dwelling characteristics such as the type of dwelling (house or apartment), the floor level (5th floor or lower, 6th-10th floor, 11th floor or higher), and the length of residence (less than one year, one to five years, more than five

[14] Maternal occupation is omitted because expectant mothers in Japan typically leave the labor market during pregnancy.

years). Neonatal characteristics, including gender and order of birth (first, second, third, or fourth), were also included.

3.4 A Dose-sensitive measure of radiation fear

A key innovation of our study is developing an objective, dose-sensitive measure of radiation-specific anxiety using Google Trends data. While the standard cohort comparisons (see Section 4) capture the overall impact of disaster exposure, they conflate multiple stress sources — radiation fear, aftershock anxiety, economic uncertainty, and media distress. Our search popularity index (*SPI*) isolates radiation-specific concerns, enabling dose-response analysis unavailable in standard disaster studies.

We constructed SPI using search queries for all Japanese nuclear power plants excluding Fukushima NPP (Appendix Figure B1). We excluded Fukushima NPP to prevent confounding from searches related to direct disaster impacts rather than general radiation anxiety. Using Google Trends data, we measured search popularity for each of the remaining 15 NPPs during the month following the accident (March 12–April 11, 2011) compared to the same period in 2010. Because Google Trends internally scales results making cross-query comparisons problematic, we employed a normalization procedure using "Uniqlo" as a reference keyword—selected for its national recognition and search stability unaffected by the accident. For each prefecture, we normalized each NPP's search popularity by dividing it by Uniqlo's popularity from the same query batch, then multiplying by Uniqlo's baseline popularity obtained from a single-keyword search. We then aggregated these normalized values across all 15 NPPs to create our prefecture-level index. The final index is defined as: $SPI_{pt} = \sum_{i=1}^{15} NPP_{ipt}$, where NPP_{ipt} represents the normalized search popularity of NPP_i, among the remaining 15 NPPs, in prefecture p at time period t. t distinguishes before the accident ($t = 0$) and after the accident ($t = 1$) periods. This normalization procedure ensures that search intensity can be meaningfully compared across prefectures and time periods, overcoming Google Trends' internal scaling limitations.

[Figure 1]

We validated *SPI*'s utility as a proxy for radiation-specific prenatal stress through multiple lines of evidence. First, spatial correlation analysis demonstrates that *SPI* values systematically varied with radiation risk factors. As shown in Figure 1, search intensity decreased with distance from Fukushima ($\rho = -0.265, p < 0.072$) and remained consistently higher in prefectures with operating NPPs (red triangles).[15] This geographic pattern aligns with expected radiation risk perception: concerns were heightened both near the accident site and in prefectures with operating nuclear facilities that could potentially face similar accidents. Furthermore, the search activity in 2010 (purple circles) hovered near zero across all prefectures, indicating that radiation-related searches were almost negligible before the accident. This contrasts markedly with the heightened values observed in 2011, confirming that the index captures anxiety specifically triggered by the Fukushima accident rather than pre-existing concerns.

[Table 1]

Second, examining prenatal care-seeking behaviors provides direct evidence connecting *SPI* to stress responses among pregnant women. To facilitate interpretation, we standardized *SPI* to have unit SD for all subsequent analyses. Table 1 shows that following the Fukushima accident, higher *SPI* values were significantly associated with increased telephone consultations for pregnancy-related issues and higher prepartum health checkup frequency. A one SD increase in *SPI* was associated with 16.05 additional pregnancy-related telephone consultations per 1,000

[15] Appendix Figure B2 shows search popularity increased post-accident across all distance ranges, with larger increases closer to Fukushima.

population—representing a 44.5% increase relative to pre-accident levels. Similarly, prepartum care visits showed an increase of 0.56 visits per SD rise in *SPI*, equivalent to a 51.4% increase over baseline. This pattern provides behavioral evidence that *SPI* captures radiation-related anxiety among pregnant women. The increase in telephone consultations suggests that anxious mothers sought medical reassurance about radiation risks. More importantly, the concentration of significant effects in prenatal services—rather than general healthcare utilization—indicates that *SPI* specifically captures concerns about radiation's impact on fetal development rather than general disaster-related stress. These behavioral responses support the validity of *SPI* as an indicator of radiation-specific prenatal anxiety.

4. Empirical strategy

Our empirical approach employs three complementary identification strategies that progressively address challenges in isolating the causal effects of radiation anxiety on birth outcomes. Each strategy builds on the previous one by relaxing different assumptions and exploiting distinct sources of variation, together providing robust causal evidence.

The baseline analysis (Section 4.2) exploits the quasi-random timing of the Fukushima accident to compare birth outcomes between pregnancies exposed in utero and those that delivered before the accident occurred. This approach establishes the overall effect of prenatal exposure but cannot distinguish radiation anxiety from other disaster-related stressors or control for unobserved family characteristics that may correlate with exposure timing.

The within-family analysis (Section 4.3) addresses confounding from time-invariant family characteristics by comparing siblings born to the same mother, where one was exposed in utero and the other was not. This eliminates selection on unobservables—including genetic predispositions, maternal baseline health, and stress susceptibility—while accounting for natural birth-order effects. However, this approach still cannot isolate radiation-specific anxiety from the bundle of disaster-related stressors.

The dose-response analysis (Section 4.4) overcomes both limitations by directly measuring radiation anxiety intensity using the *SPI*. By exploiting geographic variation in anxiety levels, we test whether birth outcomes deteriorate proportionally with radiation-specific fear, providing evidence for a psychological stress mechanism that cannot be explained by binary exposure timing alone. This approach represents a key methodological innovation: while standard disaster studies rely on binary exposed/unexposed comparisons, our continuous anxiety measure enables us to trace dose-response relationships and isolate radiation-specific effects from other stress channels.

4.1 Research design

The research design exploits variation in exposure timing to isolate radiation anxiety effects. Consider three types of pregnancies differentiated by when the accident occurred relative to their gestational timeline. First, a pregnancy conceived early enough that delivery is *expected* to occur before the accident (postnatal cohort) experiences no radiation anxiety during the prenatal period. Second, a pregnancy in which the accident occurs during gestation (prenatal cohort) experiences anxiety while the fetus develops. Third, a pregnancy from the *previous* year with the same seasonal timing as the prenatal cohort (placebo cohort) provides a control for seasonal birth patterns unrelated to the accident. Comparing these cohorts isolates the effect of radiation anxiety exposure during pregnancy.

We formalize these cohorts using conception dates and expected delivery dates. Let c_i denote the conception date of newborn i (calculated as i's birth date minus gestational age in days), let e_i represent i's expected due date (defined as $c_i + 280$ days or 40 weeks), and let A denote the accident date, March 15, 2011. We then define three distinct cohorts:

$$S_{PRE} = \{i: c_i \leq A < e_i\},$$

$$S_{POST} = \{i: e_i \leq A < e_i + 280\},$$

$$S_{PLACEBO} = \{i: c_i \leq P < e_i\},$$

where S_{PRE} represents the prenatal cohort (pregnancies exposed to the accident during gestation), S_{POST} represents the postnatal cohort (pregnancies with expected due dates before the accident), and $S_{PLACEBO}$ represents the placebo cohort with a hypothetical accident date P set to March 15, 2010, one year before the actual accident. To implement our identification strategy, we construct two complementary analytical samples by combining the prenatal cohort with different control groups:

$$S_1 = S_{PRE} \cup S_{POST},$$

$$S_2 = S_{PRE} \cup S_{PLACEBO},$$

Sample S_1 compares the prenatal cohort with the postnatal cohort. This provides our primary counterfactual: pregnancies with expected due dates before the accident that avoided radiation anxiety during the critical prenatal period (de Oliveira et al., 2023; Deschênes & Moretti, 2009). Sample S_2 compares the prenatal cohort with the placebo cohort. This addresses concerns about seasonal patterns in birth outcomes, ensuring that observed effects reflect the accident itself rather than time-of-year variations in birth outcomes.

4.2 The baseline analysis

Our baseline analysis quantifies the overall effect of prenatal exposure to the Fukushima accident on birth outcomes. For newborn $i \in S_j, j = \{1,2\}$ born in municipality $m(i)$ and conceived in month $c(i)$, we estimate:

$$y_i = \alpha_0 + \alpha_1 PRE_i + \lambda_{m(i)} + \lambda_{c(i)} + \boldsymbol{x}_i^\top \boldsymbol{\tau} + \epsilon_i, \quad (1)$$

separately for samples S_1 and S_2. The indicator PRE_i equals 1 for the prenatal cohort (from S_{PRE}) and 0 for either the postnatal cohort (from S_{POST} in S_1) or the placebo cohort (from $S_{PLACEBO}$ in S_2). Municipality fixed effects ($\lambda_{m(i)}$) and conception-month fixed effects ($\lambda_{c(i)}$) account for geographical and seasonal variations in health outcomes (Buckles & Hungerman, 2013), while vector $\boldsymbol{x}_i$ encompasses the background characteristics. Standard errors are clustered at the municipality of parents' residence and the newborn's conception month.

The coefficient α_1 captures the overall impact of experiencing the accident during pregnancy, operating through multiple stress channels including radiation anxiety, aftershock-related fear, and other psychological responses to the crisis. While this approach follows established methods in the disaster literature (Currie & Rossin-Slater, 2013; Torche, 2011), it has two key limitations. First, it cannot distinguish between different stress pathways—we observe the net effect of all disaster-related stressors combined. Second, it may be influenced by unobserved family characteristics correlated with accident exposure timing, such as maternal stress susceptibility or health-seeking behaviors. Despite these limitations, this analysis establishes whether the Fukushima accident affected birth outcomes overall and provides a benchmark for our subsequent analyses that address these concerns through within-family variation and direct measurement of radiation-specific anxiety.

4.3 Within-parent analysis

To address confounding from unobserved family-level characteristics, we conduct a within-parent analysis exploiting sibling comparisons. We construct sibling pairs using birth records from 2006-2012, requiring stable two-parent households and sibling spacing of 2-5 years. Specifically, we identify families with multiple children and link higher-parity newborns from the three cohorts (S_{PRE}, S_{POST}, $S_{PLACEBO}$) to their immediate older siblings born in or after 2006.[16] This spacing restriction balances two objectives: limiting time-varying confounders while maintaining adequate sample size.

We construct two types of sibling pairs. Treatment pairs consist of families where the younger sibling experienced the accident during pregnancy while the older sibling did not. Control pairs consist of families where neither sibling experienced the accident during pregnancy. The control pairs are essential because they allow us to account for natural birth-order differences that occur independent of accident exposure, ensuring that our estimates isolate accident effects rather than capturing typical differences between first and second children. This design controls for all time-invariant family characteristics—genetics, baseline maternal health, socioeconomic background, and stress susceptibility—through the following specification:

[16] The within-parent analysis uses birth records without linkage to census data due to technical constraints in constructing longitudinal family panels that incorporate census information. This means we cannot control for time-varying socioeconomic characteristics such as changes in parental education, occupation, or income between siblings' births. However, the parental fixed effects in equation (2) successfully control for all time-invariant characteristics—including baseline socioeconomic status, genetic factors, maternal health, and stress susceptibility—making this a conservative approach that addresses the primary concern of selection on unobservables. The sibling identification process involved multiple steps to ensure data quality. First, we created unique parent identifiers (PID) using parental birth information and municipality of residence, restricting the sample to families with stable two-parent households throughout the observation period. Second, we sorted children within families by birth date and verified that recorded birth order increased appropriately. Third, we confirmed proper sibling relationships by verifying that the interval between siblings' births exceeded the younger sibling's gestational period. Finally, we identified treatment families where a higher-parity child was in utero during the Fukushima accident (conception date to expected delivery date encompassing March 15, 2011) and their older sibling was not, alongside control families where neither sibling experienced in utero exposure.

$$y_i = \gamma_0 + \gamma_1 PRE_{h(i)} + \gamma_2 SBL_i + \gamma_3 \left(PRE_{h(i)} \times SBL_i\right) + \lambda_{h(i)} + \lambda_{m(i)} + \lambda_{c(i)} + \boldsymbol{z}_{\boldsymbol{i}}^{\top} \boldsymbol{\tau} + \epsilon_i, \quad (2)$$

where $PRE_{h(i)}$ equals 1 for treatment pair siblings and 0 for control pair siblings, and SBL_i equals 1 for focal newborns (younger siblings) and 0 for their older siblings. $\lambda_{h(i)}$ represents parental fixed effects, controlling for all time-invariant family characteristics. $\lambda_{m(i)}$ and $\lambda_{c(i)}$ are municipality and conception-month fixed effects as defined above. $\boldsymbol{z}_i$ includes sibling-varying covariates such as gender, birth order, and household head's occupation.

The coefficient γ_3 identifies whether accident exposure during pregnancy differentially affected the younger sibling beyond typical birth-order differences observed in control families. This within-parent approach provides a conservative estimate by comparing exposed and unexposed siblings from the same mother, effectively controlling for selection into high-risk pregnancies and systematic differences across families in vulnerability to stress.

4.4 Dose-response analysis

While the baseline analysis establishes overall effects and the within-family analysis controls for unobserved family heterogeneity, neither can distinguish radiation-specific anxiety from other disaster-related stressors such as aftershock fear, economic uncertainty, or general crisis distress. The dose-response analysis directly addresses this limitation by exploiting geographic variation in radiation anxiety intensity measured through our *SPI*.

Our *SPI* measure enables three key advances over standard disaster studies. First, it allows us to test for dose-response relationships—observing whether birth outcomes deteriorate proportionally with anxiety levels strengthens causal inference beyond binary comparisons.

Second, it identifies which populations experience the highest anxiety levels. Third, and most importantly, it isolates radiation-specific fear from bundled disaster stressors by directly measuring anxiety about nuclear power plants rather than general disaster exposure. We estimate:

$$y_i = \beta_0 + \beta_1 + \lambda_{m(i)} + \lambda_{c(i)} + \boldsymbol{x}_i^\top \boldsymbol{\tau} + \epsilon_i, \qquad (3)$$

separately for samples S_1 and S_2. $SPI_{p(i)t(i)}$ represents the standardized radiation anxiety level in prefecture $p(i)$, where $t(i) = 0$ for births before the accident and $t(i) = 1$ for births after the accident. This specification directly estimates how radiation anxiety intensity affects birth outcomes across the full spectrum of fear levels observed.

A significant β_1 indicates that a one SD increase in *SPI*—reflecting greater radiation-specific anxiety—leads to proportionally stronger effects on birth outcomes. This approach offers three advantages. First, we trace the relationship across the distribution of anxiety levels, exploiting continuous variation in stress intensity rather than simple exposed versus unexposed comparisons. Second, we leverage systematic geographic variation in radiation anxiety based on distance from Fukushima and presence of local nuclear facilities, providing theoretically grounded treatment intensity variation. Third, our approach provides built-in validation: if psychological stress drives our effects, we should observe stronger impacts in areas where our anxiety measure is higher—a pattern that alternative explanations would struggle to reproduce.

4.5 Heterogeneity analyses

Understanding who is most vulnerable to radiation anxiety has direct implications for targeting interventions during future crises involving invisible threats. We examine heterogeneity along three dimensions using the *SPI* measure. First, we identify critical windows of vulnerability during pregnancy by estimating trimester-specific effects:

$$y_i = \theta_0 + \sum_{r=1}^{3} \theta_r \, SPI_{p(i)t(i)} \times \mathbb{1}(trim_i = r) + \lambda_{m(i)} + \lambda_{c(i)} + \boldsymbol{x}_i^\top \boldsymbol{\tau} + \epsilon_i, \tag{4}$$

where $\mathbb{1}(trim_i = r)$ indicates the trimester when the accident occurred ($r = 1,2,3$ for first, second, and third trimester exposure, with unexposed pregnancies as the reference category). This examines whether certain stages of fetal development are more vulnerable to maternal stress. Second, we examine socioeconomic gradients by estimating effects separately for maternal education and household income groups:

$$y_i = \delta_0 + \sum_{e \in E} \delta_e \, SPI_{p(i)t(i)} \times \mathbb{1}(edu_i = e) + \lambda_{m(i)} + \lambda_{c(i)} + \boldsymbol{x}_i^\top \boldsymbol{\tau} + \epsilon_i, \tag{5}$$

$$y_i = \rho_0 + \sum_{q \in Q} \rho_q \, SPI_{p(i)t(i)} \times \mathbb{1}(inc_i = q) + \lambda_{m(i)} + \lambda_{c(i)} + \boldsymbol{x}_i^\top \boldsymbol{\tau} + \epsilon_i, \tag{6}$$

where $E = \{HS, JC, Univ\}$ represents maternal education levels (high school, junior college, university) and $Q = \{Q1, Q2, Q3, Q4\}$ represents household income quartiles. These analyses test whether socioeconomic resources buffer against prenatal stress effects.

4.6 Threats to identification and validation tests

Our identification faces three potential threats, which we address systematically through multiple tests.

Selection into pregnancy timing. If couples strategically timed pregnancies based on anticipated disaster risk, accident exposure would not be quasi-random. We test for selection by examining: (a) sex ratios at birth, which would be affected by sex-selective abortion; (b) abortion and stillbirth rates, which would increase if women terminated high-risk pregnancies; and (c) pre-trends in birth outcomes. Appendix Table D1 shows no evidence of selection on these observables.

Analysis of universal stillbirth records reveals no significant differences in abortion rates, stillbirth rates, or sex ratios between exposed and unexposed groups, supporting the quasi-random timing assumption.

[Figure 2]

Additionally, we conduct an event study to test for parallel trends by replacing the prenatal indicator in equation (1) with indicators for months between conception and the accident. Figure 2 shows no significant pre-accident variations in birth weight for the postnatal cohort, while displaying a clear pattern of negative effects for the prenatal cohort with stronger effects at earlier pregnancy stages. The absence of pre-trends for the postnatal cohort and the systematic deterioration only after accident exposure strongly support the parallel trends assumption.

Confounding events. Post-accident government policies such as energy-saving mandates might independently affect birth outcomes, confounding our estimates. We address this concern by comparing regions subjected to mandatory energy-saving requests with regions without such policies (Appendix Table D2). Both region types show statistically significant adverse effects of comparable magnitude across all outcomes. This pattern suggests that our estimates capture psychological stress effects—which were present nationwide—rather than material deprivation or policy-induced behavioral changes that were geographically limited.

SPI measurement validity. Our dose-response analysis relies on *SPI* capturing radiation-specific anxiety rather than general crisis concerns. As detailed in Section 3.4, we validated this through three approaches: spatial correlation with radiation risk factors, temporal alignment with the accident timeline, and behavioral responses in prenatal care utilization. These multiple validation approaches confirm that SPI isolates radiation-specific fear rather than bundled disaster stressors.

Specification robustness. We conducted extensive robustness checks on our baseline specification, which forms the foundation for both our within-parent and dose-response analyses (Appendix F). We re-evaluated impacts using alternative radiation exposure thresholds, different geographic definitions, and sensitivity tests with wind direction-based measures of radiation fear. We also examined heterogeneity across various demographic and geographic subgroups. These approaches consistently confirmed our main findings across different specifications.

5. Results

5.1 Descriptive statistics

[Table 2]

Table 2 presents descriptive statistics for the three cohorts in columns (1)–(3), with columns (4)–(5) testing whether differences between the prenatal cohort and each control group are statistically significant. Panel A shows significantly worse birth outcomes for the prenatal cohort: preterm birth rates of 4.5% versus 4.1% in the postnatal cohort and 4.2% in the placebo cohort, and average birth weight of 3,024 grams versus 3,036 and 3,032 grams in the postnatal and placebo cohorts, respectively. These differences are consistent across all clinical thresholds (LBW, VLBW, and ELBW).

Panel B demonstrates the substantial difference in radiation anxiety captured by our *SPI* measure. The prenatal cohort registered an average raw *SPI* of 0.679—approximately 62 times higher than the postnatal (0.011) and placebo (0.010) cohorts. This dramatic difference reflects the surge in radiation-related searches following the Fukushima accident.

Panels C through E document demographic and socioeconomic characteristics. Gender distribution remains consistent across cohorts (approximately 51% male), as do residential patterns.

However, some differences emerge: the prenatal cohort has fewer firstborns (38.3% versus 46%) and shows variation in parental occupation and income distributions. Importantly, seismic intensity exposure is equivalent across all cohorts, confirming that our geographic exclusions successfully isolated psychological effects from direct earthquake impacts.

5.2 Fukushima accident and birth outcomes: Overall impacts

Tables 3 and 4 present results from our baseline analysis (equation 1) and within-parent analysis (equation 2), respectively. Both reveal consistent adverse effects on birth outcomes for infants exposed in utero to the Fukushima accident.

[Table 3]

[Table 4]

Table 3 shows that the prenatal cohort experienced significantly worse birth outcomes compared to both control groups. Against the postnatal cohort (Panel A), accident exposure increased preterm births by 0.67 percentage points (16% increase) and reduced birth weights by 26.27 grams (0.9% reduction). Low birth weight categories show a clear severity gradient: LBW, VLBW, and ELBW rates increased by 0.55, 0.19, and 0.10 percentage points—representing proportional increases of 7.2%, 50.0%, and 76.9% respectively. This pattern suggests particularly pronounced effects on the most vulnerable infants. Results against the placebo cohort (Panel B) are similar, with preterm births increasing by 0.68 percentage points and birth weights decreasing by 21.84 grams, confirming that effects reflect the accident rather than seasonal patterns.

Table 4 presents more conservative estimates that control for time-invariant family characteristics. Accident exposure leads to 0.25-0.36 percentage point increases in preterm births (6.1-8.6% increases) and 9.20-9.33 gram reductions in birth weight. LBW rates increased by 0.48-

0.60 percentage points (6.5-8.0% increases), while effects on VLBW and ELBW remain positive but statistically insignificant.

The baseline birth weight reduction of 22-26 grams is comparable to effects documented for natural disasters and family disruptions in prior literature (Black et al., 2016; Camacho, 2008; de Oliveira et al., 2023; Persson & Rossin-Slater, 2018; Torche, 2011), while the within-parent estimate of approximately 9 grams is more conservative, as expected when controlling for family-level confounders. This difference has two non-mutually-exclusive interpretations. First, the pure physiological impact of stress is modest when isolated from confounding factors. Second, families with certain characteristics—such as anxiety predisposition or stress sensitivity—may be both more vulnerable to accident exposure and independently prone to adverse outcomes. Despite differences in magnitude, the consistent direction and significance across approaches provide robust evidence for a detectable physiological response to psychological stress, with particularly pronounced effects on already-vulnerable fetuses, as evidenced by the severity gradient across birth weight categories (Lawn et al., 2014).

5.3 Isolating radiation fear: Dose-response analysis

Having established that accident exposure affects birth outcomes, we now use the *SPI* measure to test whether these effects vary with the intensity of radiation-specific anxiety. Table 5 presents results from equation (3), quantifying how birth outcomes respond to variation in radiation anxiety intensity across Japan.

[Table 5]

The results reveal a clear dose-response relationship between radiation anxiety and adverse birth outcomes. A one SD increase in *SPI* is associated with a 0.28-0.32 percentage point increase in preterm births and a 4.38-4.82 gram reduction in birth weight. For low birth weight categories, each SD increase in *SPI* raises LBW rates by 0.25-0.27 percentage points, VLBW rates by 0.08-0.09 percentage points, and ELBW rates by 0.04-0.05 percentage points. The consistency across both comparison groups (prenatal vs. postnatal and prenatal vs. placebo) strengthens confidence in these estimates. These dose-response effects are substantial relative to baseline means. A one SD increase in *SPI* corresponds to approximately 7% increases in preterm birth and LBW rates, 21-24% increases in VLBW rates, and 31-50% increases in ELBW rates. The pronounced gradient across birth weight severity categories mirrors our earlier findings, confirming that radiation anxiety disproportionately affects the most vulnerable fetuses.

The *SPI*-based estimates are smaller than the baseline accident exposure effects reported in Table 3. While the baseline analysis showed birth weight reductions of 22-26 grams, the dose-response analysis yields effects of approximately 4-5 grams per SD of radiation anxiety. This difference highlights a crucial distinction between our measures: the baseline *PRE* indicator captures the overall stress impact of experiencing the accident—including radiation anxiety, aftershock-related stress, media distress, and other psychological responses—while *SPI* isolates the component specifically attributable to radiation fear. The smaller magnitude of the *SPI* coefficient demonstrates that radiation anxiety, while statistically significant and meaningful, represents one of several stress channels through which the accident affected birth outcomes. This decomposition shows that radiation-specific fear accounts for roughly 20% of the total stress effect.

5.4 Vulnerability patterns: Timing and socioeconomic gradients

Understanding how radiation anxiety affects different populations has direct implications for targeting interventions in response to stressful events involving invisible threats. Figures 3-5 examine heterogeneity in the dose-response relationship across pregnancy timing, maternal education, and household income based on the *SPI* measure.

[Figure 3]

[Figure 4]

[Figure 5]

Critical windows during pregnancy. Figure 3 reveals a U-shaped pattern of effects across pregnancy stages. First-trimester exposure produces the strongest effects (6.9-8.0 grams birth weight reduction per SD increase in *SPI*), third-trimester exposure shows substantial impacts (5.2-5.5 grams), while second-trimester effects are relatively modest and statistically insignificant. This pattern aligns with prior research documenting heightened vulnerability during early pregnancy and weaker mid-pregnancy effects (Camacho, 2008; Torche, 2011; Quintana-Domeque & Ródenas-Serrano, 2017; Menclova & Stillman, 2020; Zhang et al., 2023).

The pronounced first-trimester effects support the "placental-clock hypothesis," which proposes that early prenatal stress affects fundamental developmental programming and can lead to shortened gestational periods (Torche, 2011). During this critical window, maternal stress hormones can alter fetal development trajectories and placental formation, establishing patterns that persist throughout pregnancy. The physiological component of maternal stress reactivity diminishes as the placenta matures, potentially explaining the second-trimester resilience.

The significant third-trimester effects suggest a distinct mechanism whereby rapid fetal weight gain becomes vulnerable to stress-induced disruptions during this metabolically intensive period (Sandman et al., 2015). Unlike first-trimester mechanisms that primarily involve structural organ formation, third-trimester stress affects growth maintenance through impaired placental blood flow, altered placental endocrine function, and accelerated labor initiation (Helbig et al., 2013; Stewart et al., 2015). The relative second-trimester resilience likely reflects a developmentally stable window between organ formation and intensive growth—a period when the fetus may be more buffered against external stressors.

Socioeconomic protection gradients. Figures 4 and 5 show pronounced protective effects of education and income. University-educated mothers show near-zero effects on birth weight compared to 6.2-6.9 gram reductions among high school-educated mothers. Similarly, the highest income quartile experiences 2.8-3.0 gram reductions versus 5.6-6.5 grams in the lowest quartile. These gradients persist across all birth outcomes.

These patterns demonstrate that socioeconomic resources provide significant protection against radiation anxiety effects. Higher education likely confers advantages through better access to accurate information about radiation risks, enhanced stress management capabilities, and stronger social support networks. Similarly, higher household income enables access to private healthcare, stress-reducing services, and geographic mobility away from high-anxiety areas. These findings align with established literature on socioeconomic disparities in health outcomes (Aizer & Currie, 2014; Aizer et al., 2016; de Oliveira et al., 2023) while specifically highlighting how resources can buffer against the psychological impacts of invisible environmental threats.

5.5 Alternative channels

Having established that radiation anxiety causally affected birth outcomes, we now examine the pathways through which these effects operated. A key question is whether radiation anxiety impacted fetal development through psychological stress or through behavioral changes in maternal health practices and nutrition.

To test these alternative mechanisms, we analyzed data from the National Health and Nutrition Survey, [17] examining changes in expecting mothers' health behaviors, mental health indicators, and nutritional intake following the Fukushima accident. [18] The results support psychological stress as the primary mechanism (Appendix E).

Expecting mothers showed no significant changes in key health behaviors following the accident, including smoking rates, alcohol consumption, sleep patterns, physical activity levels, and medication use. However, they experienced an increase in self-reported stress levels. This pattern suggests that behavioral pathways do not explain the observed birth outcome effects.

We also found no significant changes in mothers' nutrient intake after the accident, with no meaningful alterations in consumption of total energy, protein, fat, calcium, iron, or folic acid—key nutrients that would affect fetal development if nutritional pathways were driving the observed effects. The absence of nutritional changes, combined with stable health behaviors but elevated stress levels, points to psychological stress as the primary transmission mechanism linking radiation anxiety to adverse birth outcomes.

6. Discussion and conclusions

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[17] The National Health and Nutrition Survey is conducted triennially with approximately 10,000 individuals per wave, collecting comprehensive data on health behaviors, diet, and biomarkers. We use the 2007, 2010, 2013, and 2016 waves.

[18] We used the 2007, 2010, 2013, and 2016 waves of the National Health and Nutrition Survey and applied a triple-difference approach. Specifically, we estimated the following model and report α_7:

$$y_{imt} = \alpha_0 + \alpha_1 Preg_i + \alpha_2 High_{m(i)} + \alpha_3 Post_{t(i)} + \alpha_4 Preg_i * High_{m(i)} + \alpha_5 Preg_i * Post_{t(i)} + \alpha_6 High_{m(i)} * Post_{t(i)} + \alpha_7 Preg_i * High_{m(i)} * Post_{t(i)} + \boldsymbol{x}_i^\top \boldsymbol{\tau} + u_{imt},$$

for women i in area $m(i)$ at time $t(i)$. y is a vector of outcomes for women in the sample, including health behaviors, mental health, and nutrient intakes. $Preg$ is an indicator of being pregnant, $High$ is an indicator of residing in the high-fear area, and $Post$ is an indicator of survey years after the accident occurred. α_7 captures potential changes in the outcomes among pregnant women residing in the high-fear area post the accident.

This study examined how an invisible threat—radiation fear from the Fukushima nuclear accident—produced tangible consequences for birth outcomes across Japan. Using a unique dataset linking universal birth records with census data, we employed a multi-layered analytical strategy to isolate psychological stress from other disaster-related impacts. We developed a novel Google Trends-based measure to capture radiation-specific anxiety and employed both population-level comparisons and within-parent sibling analyses to establish causal relationships. By excluding areas with direct tsunami damage or significant radiation exposure, we focused on the psychological impact of an invisible threat that spread far beyond the geographic scope of physical damage.

Our findings reveal that radiation anxiety, despite its intangible nature, produced measurable physiological effects on fetal development. The baseline analysis shows that experiencing the accident during pregnancy led to 16% increases in preterm births and approximately 1% reductions in birth weight. The dose-response analysis using the standardized radiation anxiety measure demonstrates that these effects operate through a specific psychological mechanism: each standard deviation increase in radiation fear corresponds to 4-5 gram reductions in birth weight and 7% increases in preterm birth rates. While these dose-response estimates appear modest in absolute terms, they represent the isolated effect of radiation-specific anxiety—purged of other stress channels, family characteristics, and confounding factors that inflate estimates in the broader disaster literature (Camacho, 2008; Currie & Rossin-Slater, 2013; Torche, 2011).

The modest magnitude of our radiation-specific estimates, far from diminishing their importance, underscores three crucial insights. First, even after extensive controls and methodological refinements to isolate psychological stress mechanisms, we observe statistically significant and consistent effects across multiple specifications. This persistence demonstrates a robust pathway through which maternal anxiety becomes embedded in fetal development (Dunkel Schetter, 2011). Second, these isolated estimates of radiation fear represent only one component of the total psychological impact—our baseline results suggest that radiation anxiety accounts for roughly 20% of the overall stress-related effects from the accident, with other disaster-related stressors contributing the remainder. Third, the dose-response relationship demonstrates that effects scale with anxiety intensity, indicating that populations experiencing higher levels of fear about invisible threats—regardless of actual risk levels—could experience substantially larger impacts.

The practical significance becomes clearer when considering the distribution of effects across the population. Among the 340,019 pregnancies exposed to radiation anxiety, the effects were highly concentrated among vulnerable populations. Areas with the highest anxiety levels experienced birth weight reductions of 8-12 grams—magnitudes comparable to effects documented in studies of other prenatal stressors (Almond & Currie, 2011; Camacho, 2008). More importantly, socioeconomically disadvantaged populations showed effects 2-3 times larger than average, suggesting that radiation anxiety exacerbated existing health disparities (Aizer & Currie, 2014; Aizer et al., 2016). The U-shaped vulnerability pattern across pregnancy stages reveals that both early developmental programming and late-pregnancy growth are susceptible to maternal anxiety, extending the window of concern throughout gestation.

The Fukushima experience offers important lessons for managing invisible threats in our increasingly interconnected world. Unlike traditional disasters where damage correlates with proximity, radiation fear spread nationwide through media coverage and social networks, demonstrating how modern information systems can amplify psychological impacts far beyond physical danger zones (Tateno & Yokoyama, 2013). This pattern has direct parallels to recent global crises: the COVID-19 pandemic similarly involved invisible pathogen exposure, uncertain long-term consequences, and widespread media coverage that generated anxiety among pregnant women worldwide (Lebel et al., 2020). Our methodology—using digital trace data to measure population anxiety and examine dose-response relationships—provides a framework for studying psychological impacts during future crises involving invisible threats.

This study contributes to the fetal origins literature in three ways. First, we introduce an objective, real-time measure of population-level anxiety that captures geographic and temporal variation in psychological stress, overcoming limitations of binary exposure indicators commonly used in disaster studies (Almond & Currie, 2011; Currie, 2011). Second, we exploit the Fukushima setting's unique geographic separation of physical and psychological impacts to identify how maternal stress independently affects fetal development—a distinction rarely achievable in natural disaster research. Third, our multi-layered identification strategy—combining population comparisons, within-family variation, and dose-response analysis—provides robust causal evidence while revealing systematic heterogeneity across pregnancy stages and socioeconomic groups. These findings have direct policy implications: disaster preparedness should include psychological support systems, particularly for pregnant women, and risk communication strategies must account for how invisible threats can generate widespread anxiety with tangible intergenerational consequences.

Despite these contributions, several limitations suggest directions for future investigation. First, our *SPI* measure captures radiation anxiety at the prefecture level, potentially masking individual-level variation in stress responses within prefectures. Relatedly, our prefecture-level measure may be subject to ecological inference limitations, as aggregate search patterns may not perfectly reflect individual pregnant women's anxiety levels. Individual-level anxiety data would enable more precise estimates of dose-response relationships. Second, examining long-term cognitive and mental health outcomes would provide a more comprehensive understanding of how prenatal radiation fear affects development beyond birth. Third, investigating compensatory behaviors by parents following perceived stress exposure would illuminate how families may mitigate risks. Future research would benefit from accessing detailed neonatal and maternal medical records to examine radiation fear's impact on healthcare utilization patterns and a broader spectrum of birth outcomes, including labor complications and conditions not captured in vital statistics.

In conclusion, this study documents how invisible threats can produce tangible consequences that extend far beyond their physical boundaries. The Fukushima accident created a natural experiment in which radiation fear, even in areas without substantial physical exposure, affected birth outcomes across Japan. Our findings demonstrate that maternal anxiety becomes biologically embedded during pregnancy, creating measurable effects on fetal development through psychological stress pathways. As societies increasingly face invisible threats—from pandemics to environmental hazards to climate change—these findings highlight the importance of addressing psychological dimensions alongside physical impacts. The Fukushima experience teaches us that effectively managing invisible threats requires not only physical containment but also acknowledging and supporting populations most vulnerable to psychological impacts—including those yet to be born.

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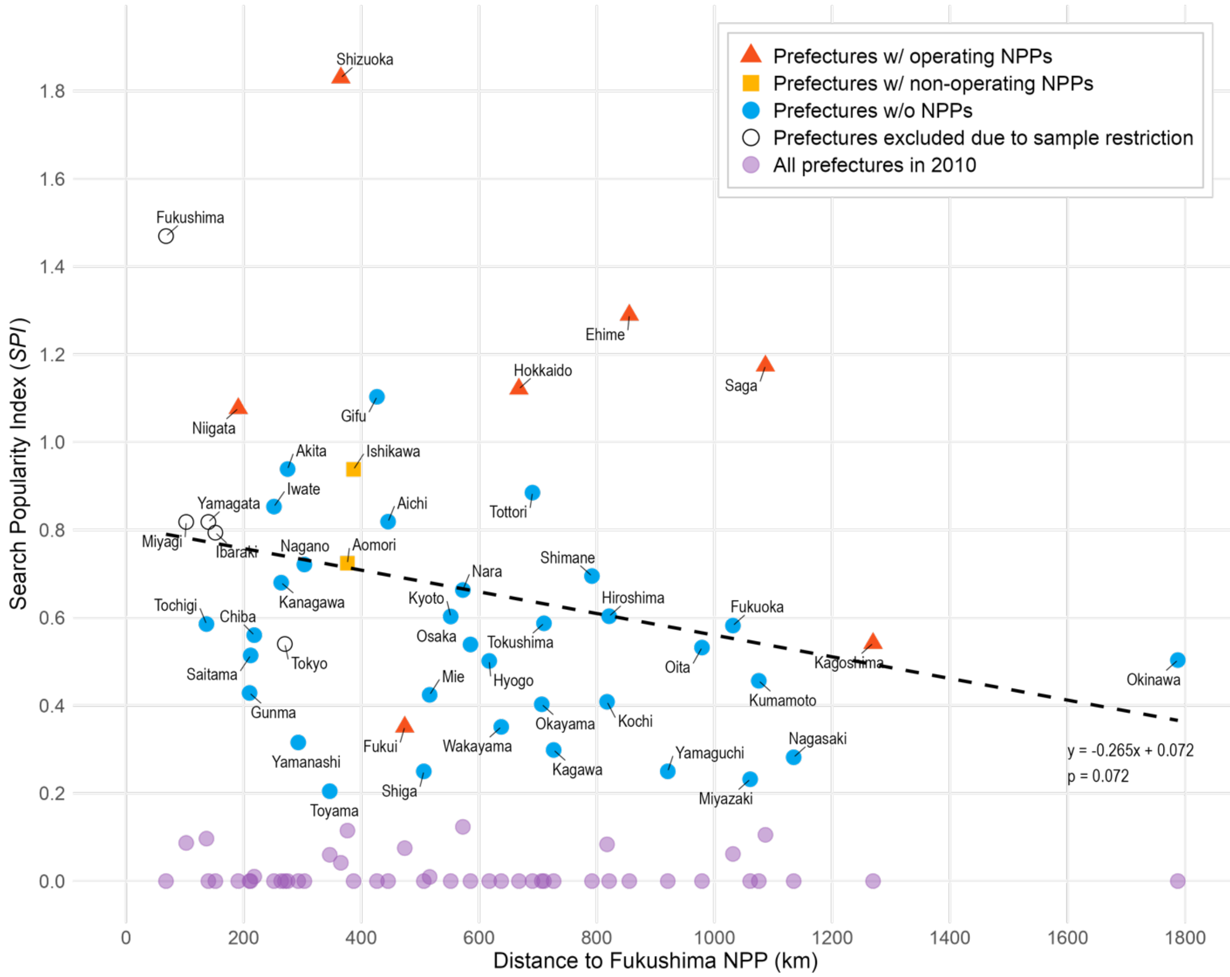

Figure 1. Radiation Anxiety by Distance from Fukushima Daiichi and Nuclear Power Plant Status

Notes: Each dot represents a prefecture, color-coded by nuclear power plant (NPP) status: red triangles for prefectures with operating NPPs, orange squares for prefectures with non-operating NPPs, and blue circles for prefectures without NPPs. Black outlined circles show prefectures excluded from the analysis due to sample restrictions. Purple circles show all prefectures' SPI values in 2010 (pre-accident baseline). The x-axis measures distance from the Fukushima Daiichi NPP in kilometers; the y-axis shows the raw *SPI* values in 2011 (post-accident). The trend line is based on 2011 data and indicates a negative correlation ($\rho = -0.265$, $p = 0.072$) between distance from Fukushima and radiation anxiety after the accident, demonstrating that proximity to the accident site was associated with higher search activity for NPP-related terms, reflecting greater concern about radiation.

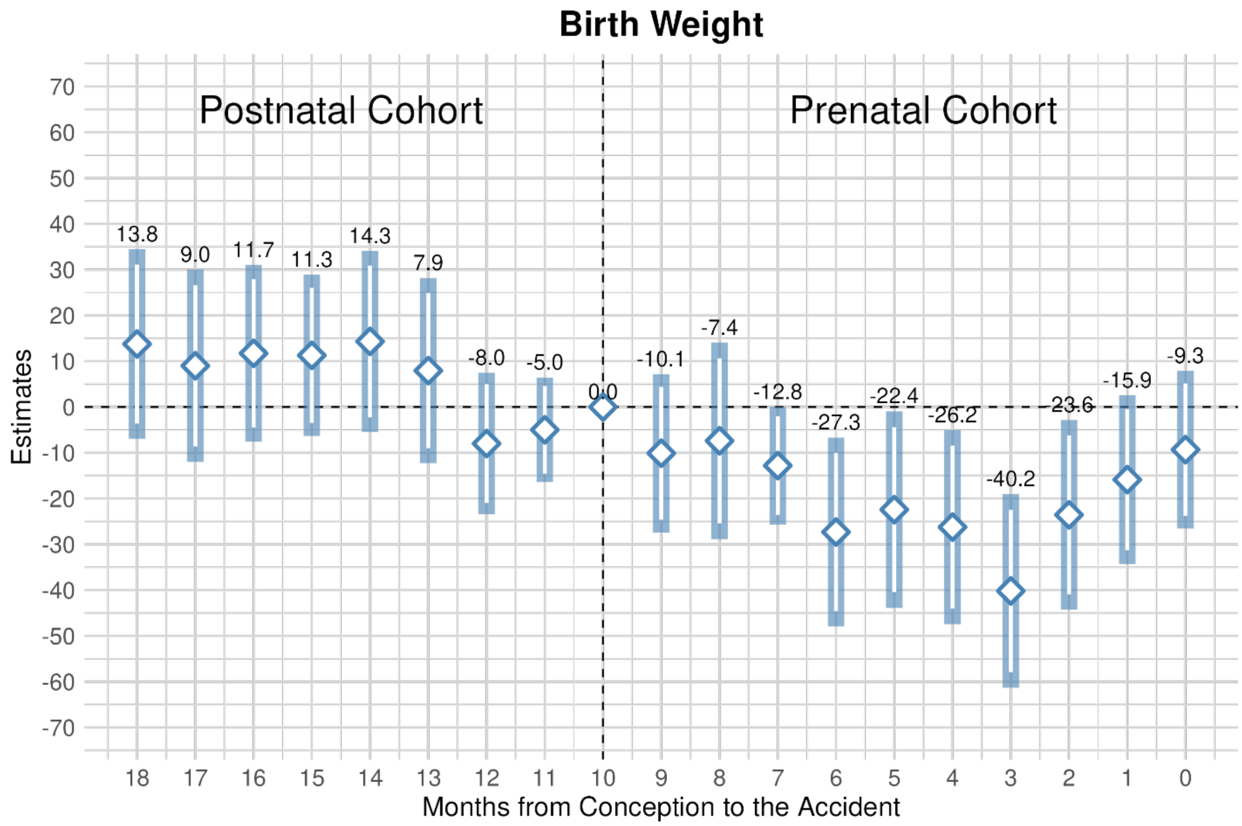

Figure 2. Event study: Effects on Birth Weight by Conception Timing Relative to the Fukushima Accident

Notes: The figure shows birth weight effects by conception timing relative to the Fukushima accident. Coefficient estimates with 90% (thin white bars) and 95% (thick colored bars) confidence intervals are derived from regressions where the prenatal indicator in Equation (1) is replaced with indicators for months between conception and the accident, with 10 months before the accident as the reference category. The left panel shows the postnatal cohort (expected delivery before the accident); the right panel shows the prenatal cohort (pregnancy exposed to the accident, with pregnancy overlap with the accident during the accident period). All regressions include municipality and conception month fixed effects plus controls for parental age and education, father's occupation, household income, residential characteristics, and child gender and birth order. Standard errors are clustered by parents' municipality of residence and newborn's conception month.

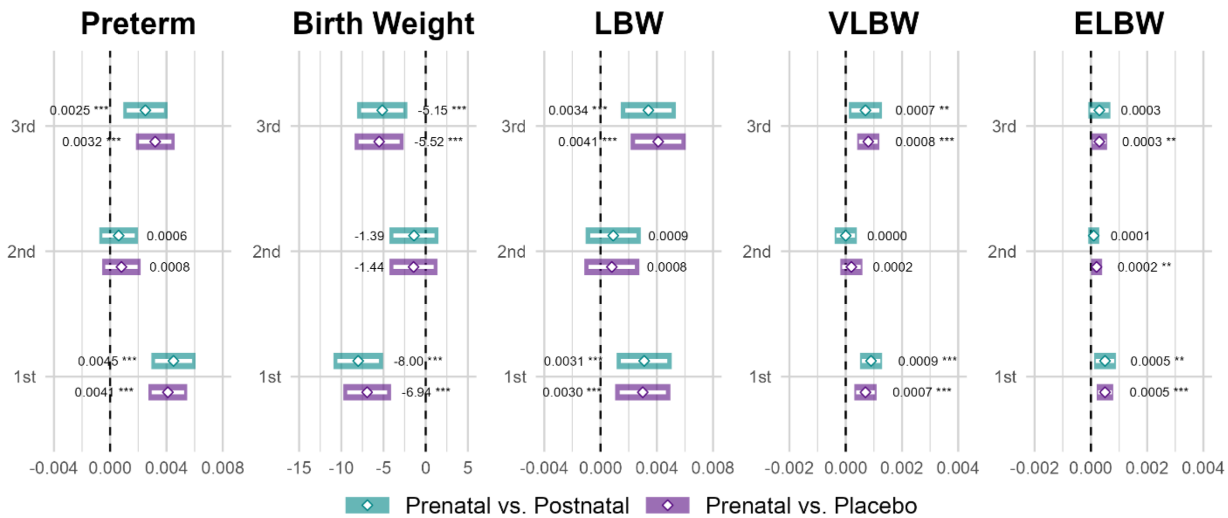

Figure 3. Trimester-Specific Radiation Anxiety Effects on Birth Outcome

Notes: Each panel shows coefficient estimates with 90% (thin white bars) and 95% (thick colored bars) confidence intervals from separate regressions of birth outcomes on standardized *SPI* with trimester-specific coefficients, based on Equation (4). Estimates represent the effect of a one standard deviation increase in radiation anxiety for pregnancies exposed during each trimester. Trimesters are defined as: first (0-91 days post-conception), second (92-182 days), and third (183 days to expected delivery). All regressions include municipality and conception month fixed effects plus controls for parental age and education, father's occupation, household income, residential characteristics, and child gender and birth order. Standard errors are clustered by parents' municipality of residence and newborn's conception month. Blue diamonds show prenatal vs. postnatal comparisons; purple diamonds show prenatal vs. placebo comparisons. 1st = first trimester, 2nd = second trimester, 3rd = third trimester. Statistical significance: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

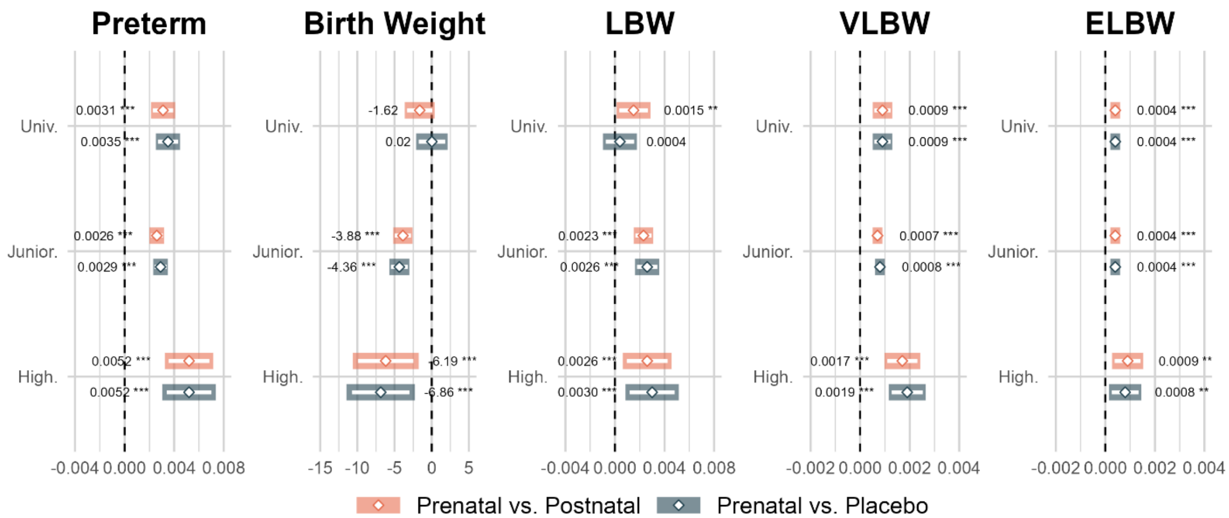

Figure 4. Radiation Anxiety Effects by Maternal Education Level

Notes: Each panel shows coefficient estimates with 90% (thin white bars) and 95% (thick colored bars) confidence intervals from separate regressions of birth outcomes on standardized *SPI* with education-specific coefficients, based on Equation (5). Each education indicator allows *SPI* to have a distinct effect for that maternal education group. Estimates represent the effect of a one standard deviation increase in radiation anxiety for each education level. All regressions include municipality and conception month fixed effects plus controls for parental age, father's education and occupation, household income, residential characteristics, and child gender and birth order. Standard errors are clustered by parents' municipality of residence and newborn's conception month. Orange diamonds show prenatal vs. postnatal comparisons; gray diamonds show prenatal vs. placebo comparisons. Education levels: High. = high school or less, Junior. = junior college/vocational school, Univ. = university or above. Statistical significance: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

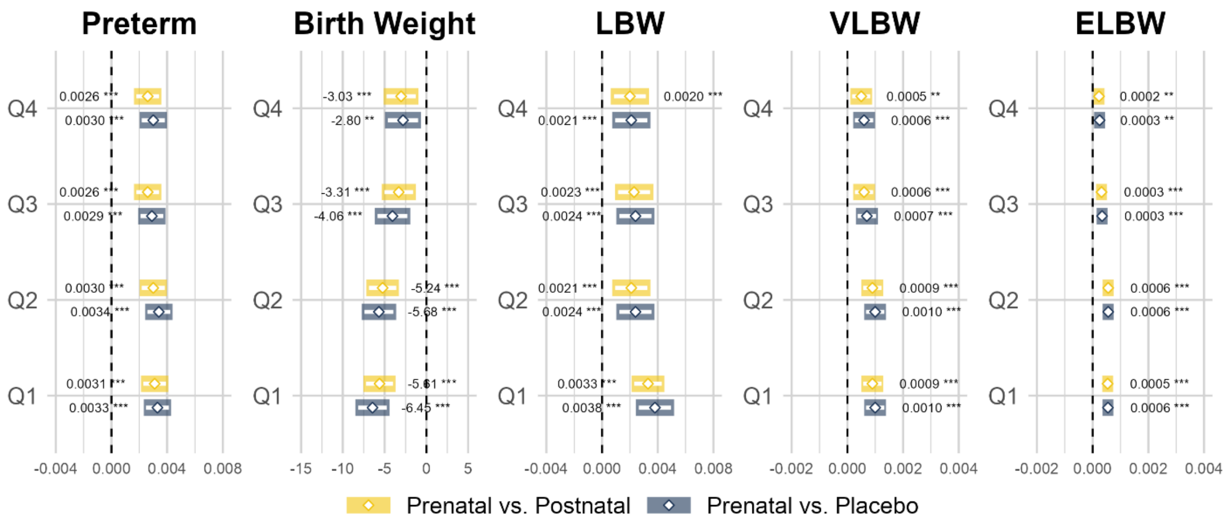

Figure 5. Radiation Anxiety Effects by Household Income Level

Notes: Each panel shows coefficient estimates with 90% (thin white bars) and 95% (thick colored bars) confidence intervals from separate regressions of birth outcomes on standardized SPI with income-specific coefficients, based on Equation (6). Each income quartile indicator allows *SPI* to have a distinct effect for that income group. Estimates represent the effect of a one standard deviation increase in radiation anxiety for each income quartile. All regressions include municipality and conception month fixed effects plus controls for parental age and education, father's occupation, residential characteristics, and child gender and birth order. Standard errors are clustered by parents' municipality of residence and newborn's conception month. Yellow diamonds show prenatal vs. postnatal comparisons; blue diamonds show prenatal vs. placebo comparisons. Income quartiles: Q1 = lowest, Q4 = highest. Statistical significance: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Table 1. Effects of Radiation Anxiety on Prenatal Care Utilization

	Cum. Tel. Consultations		Care Visit Frequency				
			Prepartum		Postpartum	Infants	Toddler
SPI × Post	16.05	*	0.56	*	0.09	0.14	0.27
	(8.45)		(0.32)		(0.13)	(0.26)	(0.26)
SPI	-17.94	**	-0.56		-0.13	-0.14	-0.28
	(8.45)		(0.34)		(0.10)	(0.26)	(0.26)
Post	8.29	***	0.50	*	0.02	-0.09	0.23
	(1.80)		(0.28)		(0.10)	(0.21)	(0.21)
Mean	36.11		1.09		1.35	1.52	1.53
Prefecture FE	Yes		Yes		Yes	Yes	Yes

Notes: The table presents difference-in-differences regression results examining the relationship between radiation anxiety (measured by standardized SPI) and maternal health service utilization patterns. Data cover the pre-accident (April 2009-March 2010) and post-accident (April 2011-March 2012) periods. Outcome variables include cumulative telephone consultations (Cum. Tel. Consultations) for pregnancy-related concerns (per 1,000 population) and health checkup frequency across different types of services (calculated as extended visits divided by actual individuals). All specifications include prefecture fixed effects. Robust standard errors are reported in parentheses. Statistical significance: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Table 2. Descriptive Statistics

	Prenatal N=340,019	Postnatal N=447,964	Placebo N=496,407	Diff. I		Diff. II	
	(1)	(2)	(3)	(4)=(1)-(2)		(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 or 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 or 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)				

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 given in parentheses for continuous variables. *SPI* values show raw search popularity indices. Regression analyses use standardized *SPI* for coefficient interpretation. Household income is in units of millions of Japanese Yen. Statistical significance: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Table 3. Effects of Accident Exposure During Pregnancy on Birth Outcomes

	Preterm		Birth Weight		LBW		VLBW		ELBW	
	(1)		(2)		(3)		(4)		(5)	
A. Prenatal vs Postnatal										
PRE	0.0067	***	-26.27	***	0.0055	***	0.0019	***	0.0010	***
	(0.0006)		(1.13)		(0.0007)		(0.0002)		(0.0001)	
Mean	0.0403		3027.96		0.0759		0.0038		0.0013	
N	700,197		700,175		700,175		700,175		700,175	
B. Prenatal vs Placebo										
PRE	0.0068	***	-21.84	***	0.0042	***	0.0016	***	0.0012	***
	(0.0005)		(0.99)		(0.0007)		(0.0002)		(0.0001)	
Mean	0.0380		3030.79		0.0738		0.0033		0.0010	
N	594,018		593,997		593,997		593,997		593,997	

Notes: Each column represents a separate regression of the indicated outcome on the prenatal indicator (PRE) from Equation (1). Panel A compares the prenatal cohort to the postnatal cohort; Panel B compares the prenatal cohort to the placebo cohort. All regressions include municipality and conception month fixed effects, controls for parental age and education, father's occupation, household income, residential characteristics, and child gender and birth order. Standard errors are clustered by parents' municipality of residence and newborn's conception month. Statistical significance: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Table 4. Within-Parent Analysis: Effects of Accident Exposure During Pregnancy on Birth Outcomes

	Preterm		Birth Weight		LBW		VLBW	ELBW
	(1)		(2)		(4)		(5)	(6)
A. Prenatal vs Postnatal								
$PRE \times SIB$	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								
$PRE \times SIB$	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: Each column shows results from regressing the outcome on prenatal exposure, sibling indicator, and their interaction (PRE × SIB) from Equation (2), with parental fixed effects. Panel A uses the postnatal cohort as the control; Panel B uses the placebo cohort. The interaction coefficient identifies the differential effect of prenatal accident exposure on the younger sibling beyond typical birth-order differences. All regressions include municipality and conception month fixed effects plus controls for child gender, birth order, and household head's occupation. Standard errors are clustered by parents' municipality of residence and newborn's conception month. Statistical significance: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Table 5. Dose-Response Effects of Radiation Anxiety on Birth Outcomes

	Preterm		Birth Weight		LBW		VLBW		ELBW	
	(1)		(2)		(3)		(4)		(5)	
A. Prenatal vs Postnatal										
SPI	0.0028	***	-4.38	***	0.0025	***	0.0008	***	0.0004	***
	(0.0003)		(0.58)		(0.0004)		(0.0001)		(0.0001)	
Mean	0.0403		3027.96		0.0759		0.0038		0.0013	
N	700,197		700,175		700,175		700,175		700,175	
B. Prenatal vs Placebo										
SPI	0.0032	***	-4.82	***	0.0027	***	0.0009	***	0.0005	***
	(0.0003)		(0.61)		(0.0004)		(0.0001)		(0.0001)	
Mean	0.0380		3030.79		0.0738		0.0033		0.0010	
N	594,018		593,997		593,997		593,997		593,997	

Notes: Each column shows results from regressing the outcome on standardized SPI from Equation (3). Panel A uses the postnatal cohort as the control; Panel B uses the placebo cohort. SPI is standardized to have mean zero and unit standard deviation, so coefficients represent the effect of a one standard deviation increase in radiation anxiety intensity. All regressions include municipality and conception month fixed effects plus controls for parental, household, and child characteristics. Standard errors are clustered by parents' municipality of residence and newborn's conception month. Statistical significance: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.