The Impact of Prenatal Exposure to Chernobyl Fallout in Finland

Matti Sipiläinen*
December 7, 2022

Abstract

I estimate the impact of low doses of radiation on school performance and income levels by exploiting regional and temporal variation in levels of radioactivity combined with variation in radiosensitivity during the foetal period. I observe a significantly lower school performance among students exposed to higher levels of prenatal irradiation as well as a lower level of educational attainment. I also estimate the impact on income at ages 26–31. My findings align with the recent literature and confirm the findings presented in Almond et al. (2009).

Keywords: *Cognition, Prenatal irradiation, School performance, Human capital*

* *Aalto University School of Business. I would like to thank my advisor Professor Matti Sarvimäki for his advice and support throughout my thesis work, and Professors Marko Terviö and Manuel Bagues for all the advice and countless discussions. Jan Jääskeläinen for his brilliant comments and endless encouragement throughout the process. I also thank Timo Autio, Carolina Kansikas, Jaakko Markkanen, Matti Mitrunen, Jenni Nevavuo, and William Beckman for their comments. Finally, I would like to thank our department and especially Maria Nyberg for enabling and facilitating the research.*

1. Introduction

This paper revisits the robustness of the influential study by Almond, Edlund & Palme (2009). The authors of the original study, using data from Sweden, demonstrated how exposure to radioactive fallout from the Chernobyl accident impaired neural development during the foetal period: Children born in the most contaminated areas showed a 2.5 point lower average performance during the final year of compulsory schooling and a 3 percent lower probability of qualifying for high school. Using data from a neighbouring country, Finland, I observe on average a 0.03 standard deviations lower average matriculation examination (upper secondary school exit exam) performance and a 1 percentage point lower probability of obtaining higher education such as a Bachelor's degree every time the level of contamination doubles.

Ionising radiation is increasingly more present in modern society[1] making it even more necessary to understand the risks involved and how they change over the lifespan of an individual. The focus of this study is to increase the understating risks of prenatal exposure to low doses of irradiation. For this purpose, I estimate the effect of prenatal irradiation on cognitive performance at radiation levels generally regarded as safe.

In the literature, the impacts of early childhood endowments and their persistence have been demonstrated and discussed in detail before. For example, Currie & Almond (2011) show how events before age five can have long-lasting and large impacts on adult outcomes. A specific focus is shifting in the direction of nongenetic endowments. Bergman et al. (2007) illustrates the link between prenatal stress and birth weight. Similarly, Alderman et al. (2006) links improved nutritional status with the number of educational grades completed. By studying the survivors of atomic bombs, Shaw et al. (2011) demonstrate the adverse effects of prenatal irradiation on the developing brain.

One of the great challenges facing research of this nature is to identify and differentiate the effect originating from different factors that arise from a common root cause. For example, there have been situations where individuals of different socioeconomic status are affected differently (Currie & Hyson, 1999) or can avoid the effects altogether by sorting themselves accordingly (Banzhaf & Walsh, 2008).

Almond et al. (2009) demonstrate hindered educational endowment due to prenatal irradiation. A more recent study (Black et al., 2019) reports similar estimates observed in somewhat similar surroundings. For men exposed to irradiation prenatally, they observe declines in IQ scores, years of education obtained, and earnings at 35.

With the objective of evaluating the results presented in Almond et al. (2009) and Black et al. (2019), Finland provides almost optimal surroundings: the levels of contamination originating from the Chernobyl accident in Finland are close to those of Sweden and Norway, the institutional setting is fairly similar, and the coverage of the available data is comprehensive. Taking advantage of the regional and temporal variation in radioactivity levels combined with the variation in radiosensitivity during the foetal period, I estimate the effect of prenatal irradiation on cognitive performance at radiation levels generally considered safe. In other words, I estimate how exposure to low amounts of radiation affects cognitive skills in a setting where exposure occurs during a more radiosensitive part of the foetal period.

My study builds on previous literature that examined the effects of prenatal shocks on school endowment and its implications. Similarly to Almond et al. (2009), who exploit the variation in regional radioactivity in Sweden originating from the Chernobyl accident, my finding suggests impairment of neural development at levels of ionising radiation currently considered safe.

Moving from the 10th to the 90th percentile municipality in the nuclear fallout exposure distribution, I observe roughly 0.1 standard deviations lower average matriculation examination performance for students exposed to higher levels of prenatal irradiation. Furthermore, access to richer data allows us to estimate the impacts of prenatal exposure to irradiation on labour market outcomes. My findings on examination performance are consistent with the findings presented in

[1] *Sources of radiation can be divided into two categories: natural and man-made. Where the natural variation is low, the exposure to artificial sources of radiation are affected by technology and technology induced practices such as medical treatments or flying (Eleveld, 2003).*

Almond et al. (2009) and Black et al. (2019) and confirm previous evidence on variation in radiosensitivity during the foetal period. Contrary to Almond et al. (2009), I observe a lower probability of obtaining a higher educational degree and find a negative point estimate on wages at ages 26 to 31. However, the estimates for the impact on wages bear no statistical significance.

2. Background

2.1 The accident

The meltdown during the Chernobyl nuclear power plant accident occurred in the former Soviet Union on April 26, 1986. One of the power plant reactors malfunctioned due to an unfortunate failed experiment. The explosion following the malfunction caused the release of a substantial amount of radioactive substances into the environment. The eruption of radionuclides continued for 10 consecutive days, where the payload totalled 10 exabecquerels[2].

As a contributor to the radiation dose, the importance of specific radionuclides changes over time. From the spectrum of isotopes, iodine-131, caesum-134 and caesium-137 (^{131}I, ^{137}Cs and ^{134}Cs hereafter) were the most contributed to the fallout contaminating Europe. Immediately after the accident, the short-lived radionuclides contributed the most, namely iodine-131 with a half-life of 7 days, but in a longer run as the iodine loses energy through decay, caesiums 137 and 134 become more important. The small particle size of Iodine and Caesium also allowed them to disperse in water and air faster than their larger counterparts (De Cort, 1998). There was no official report of the accident before the alarms of a power plant in Forsmark, Sweden, blew off nearly two days later. To put this into perspective, the Forsmark power plant is roughly 1,000 km from the Chernobyl power plant. (UNSCEAR, 2000).

2.2 Transportation of the nuclides

The initial release of radioactive substances into the atmosphere from the Chernobyl accident was due to two thermal explosions that occurred at the power plant. The explosions created a cloud several kilometers high, where some of the particles were dispersed well above the planetary boundary layer into the free atmosphere.

About one-fourth of the total amount of radioactive substances were released during the early phases of the accident. The combustion of the graphite moderator drove the subsequent rather large release of radionuclides into the atmosphere during the following ten days. The aerial and ground radiation measurements across Europe reveal a substantial amount of geological variation in the dispersion of radioactive substances (Cort, 1998).

Strong winds from the free atmosphere combined with the alteration of directions during the ten-day release period transported the radionuclides quickly across the larger part of Europe. Sweden and Finland, for example, were reached within days from the initial explosions (Cort, 1998). More specifically, as the initial plume was travelling north, on 27 April, the plume split into two separate clouds over the Baltic. One part of the plume continued to Sweden where it was detected on 28th and the other to Finland (Pöllänen et al., 1997).

Increased measurements of radioactive fallout and rainfall show a strong positive correlation. In other words, a significant proportion of radioactive substances that descend to Finland and Sweden were deposited due to rainfall. This process is known as wet deposition.

---

[2] *Becquerel is defined as the activity of radioactive material. Exabecquerel is defined as the activity of the quantity of radioactive material in which 10^{18} nuclei decay per second.*

As a result of the deposition mechanism, the distribution of the fallout was not uniform in Finland or Sweden (Paatero et al., 2010).

2.3 Proposed mechanism

Absorption of the dose: Possible pathways

Exposure to irradiation can take place directly through gamma rays emitted by radionuclides currently present in the air or on the ground. Similarly, inhaling the particles or absorbing them through the skin exposes a person to irradiation. Another way of exposure is the consumption of contaminated food in the case where radionuclides are deposited directly on plants or animals, or when plants have absorbed the fallout through their roots, or when an animal has eaten contaminated plants or other animals (Kinly III, 2006).

The deposition of calcium after the accident varied across Europe. The estimate for the caesium deposition from the Chernobyl accident across Europe totals 63 peta becquerels. The fallout received by Finland and Sweden was of the same magnitude. Cort (1998) estimates that the total amount of caesium deposited in Sweden due to the Chernobyl accident was 2.9 pBq while in Finland the corresponding number was 3.1 pBq.

Development of the brain and radio sensitivity

Gestational weeks 8–25 are believed to be most sensitive to the adverse effects of irradiation. The age, more specifically the gestational age in this context, of the subject exposed to ionising radiation plays an important role in predicting the proposed damage caused by exposure radiation. This assumption is a combination of two different factors: how irradiation affects mitosis and the increased mitotic activity in developing organs. Ionising radiation carries enough energy to break chemical bonds such as DNA strands, especially during the cell division phase (Nowakowski & Hayes, 2008).

Mitotic activity within the brain is not uniform over the embryonic phase as different organs develop during different phases of pregnancy. The nervous system develops through rapid division of stem cells (Martin, 2012). On average, a newborn baby is equipped with more than 100 billion neurones. To reach this number, the average brain growth rate is around 250,000 neurones every minute during pregnancy (Ackerman, 1992). Terminally differentiated neurones are also known to no longer divide. Although it does not mean that all neurones in an adult brain would have developed during the embryonic period, the mitotic activity of the brain, after the development phase, is substantially lower (Pilaz et al., 2016).

The development of the nervous system starts early during pregnancy; however, it is only after the closing of the neural tubes, during week 4, that the cerebellum begins to develop and the cerebral hemispheres begin to grow more rapidly. During week 14, the cerebellum starts to resemble its adult form (Martin, 2014).

The expansion of the neocortex during the weeks of 8 to 25 is discussed in Nowakowski & Hayes (2008). Similarly, De Santis et al. (2005) narrows the increased sensitivity to radiation with the development of the central nervous system and the increased mitotic activity of neuronal cells from 2 to 25 weeks, where weeks 8 to 15 are proposed to be the most critical.

There exists a clear difference between the brain and other organs. After the brain has reached its final size, there exists only limited mitotic activity. As mitosis is the driver behind the proliferation that causes the brain to grow in the first place, it is also the process responsible for allowing the renewal of the organs and repairing some of the damage obtained. Therefore, any brain damage is more likely to be considered permanent (Nowakowski & Hayes, 2008).

This motivates the estimate of the impacts on individuals who were presumably exposed to ionising radiation during the presumably more sensitive stages of gestational weeks 8 and 25.

3. Data

3.1 Fallout data

I use municipal-level Caesium-137 measures, which will be referred to as ^{137}Cs, deposition in kilo-Becquerels[3] reported by Radiation and Nuclear Safety Authority of Finland. The variation in ^{137}Cs deposition is described in panel A of Figure 1. Radiation data were collected with a mobile survey station between May 1986 and June 1987 (Arvela et al., 1990). The measurements have been corrected for decay[4] and washout[5] effects. The averages at the municipal level are calculated for the municipal division effective in 1998[4].

Measure of radioactivity

As noted in Almond et al. (2009), the average regional ^{137}Cs contamination is a rather noisy proxy of the actual dose. To begin with, the recorded birthplace of an individual does not reveal the exact location of her mother at the time of exposure. Similarly, alongside ^{137}Cs, more than 25 (Saxen et al., 1987) isotopes contributed to the initial radiation spike: The highest measured level of the short-lived ^{131}I was 420 kBq/m^2 (Hirose et al., 1993). Furthermore, assuming that an individual was only exposed to radiation directly due to rain, thereby staying indoors, a significant proportion of the exposure could have been avoided. Without knowing the actual dose, the estimate that I obtain is more likely to be a lower bound of the true effect of ionising radiation.

3.2 Register data

Almond et al. (2009) observe the school performance of individuals born between 1983 and 1988, who have at least one Swedish parent not older than 47 years at the time of accident. Using similar criteria, I sample individuals born 1980–1990 in Finland.

In contrast to Almond et al. (2009) where at the individual level the month of birth was observed, the data from the Finnish registry record the exact dates of birth. This allows for a more accurate identification of the *inutero* cohort. The register data (FOLK and YTL data bases) are provided by Statistics Finland[7]. Furthermore, contrasting Almond et al. (2009), I also include people living with their nonbiological parents without any age restrictions for the parents.

Educational data include subject-specific results from the matriculation examinations, as well as the highest degree of education obtained. Similarly, the data records the exact date of birth, the municipality and the county of birth, family and employment statistics. In Finland, the maternal municipality of residence is recorded as the place of birth. The family data record the number of children and the position in the family and a family identifier. The family identifier allows the identification of individuals belonging to the same family during a given year. Individual-level data is reported at the end of each calendar year. The coverage of the data is extensive, encompassing Finnish nationals living in Finland with the exception of emigrants.

---

[3] Becquerel describes the level of radioactivity, and is used as a proxy for the actual dose. [4] Decay correction is a process for estimating the amount nuclear decay for known period of time. [5] Due to the fact that the measurements of the level of fallout were gathered over time, the consequential rainfalls washed away some of the radioactive substances.

[4] In the situation where a municipal merger took place between the date of birth and 1998, the individual is assigned to the municipality existing after the merger. [7] Statistics Finland is a public authority responsible for producing the majority of the official Finnish statistics. Data include individual-level information on the structure of the population. More specifically, with regard to family composition, education, birth, including municipality of birth, and gender.

A limitation of the data is the lack of information that identifies the biological parents of a given individual. I use the family identifier to identify a family in a given year and assume guardian status based on the family status, age, and gender of the individual. Similarly, in the absence of the exact location of a pregnant mother at the time of the accident, the municipality of birth is used instead and combined with the corresponding level of fallout. The resulting measurement error is likely to attenuate estimates towards zero.

Cohort

The radioactive plume was estimated to have arrived in Finland on 27 April 1986. Rains during 28–30 April are believed to be the main mechanism for the deposition of volatile radionuclides in Finland (Aaltonen et al., 1986). The definition of the *inutero* cohort is motivated by the increased radiosensitivity between pregnancy weeks from 8 to 25 (Otake, 1998). Shaw et al. (2011) find the foetus being in its most sensitive stage from gestational age 8 to 15. However, since the administration of the dose is not homogeneous and does not take place at exactly the same time, I assume that the exposure to radiation took place on 28 April 1986. Alternative approaches would require a series of assumptions regarding the absorption pathways of the dose. Given an average gestational period of 268 days (Jukic et al., 2013), the *inutero* cohort, consisting of individuals 8 to 25 weeks of gestational age at the time of exposure, would have been born between 30 July and 26 November[5].

3.3 Outcome Variables

I use the results of the matriculation examination as my main outcome. Matriculation examination is a nationally standardised exit exam for upper secondary school academic track. A distinguishing feature of the Finnish educational system is the division between vocational training and upper secondary education. After 9–10 years of mandatory basic education, continuing students make a decision between general and vocational upper secondary education. In 2002, approximately 54.8 % of the 61,477 students who completed compulsory education continued to upper secondary schools and 36.7 % to vocational training. Focusing on the matriculation examination results excludes a portion of affected cohort, yet the remaining sample is large enough to produce rather accurate estimates. This should not affect the external validity of the results as the impact of irradiation is not likely to be affected by individual-level educational decisions.

The qualifying process for general upper secondary education differs slightly between Finland and Sweden. In Sweden, to qualify for high school, a passing grade is required in core subjects. In the Finnish context, the qualification is based on average grades calculated from the basic education certificate. The benefit of focusing on the results of the matriculation examinations in Finland arises from the fact that the examinations in Finland are normalized on a national level, where the grades in the basic education certificate are not.

This encourages focusing on the results of the matriculation examinations in basic education. A distinctive feature of the Finnish matriculation examination is the degree of freedom of students to choose the subjects to test. For the cohort of interest, the minimum number of subjects was four. The matriculation examination is organized by a national institution, the Matriculation Examination Board. The examination takes place twice a year in all Finnish upper secondary schools. Approximately 35,000 students pass the exam each year.

The Finnish educational system is described in Figure 7. The variation in the average performance in the matriculation examination over time is described in figure 3 Not surprisingly, there exists a noticeable variation in the matriculation examination performance. Similarly, the cyclic effects of the timing of birth are clearly visible. For the analysis, the scores received from the individual examinations are standardized to a mean of zero and a standard deviation of one.

[5] *These simplifying assumptions are likely to decrease the accuracy of the estimates.*

Mathematics examination score

Students participating in a mathematics matriculation exam get to choose between basic and extended mathematics tests. The basic and extended examinations consist of 13 questions. The students are asked to answer a maximum of 10 questions. Each question is worth 6 points, answering 10 questions yields a maximum of 60 points (Ylioppilastutkintolautakunta, 2017a).

Finnish language examination score

The national language examination[6], in this case Finnish, aims to measure the ability of the student to express themselves through textual communication, their level of comprehension of the language, and the maturity to participate in further studies. The examination consists of two sections: essay with a maximum of points of 60 and reading comprehension (regarded as tekstitaito in Finnish) with a maximum of 54 points totaling 114 points Ylioppilastutkintolautakunta (2017b).

Average matriculation examination performance

Average performance is calculated as the mean of the standardized points received from subject-specific examinations at the individual level. Students undertaking the Finnish matriculation examination are entitled to a great degree of freedom in choosing the subjects for their individual examination; hence, the average performance is a rather coarse measure: For one would expect individuals to choose to perform their matriculation examination based on the disciplines they excel in. Second, the number of different possible combinations of subject-specific examinations is large. However, assuming universality of the proposed effect, I expect the impact of being systematic and thereby visible even on an aggregate level.

Highest obtained degree of education

My analysis focusses mainly on performance in the matriculation examinations; however, I also estimate the impact of prenatal irradiation on the highest educational degree obtained. For this purpose, an indicator variable has been assigned taking a value of one for individuals with a bachelor's degree or higher[7], a zero otherwise. The purpose of the variable is to estimate any difference in education obtained at the aggregate level.

Income

Due to the availability of the data, income is observed between years 26 and 31. This is a clear limitation of the data, as some of the university students in the sample are yet to enter the labour force and, therefore, biasing the observed effect towards zero. For a more reliable estimate of the impact, observing the level of income for over a much longer period of time, for example from 2016 to 2026, would be necessary.

3.4 Control variables

For the majority of the observations, guardians are identified in 1990. Eight levels of education are used, following the ISCED classification, in addition to one where the level of education is not known, to indicate the level of education for both guardians. Regional differences are controlled by municipal level indicator variables. I also allow fixed effects for gender and day of birth by year of birth.

[6] *Besides the official languages Finnish and Swedish, the examination can also be taken for Saami.*

[7] *ISCED-classified degree six or higher.*

4. Empirical strategy

The identification strategy uses regional and temporal variation in radioactivity resulting from the Chernobyl nuclear power plant (CNPP hereafter) accident. Radioactive substances originating from the CNPP accident caused radiation levels to spike (see Figure 2). Combined with regional variation in levels of contamination and the presumably critical stages of prenatal neural development, it is possible to estimate the effect of low doses of prenatal irradiation on cognitive abilities.

Linear model with continuous measure of fallout

$$y_i = \alpha_0 \times I(inutero)_{muni} + \alpha_1 \times log(fallout_i) \times I(inutero)_i \\ + \beta X_i + \tau_{yob} + \gamma_{dob} + \kappa_{yob \times dob} + \lambda_{muni} + \epsilon_i \quad (1)$$

Motivated by the specifications defined in Almond et al. (2009), my main strategy uses the average ^{137}Cs contamination at municipality level. y_i is the outcome variable. I(*inutero*) is an indicator variable and is set to zero for the individuals born between 1980 and 1991 and to one for the individuals born between August 7 and November 26, 1986 (the cohort *inutero*. X_i represents individual level controls: gender of the individual and the level of education of both parents). I also add controls for the year of birth (τ_{yob}), day of birth (γ_{dob}), the interaction between the year and the day of birth ($\kappa_{yob \times dob}$) and the municipality of birth (λ_{muni}). The specification allows us to observe the change in outcomes within the *inutero* cohort as the degree of potential exposure increases.

A Simple model without variation in exposure

$$y_i = \alpha_0 \times I(inutero)_i + \beta X_i + \tau_{yob} + \gamma_{dob} + \kappa_{yob \times dob} + \lambda_{muni} + \epsilon_i \quad (2)$$

This specification illustrates the difference in outcomes between the *inutero* cohort and the rest of the sample. This specification exploits only the time of birth while ignoring any regional variation in the level of ^{137}Cs contamination.

Classified measure of fallout

$$y_i = \alpha_0 \times I(inutero)^i + \sum_{j=0}^{3} [\alpha j \times Rj \times I\,(inutero)_i] \\ + \beta X_i + \tau_{yob} + \gamma_{dob} + \kappa_{yob \times dob} + \lambda_{muni} + \epsilon_i \quad (3)$$

y_i is the outcome variable. I(*inutero*) is set to zero for individuals born between 1980 and 1991 and to one for individuals born between August 7 and November 26, 1986 (the *inutero* cohort). R_j represents grouping of the municipalities based on the degree of contamination, from low (R1) to high (R3). R0 is always included in or composes the reference area. X_i represents individual level controls for gender and indicator variables for the level of education for both parents. I also add controls for the year of birth (τ_{yob}), day of birth (γ_{dob}), the interaction between the year and the day of birth ($\kappa_{yob \times dob}$) and the municipality of birth (λ_{muni}).

This non-linear specification allows for comparison between multiple reference groups. The specification illustrates the differences in results between the students within the *inutero* cohort born in more contaminated regions and the students within the *inutero* cohort born in the reference area. It also allows for an evaluation of the consistency of the observed estimates. As a result of the proposed mechanism of impaired neural development for individuals exposed during critical weeks of pregnancy, I expect to observe a negative correlation between school performance and the level of ^{137}Cs contamination.

Classification

The exact shape of the dose-response curve regarding low doses of radiation is subject to a lot of debate in the literature, where the simplest approach takes the form of the linear, no-threshold model. Besides the continuous linear specification, I also estimate the impact using a non-linear discrete specification. For this purpose, municipalities are classified into four categories (R0-R3) based on the level of ^{137}Cs contamination. Region R0 consists of municipalities with the lowest (< 2 kBq/m^2) measurements of contamination. The level of contamination in the municipalities labelled R1 varies between 2 and 6.4 kBq/m^2, R2 between 6.4 and 20 kBq/m^2, while R3 represents the municipalities with the highest measurements of ^{137}Cs contamination (above $18.25 kBq/m^2$)[8]. The classification of the fallout is motivated by balancing the number of observations between the treatment groups. I also estimate the model by using the class boundaries introduced by Almond et al. (2009).

Clustering standard errors

The data describing the municipality level ^{137}Cs contamination is estimated for municipalities that existed in 1998. I harmonize the observations for the municipality of birth to 1998 correspondingly and cluster standard errors at the municipality level[12]. The level of clustering is chosen to correspond to the resolution of the treatment.

Assumptions

Rely on a simple assumption that in absence of being exposed to ionising radiation, the individuals now categorized as being exposed to slightly larger fallout during the more sensitive period of the gestation would have performed just the same as the individuals who were exposed to lover levels of irradiation. A possible threat to the strategy would be if the interaction between the spatial and temporal variation of irradiation would be correlated with other performance hindering phenomenon. The fact that the empirical strategy relies on the interaction term of space and time allows controlling the two individual dimensions. I feel confident arguing that the relatively large sample combined with the randomization of the varying degree of fallout stemming from the rain patters eliminate any fear of the results being driven by observable factors.

5. Results

I observe lower school performance and lower probability of obtaining higher education for the individuals exposed to ionising radiation during the presumably more radiosensitive gestational age. My observations imply that radiation levels generally regarded safe can hinder neural development. The observed impacts are of the same magnitude of Almond et al. (2009) and, therefore, support those made by Almond et al. (2009).

---

[8] The class-boundaries of the contamination differ from the ones introduced in Almond et al. (2009). The regional classification is described in more detail in Table 8. The classification is performed by using the class boundaries that mimic the boundaries introduced in Almond et al. (2009) is illustrated in panel B2 of the figure 1 and is described in table 9. Arbitrary boundaries are chosen to create a satisfactory reference group (R0) in terms of the average level of ^{137}Cs contamination and the number of observations. The rest of the sample is divided for the purpose of balancing the number of observations between R1 and R3. It should be noted that manipulation of the class boundaries affects the estimates [12] 461 municipalities translate to 461 clusters.

5.1 Linear model with continuous measure of ^{97}Cs contamination

The results of the model using a continuous measure of the fallout (Equation 1) are presented in Table 1. Columns 1–5 report estimates of the impact on performance on the matriculation examination using a continuous measure of ^{137}Cs. I observe the performance of the examination as points[13] obtained in the corresponding examination. The municipality level averages[14] of ^{137}Cs contamination are in log format. I add controls for the municipality of birth, gender, and parental education[15]. I control seasonality by allowing fixed effects for individual days of birth by year of birth[16]. Scores are reported as distances from the mean in standard deviations. The average score is calculated as the mean of the standardized scores of the subject-specific examinations. The sixth column estimates the impact on the level of acquired education. The indicator variable *higher education* takes a value of 1 for individuals with an ISCED classified level of education of 6 or higher. The classification of the degree of education is described in Figure 7.

The main purpose of the estimate reported in column 1 of the table 2 is to check if the *inutero* cohort differs from the rest of the population regardless of the exposure. The coefficient of the *inutero* indicator reported in column 1 of the table 2, suggests that, in general, individuals born between June 7 and November 11th 1986 performed 0.002 standard deviations worse than the rest of the sample[10]. However, the difference is small and does not carry statistical significance. The *inutero* represents the treatment group (students born in the fall of 1986) regardless of regional differences in the levels of ^{137}Cs contamination. From Table 2 (columns 2–5) we can see that allowing fixed effects year and year and day level and eventually in column 5 at day of the year-by-year level, the coefficient and the standard error of the interaction term remain relatively steady. The statistical significance *inutero* coefficient reported in columns 2–4 of Table 2 is likely to arise from misclassification[18] arising from the definition of the *inutero* cohort. Adding controls for day of birth by year of birth eliminates all seasonality.

The interaction term between the temporal and regional dimensions in Tables 2 and 1 reveals a negative relationship between the level of radioactivity and all the outcome variables. The coefficient of the interaction term from column one suggests that when the level of radioactivity doubles, the average score received in the matriculation examination decreases by 0.03 standard deviations. A change from 10th (1.96kBq/m^2) to 90th (41.25kBq/m^2) percentile in the logarithmic distribution of ^{137}Cs thereby implies a decrease of 0.092 standard deviations in the average matriculation examination points. To exemplify, a shift from the 10th to the 90th percentile in the fallout distribution after controlling seasonality and persistent regional differences corresponds roughly to a comparison of students born in Tampere in the fall of 1986 and students born in Oulu during the fall of 1986. I would expect the students born in Tampere during the fall of 1986 to perform on average 0.1 standard deviations worse in the matriculation examination due to the prenatal exposure to ionising radiation. Almond et al. (2009) estimate the impact of a similar increase in radioactivity on average grades during the last year of compulsory schooling. They observe a -4.5 percent below average performance among prenatally exposed students.

I observe the highest estimated impact on the extended mathematics examinations (Table 1, column 4). Doubling the level of radioactivity decreases the test scores by 0.053 standard deviations. Using the same analogue as before, a change from the 10th to the 90th percentile in the logarithmic distribution of ^{137}Cs implies 0.163 standard deviations lower performance in the extended mathematics matriculation examination.

Using a linear probability model, I estimate a 0.9 percentage points lower probability of obtaining a higher educational degree as the level of ^{137}Cs radioactivity doubles. The estimate for obtained *higher education* is reported in column 6 of Table 1. Similarly, a change from the 10th to the 90th percentile in the logarithmic distribution of ^{137}Cs implies a decrease of 2.7 percentage points in the probability of having obtained an ISCED classified level of education of 6 or higher.

---

[9] *Maximum examination score varies across different subjects. The test score is standardized at the examination level.* [14] *I use the 1998 declaration of municipalities (436 municipalities).* [15] *Parental education covers applies also to non-biological parents.* [16] *Sensitivity to the added controls is noted in table 2.*

[10] *The sample includes all the individuals born in Finland between Jan 1st of 1980 and Dec 31 of 1990 where family could be identified.* [18] *As the* inutero *cohort is defined by assuming a uniform duration of gestation; it is likely that some individuals belonging to the real* inutero *cohort are misclassified.*

Table 5 reports the estimated impact on the level of annual income between ages 26–31. All the estimates are negative, regardless of the individual's age at the time of the observation. However, none of the estimates bear statistical significance. With a 95 % confidence interval, the lower bound of the impact at the age of 31 corresponding to a shift from the 10th percentile to the 90th percentile in the fallout distribution would be -1573, while the upper bound would be 1483. Combining the results from a simple correlation table (table 6) with the results obtained by using the linear model for continuous measure of fallout (table 1) 0.1 standard deviations lower average matriculation examination performance can be associated with 300 euros lower annual earnings.

5.2 Non-linear estimates

Estimates using the nonlinear measure of fallout (equation 3) are reported in table 3. Consistent with the estimates using the continuous measure of fallout, the model estimates increasingly worse performance for students exposed during the presumable critical weeks of gestation as the potential level of exposure increases.

Columns 1–6 report the estimates from the non-linear model (3) allowing for regional variation in the levels of radioactivity. Radiation levels are classified into four categories[11]. Municipalities classified as R0 create the reference group because they received the lowest amounts of fallout. The municipalities marked R3 are the municipalities with the highest measured levels of ^{137}Cs contamination[20]. Columns 1 and 3 report estimates where individuals belonging to the *inutero* cohort and who are born in the regions with the highest levels of fallout (R3) are compared with the rest of the *inutero* cohort, regions R2–R0. Columns 2 and 5 report the estimates of the individuals in the *inutero* cohort born in municipalities R3 or R2 compared to the *inutero* cohort born in regions R1-R0. Columns 3 and 6 report the estimates where the individuals within the inutero cohort born in the R3 region are compared with those born in the reference area.

The interaction coefficients for R3–R1 are consistent with the linear estimates: Higher levels of potential exposure produce larger negative effects. Similarly, by introducing the interaction term between the *inutero* indicator and the regional indicator for R1 and R2, the estimate for the interaction term R3 increases as the average level of contamination in the reference area decreases. In column 3 of table 3 the interaction term for the regions with the highest levels of contamination (R3) estimates the impact with an average score of -0.092 standard deviations compared to the reference area (R0).

6. Sensitivity analysis

Randomization inference

How likely would it be to observe similar results in the absence of any known treatment simply due to natural variation in the matriculation examination performance? To answer this question, I run a series of placebo experiments by moving the boundaries of the presumably critical birth cohort (*inutero*) over time at one-week intervals. By doing this, I create more than 400 placebo experiments, where the regional variation is kept constant while the assumed timing of the exposure is randomized over time. For this analysis, I estimate the impact on average matriculation performance using the linear model with a continuous measure of the fallout (Model 1). Of the 415 regressions, only two produced larger estimates compared to the estimate obtained by using the main identification strategy. Similarly, in comparison to the estimated impact on points received from the Finnish matriculation examination, one of the placebo experiments produced equally large or larger estimates. Interpreting the results is based on the tenability of the null hypothesis. If overlap with the original definition of the presumably critical (*inutero*) cohort is not allowed, the share of placebo experiments

[11] The classification is described in table 8 and in panel B2 of figure 1 [20] The somewhat arbitrary class boundaries are chosen for two reasons, first, to create a believable reference group (R0) and second, to balance the observations in the remaining categories. The class boundaries differ from those introduced in Almond et al. (2009). The same specification is also estimated using the class boundaries proposed by Almond et al. (2009). The results are reported in Table 4 and the corresponding descriptive statistics in Table 9 in the Appendix.

reporting equally large or larger estimates decreases to zero. That is to say, after excluding placebo treatments that overlap the actual treatment, all estimates are smaller in size. The results of the sensitivity analysis are reported in Figure 6.

The results of this exercise suggest that, given the identification strategy, the possibility of observing an effect of the same size or larger is low. Out of 415 estimates, no larger or equally large effects can be observed outside the presumably critical time window. Estimates reporting equally large or larger impacts take place within the fall 1986 cohort, underlining inaccuracy regarding the expected timing of the exposure.

A proper randomization inference that would produce real p-values would also require regional randomization of the ^{137}Cs contamination. However, due to the nature of the natural clustering of fallout that occurs due to rain patterns, a simple randomization of the contamination at the municipality level would not produce meaningful results.

Regarding classification and the heterogeneity of the observed effect

The results from the non-linear model (Model 3) alone should be treated with caution, as the classification process provides extended degrees of freedom to the analyst. This motivates a sensitivity analysis that focusses on the duration and timing of the *inutero* cohort, denoting the assumed critical weeks of gestation. The exercise aims to evaluate the heterogeneity of the effect and the robustness of the observed estimates.

The analysis is performed by randomizing the length and starting position of the assumed critical period in time within the potential time window[12]. I use an interval of one week for length and timing and a lower limit of seven weeks for the duration of the hypothetical *inutero* indicator. The largest estimates of the impact measured in average standard points obtained from the matriculation examination can be observed when the *inutero* cohort is defined between August 3 and September 23 with an increase of -0.04 standard points for and an increase of one on a logarithmic scale of ^{137}Cs contamination. The results of the sensitivity analysis are reported in detail in figure 5. All the largest estimates are observed within the original *inutero* time frame motivated by the literature.

Another aspect of the analysis is the dose-response curve. A quick visual inspection of the results places the highest estimates between gestational weeks 8–25, while the highest estimates can be observed when the *inutero* cohort is defined toward the end of the presumably critical period of gestation. According to earlier literature (De Santis et al., 2005; Shaw et al., 2011) the foetus is increasingly sensitive to irradiation during pregnancy weeks 8–25. The results of the analysis confirm the previous findings.

Robustness of choice of model

One concern could be that the observed estimates are sensitive to the functional-form assumptions. Estimates from a specification using a continuous measure of the ^{137}Cs contamination without the log transformation are rather similar. Estimates from the altered specification are reported in table 7 panels A and C. Panel C reports the estimate in raw points received from the matriculation examination, while panel A uses standardized points.

The results obtained using the non-linear model reported in Table 3 and also in Figure 4 demonstrate for most parts that as the potential level of exposure to irradiation increases, the observed negative impact increases. This observation strengthens the plausibility of the proposed mechanism.

---

[12] *Assuming an average pregnancy lasted for 268 days (Jukic et al., 2013), the individuals born between April 28 1986 and January 19 1987 were arguably exposed during gestation. The current literature defines the critical weeks of gestation between 8 and 25 (Nowakowski & Hayes, 2008; De Santis et al., 2005).*

More on robustness

It could be argued that the observed effect is driven by an omitted variable. For example, instead of irradiation, the observed drop in school performance could be caused by elevated stress levels of pregnant mothers (Bergman et al., 2007). Additionally, the foetal period that appears as increasingly radiosensitive could simply be a period in which the developing foetus is just more sensitive to prenatal stress. Another explanation could be the parental response, which could possibly exacerbate, mitigate, or even drive a nocebo effect on its own. On the other hand, to produce similar results, the level of parental stress should be correlated with the interaction of regional contamination and the half-life of iodine-131.

Additionally, a recent study (Black et al., 2019) suggests that this is not the case: A significant portion of the research exploits variation originating from events well-known to the public: nuclear explosions of Hiroshima and Nagasaki and the nuclear power plant accident of Chernobyl and Fukushima to name a few. Black et al. (2019) exploit variation from events that were unknown to the public at the time which effectively decreases the possibility of the effect of being explained by increased levels of stress.

7. Conclusion

In a modern world where ionising radiation is progressively more present in everyday life, it is important that we understand its implications throughout the dose-response curve. My findings imply that radiation levels generally regarded safe can hinder neural development under certain conditions with the assumption that the measured outcomes manage to capture the impact on neural development. My study fills in the gaps in the previous literature on the change in radiosensitivity during the foetal period and confirms existing observations. In terms of comparison, my study looks at differences in radiosensitivity throughout the foetus period. Taking advantage of regional variation in levels of radioactivity originating from the Chernobyl accident, I find that prenatal exposure to ionising radiation has long-lasting negative impacts on school performance and causes a lower probability of obtaining a higher education degree. I also observe a negative point estimate for level of income at ages 26 to 31, however, the point estimate for the impact on wages carries no statistical significance.

As an additional contribution, my finding supports previous literature illustrating how gestational weeks 8 to 25 appear to be increasingly sensitive to irradiation, while the largest negative effects are observed towards the beginning of the 17-week critical window.

While the possibility of nuclear accident of the same magnitude of the Chernobyl accident taking place in near future is relatively low, sources of low doses of radiation are numerous ranging from natural background radiation to occupational radiation. Better understating of the potential impacts of ionising radiation allow more accurate estimates of the health risks assigned to low doses of radiation. □

Tables and Figures

Table 1: *Continuous measure of ^{137}Cs contamination. Performance in matriculation examination and obtained level of education.*

	(1) Average score	(2) Finnish	(3) Math basic	(4) Math ext.	(5) English	(6) Higher education
Inutero × Log^{137}Cs	-0.0295***	-0.0382***	-0.0193	-0.0511***	-0.0120	-0.00913**
	(0.00739)	(0.0102)	(0.0145)	(0.0149)	(0.00973)	(0.00410)
Observations	345200	323204	154476	121805	332388	579152
r2	0.0885	0.105	0.0556	0.0799	0.0794	0.107

Notes: Columns 1–6 report the impact of increased radioactivity on average performance on average matriculation examination performance, as well as subject-specific matriculation examination performance. Impact is estimated using the model for continuous measure of fallout (Model 1). The measurement of caesium-137 in logarithmic form are used as a measure of radioactivity. Performance in the matriculation examination is measured in standardised examination points. Clustering at the municipality level. Controls for municipality of birth, gender, parental education, and day of birth by year of birth. Due to collinearity with the birth-day fixed effects the main effect cannot be identified. Higher education *is an indicator variable that takes a value of one for individuals with an ISCED classified degree of 6 or greater and zero otherwise. * (p < 0.1), ** (p < 0.05), *** (p < 0.01).*

Table 2: *Continuous measure of ^{137}Cs. Performance in the matriculation examination.*

	(1)	(2)	(3)	(4)	(5)
	Average matriculation performance				
Inutero	-0.00165	0.0630***	0.0490**	0.0564***	0
	(0.00792)	(0.0185)	(0.0198)	(0.0193)	(.)
Inutero × Log^{137}Cs		-0.0302***	-0.0302***	-0.0300***	-0.0295***
		(0.00734)	(0.00736)	(0.00736)	(0.00739)
Observations	353120	345200	345200	345200	345200
r2	0.0774	0.0777	0.0779	0.0791	0.0885
Year	No	No	Yes	Yes	Yes
Day	No	No	No	Yes	Yes
Year×Day	No	No	No	No	Yes

*Notes: Columns 1–5 report the impact of increased radioactivity on average matriculation examination performance. The first column estimates the impact using the simple model (Model 2) using only temporal variation and disregarding all regional variation in the level of contamination. Columns 2–5 estimate the impact using model 1 that allows the degree of contamination to vary across municipalities. The measurement of caesium-137 in logarithmic form are used as a measure of radioactivity. Average performance in matriculation examination is a mean of standardised subject-specific individual level examination scores. Standard errors are clustered at the municipality level. Controls for municipality of birth, gender, parental education and day of birth by year of birth. * (p < 0.1), ** (p < 0.05), *** (p < 0.01).*

Table 3: *Classified fallout: Performance in Matriculation examination*

—Panel A—	(1)	(2)	(3)	(4)	(5)	(6)
Inutero x Area		Average examination performance			Finnish	
R3	-0.0366**	-0.0569***	-0.0889***	-0.0420*	-0.0739***	-0.0963**
[20–71]	(0.0175)	(0.0200)	(0.0320)	(0.0225)	(0.0254)	(0.0444)
R2		-0.0487**	-0.0807**		-0.0750***	-0.101**
[7–20]		(0.0206)	(0.0325)		(0.0239)	(0.0463)
R1			-0.0438			-0.0299
[2–7]			(0.0306)			(0.0427)
Observations	353120	353120	353120	330236	330236	330236
r2	0.0881	0.0881	0.0881	0.104	0.104	0.104
—Panel B—	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Inutero x Area		**Math Extended**			**Math Basic**	
R3	-0.0862**	-0.124***	-0.141**	-0.0177	-0.0343	-0.0996*
[20–71]	(0.0379)	(0.0417)	(0.0566)	(0.0302)	(0.0357)	(0.0514)
R2		-0.0985***	-0.116**		-0.0374	-0.103**
[7–20]		(0.0377)	(0.0524)		(0.0340)	(0.0515)
R1			-0.0242			-0.0905*
[2–7]			(0.0591)			(0.0511)
Observations	124399	124399	124399	158095	158095	158095
r2	0.0791	0.0792	0.0792	0.0554	0.0554	0.0554

Columns 1–6 in panels A and B report the impact of increased radioactivity on average matriculation examination performance. The impact is estimated using the noncontinuous model (Model 3). In colunms 1 and 4, the regions classified as the most contaminated (R3) are compared against the rest of Finland (R0-R2). Columns 2 and 5 report the estimate for the highest and second highest regions (R3 & R2) in comparison with the rest of the Finland (R0 & R1). Columns 3 and 6 report the estimates for regions classified into three categories, based on the severity of the contamination, compared with the least contaminated municipalities (R0). In panel A, columns 1-3 examine the impact on average matriculation performance, and columns 4–6 estimate the impact on Finnish language test. Panel B reports on the estimates of mathematics. The sample includes individuals born between 1980 and 1991. inutero *indicator variable is set to one for individuals born between August 7 and November 26, and to zero otherwise. Caesium-137 measurements are used as a measure of radioactivity. Indicators R0 to R3 represent the classification of regional radioactivity. R0 composes or is included in the reference area. Class boundaries, reported in square brackets, set for balanced observations. Estimates are reported in standard points. Clustering at the municipality level. Controls for municipality of birth, gender, and parental education.*
*Days of birth by year of birth are controlled to eliminate seasonality. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.*

Table 4: *Classified fallout 2 Performance in Matriculation examination.*

—Panel A—	(1)	(2)	(3)	(4)	(5)	(6)
Inutero x Area		**Mean standard points Inutero x**			**Finnish**	
AEP R3	-0.0315	-0.0939***	-0.133***	-0.0429	-0.0920**	-0.181***
	(0.0206	(0.0330)	(0.0376)	(0.0262)	(0.0432)	(0.0630)
AEP R2		-0.0749**	-0.114***		-0.0597	-0.149**
		(0.0290)	(0.0338)		(0.0384)	(0.0598)
AEP R1			-0.0494			-0.113*
			(0.0442)			(0.0674)
Observations	353120	353120	353120	330236	330236	330236
r2	0.0881	0.0881	0.0881	0.104	0.104	0.104
—Panel B—	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Inutero x Area		**Math Extended**			**Math Basic**	
AEP R3	-0.0803*	-0.175***	-0.0871	0.0160	-0.0869	-0.0374
	(0.0445)	(0.0654)	(0.102)	(0.0349)	(0.0539)	(0.104)
AEP R2		-0.117**	-0.0288		-0.122***	-0.0730
		(0.0559)	(0.0962)		(0.0466)	(0.0995)
AEP R1			0.114			0.0629
Observations	124399	124399	124399	158095	158095	158095
r2	0.0791	0.0791	0.0791	0.0554	0.0554	0.0554

Columns 1–6 in panels A and B report the impact of increased radioactivity on average matriculation examination performance. The impact is estimated using the non-continuous model (Model 3). In columns 1 and 4, the regions classified as the most contaminated (R3) are compared against the rest of the Finland (R0–R2). Columns 2 and 5 report the estimate for highest and the second highest regions (R3 R2) in comparison with the rest of the Finland (R0 R1). Columns 3 and 6 report the estimates for regions classified in three categories, based on the severity of the contamination, in comparison with the least contaminated municipalities (R0). In panel A, Columns 1–3 examine the impact on average matriculation performance and columns 4–6 estimate the impact on Finnish language test. Panel B report the estimates on mathematics. The sample includes individuals born between 1980 and 1991. Inutero *indicator variable is set to one for individuals born between Aug 7th and Nov 26th and zero otherwise. Class boundaries mimic those used in Almond et al. (2009). Indicators R0 to R3 represent classification of regional radioactivity. R0 composes or is included in the reference area. Estimates are reported in standard points. Clustering at municipality level. Controls for municipality of birth, gender and parental education. Year of birth, day of year, and the interaction of the year of birth and the day of year are absorbed to eliminate seasonality.* * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 5: *Continuous measure of ^{137}Cs contamination. Estimated impact on the level of income at different ages.*

	(1)	(2)	(3)	(4)	(5)	(6)
	Annual income					
	at 26	at 27	at 28	at 29	at 30	at 31
Inutero×Log^{137}Cs	-13.17 (89.33)	-63.22 (110.5)	-46.27 (111.6)	-49.27 (111.6)	-12.31 (139.7)	-15.21 (259.9)
Observations	340829	399913	400445	402044	401167	402635
r2	0.0355	0.0428	0.0531	0.0628	0.0707	0.0618
Mean	17784	19650	21072	22199	23185	24115

Notes: Estimated impact on levels of income at ages from 26 to 31. The impacts are estimates using the model for continuous measure of contamination (Model 1). Measurements of caesium-137 in logarithmic form are used as a measure of radioactivity. Clustering at municipality level. Controls for municipality of birth, gender, parental education and day of birth by year of birth. Annual income in euros. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 6: *Relation between earned income and average matriculation performance.*

	Annual income									
	at26	at27	at28	at29	at30	at31	at32	at33	at34	at35
AverageScore	605 (22)	1748 (56)	2491 (74)	2983 (81)	3292 (83)	3520 (74)	3815 (75)	4076 (72)	4406 (71)	4798 (67)
Mean	17784	19650	21072	22199	23185	24115	24977	25912	26881	27855

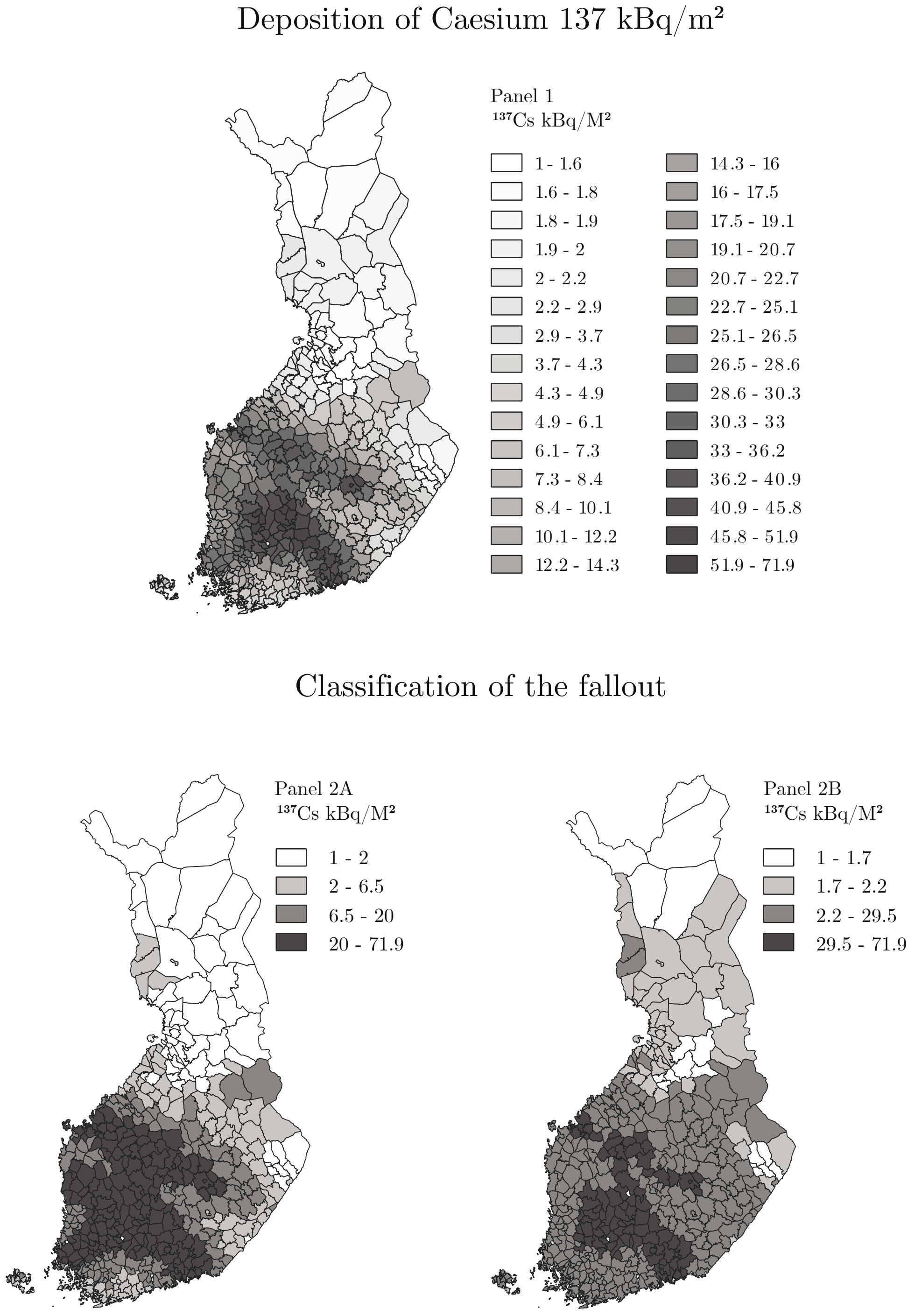
Notes: Estimated associated changes in levels of annual income corresponding to a increase of one standard deviation in average matriculation examination score. The estimates are calculated for individuals born between 1980 and 1991. Clustering at municipality level. Controls for municipality of birth, gender, parental education and for day of birth by year of birth. Standard errors in parentheses. Annual income in euros.

Table 7: *Continuous measure of ^{137}Cs contamination.*

—Panel A—	(1)	(2)	(3)	(4)	(5)	(6)
	Estimates in standard points. No log transormation.					
	Average score	**Finnish**	**Mathbasic**	**Mathext.**	**English**	**Higher education**
Inutero×Log^{137}Cs	-0.00155***	-0.00189***	-0.000619	-0.00325***	-0.000688	-0.000527
	(0.000493)	(0.000594)	(0.000897)	(0.000928)	(0.000664)	(0.000350)
Observations	345200	323204	154476	121805	332388	579152
r2	0.0885	0.105	0.0556	0.0798	0.0794	0.107
–Panel B–	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	Estimates in standard points. Inutero as in Almond et al. (2009)					
	Average score	**Finnish**	**Math basic**	**Math ext.**	**English**	**Higher education**
$Inutero_{AEP}$×Log^{137}Cs	-0.0163***	-0.0257***	-0.00744	-0.0470***	-0.0031	-0.00590
	(0.00617)	(0.00829)	(0.0124)	(0.0136)	-0.00839	(0.00431)
Observations	345200	323204	154476	121805	332388	579152
r2	0.0885	0.105	0.0556	0.0799	0.0794	0.107
—Panel C—	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	Estimates in examination points. No log transformation.					
	Average score	**Finnish**	**Math basic**	**Math ext.**	**English**	**Higher education**
Inutero×Log^{137}Cs	-0.0205***	-0.0232***	-0.0228	-0.0789***	-0.00999	-0.000527
	(0.00770)	(0.00730)	(0.0212)	(0.0216)	(0.00986)	(0.000350)
Observations	345200	323204	154476	121805	332388	579152
r2	0.145	0.440	0.0622	0.113	0.0865	0.107
—Panel D—	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	Estimates in examination points.					
	Average score	**Finnish**	**Math basic**	**Math ext.**	**English**	**Higher education**
Inutero×Log^{137}Cs	-0.388***	-0.411***	-0.497	-1.231***	-0.170	-0.00913***
	(0.117)	(0.115)	(0.320)	(0.344)	(0.146)	(0.00410)
Observations	345200	323204	154476	121805	332388	579152
r2	0.145	0.440	0.0622	0.113	0.0865	0.107

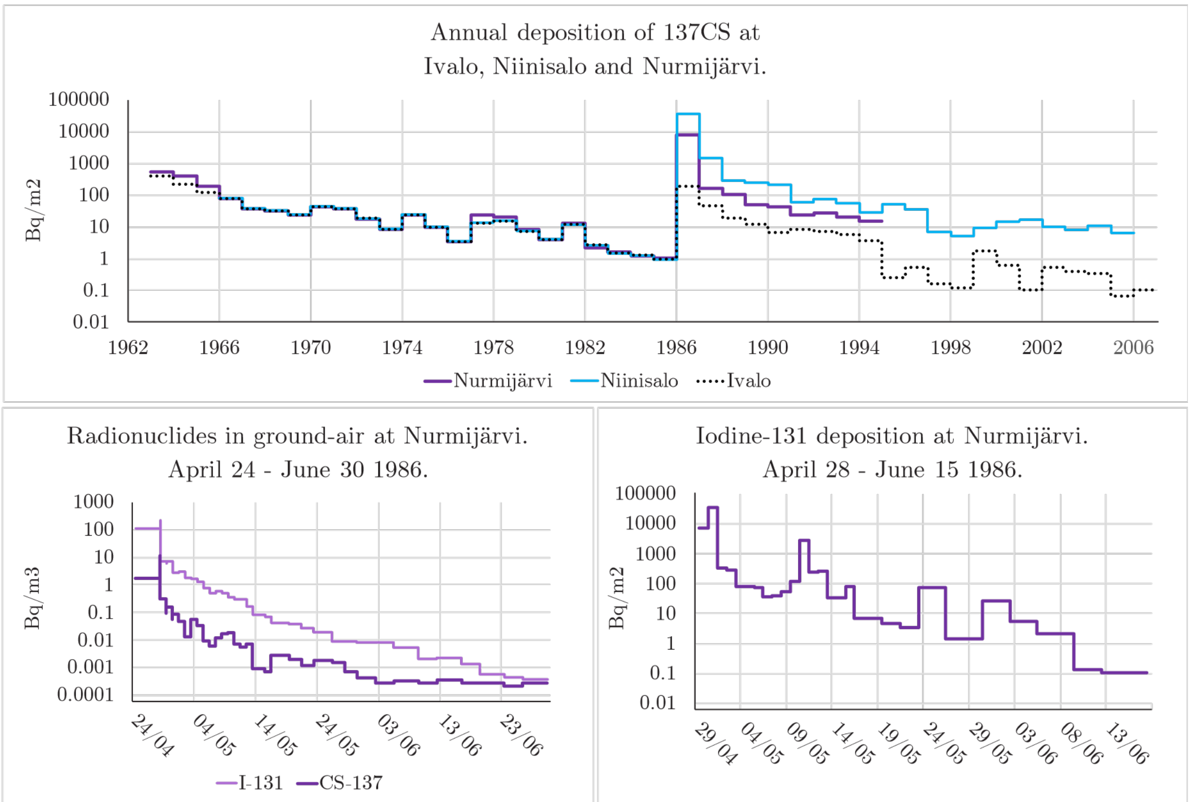
Notes: Panael A and B measures the performance in standard points. Panels C and D measure the performance in raw points received from the examination. Panels B and D measure fallout on a logarithmic scale. Higher education is an indicator variable taking value of for individuals with ISCED classified educational degree of 6 or higher and zero otherwise. Clustering at municipality level. Controls for municipality of birth, gender, parental education and day of birth by year of birth. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Figure 1: *Regional variation of the fallout*



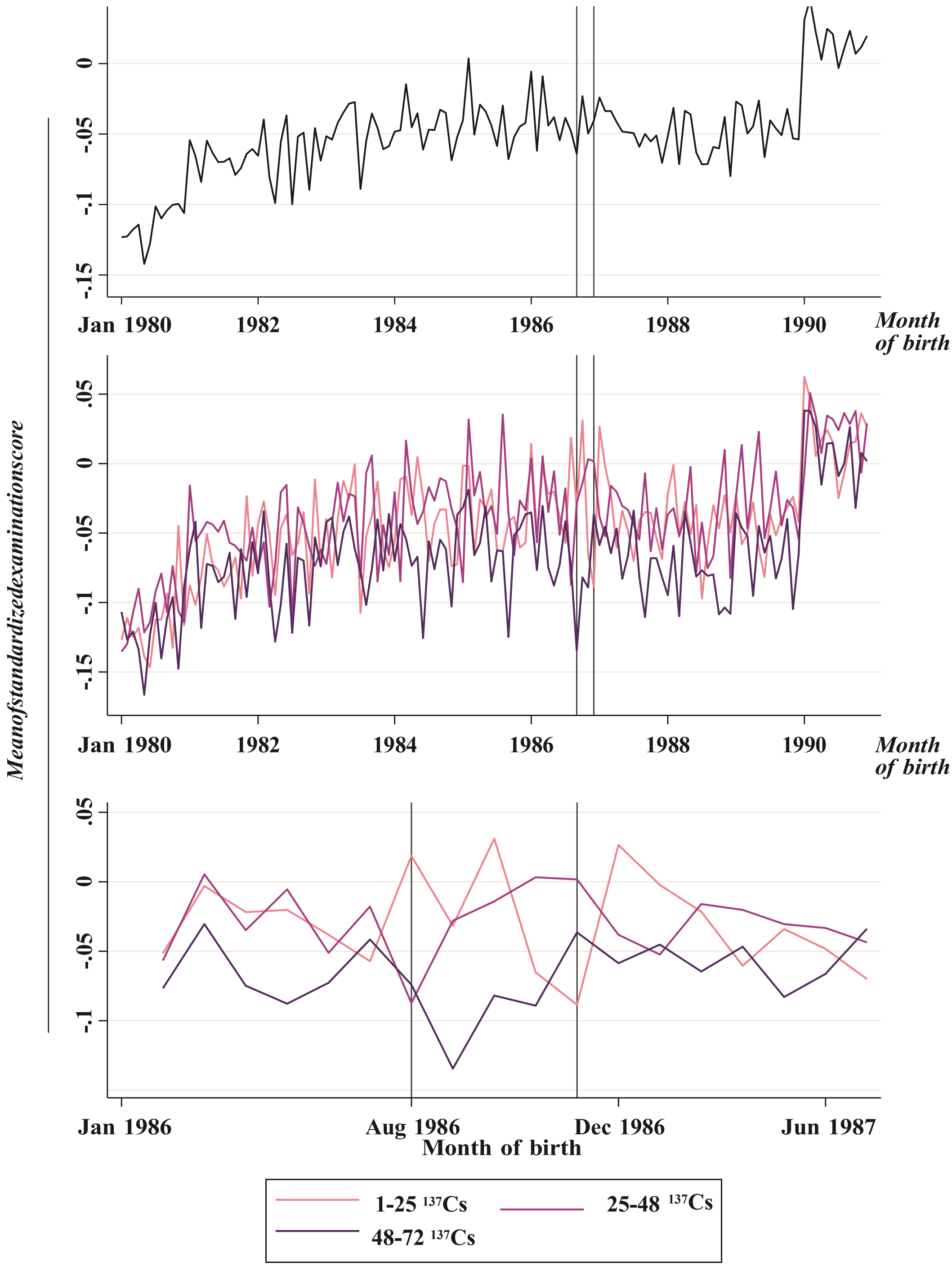
Notes: Panel A illustrates regional variation in deposition of Caesium-137 in Finland. The measurements are decay and wash-out corrected by the Radiation and Nuclear Safety Authority (STUK). Municipality level averages are calculated for municipal division effective in 1998. Panel B1 illustrated the classification of the fallout motivated by balancing the number of observations in the more treatment groups. Panel B1 illustrates the classification mimicking the class boundaries introduced in Almond et al. (2009).

Figure 2: *Regional differences in deposition of radionuclides*



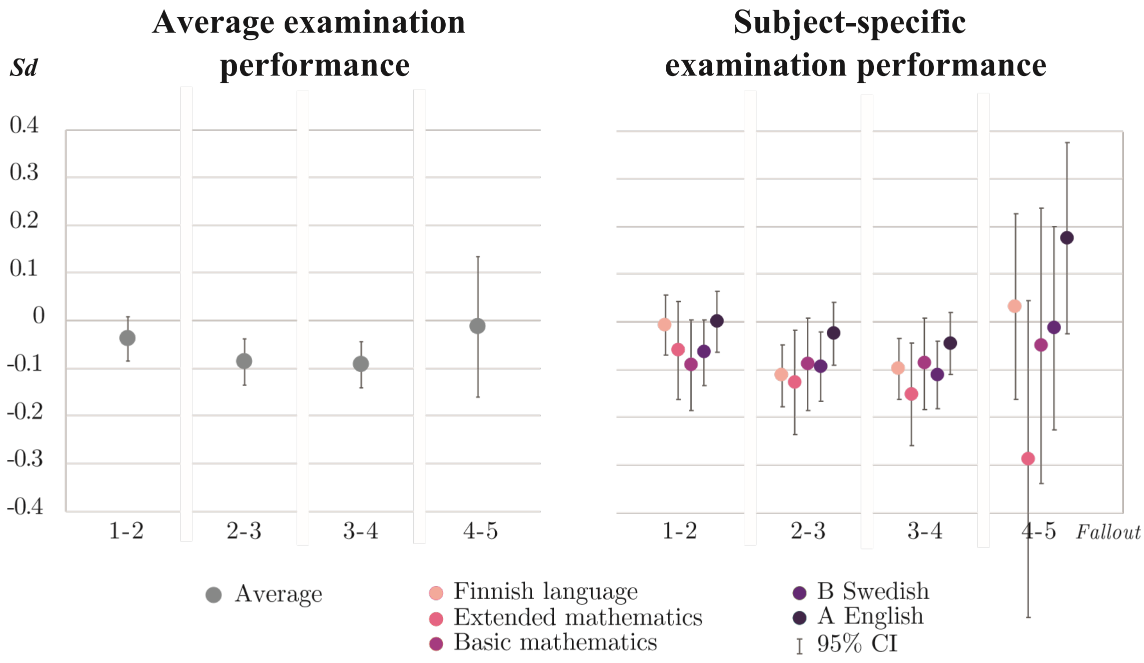
Notes: Upper panel reports the annual deposition of ^{137}*Cs in Ivalo, Niinisalo and Nurmijärvi. The lower panels report the levels of radioactivity immediately after the accident in Nurmijärvi.*

Figure 3: *Average matriculation examination performance by month of birth.*



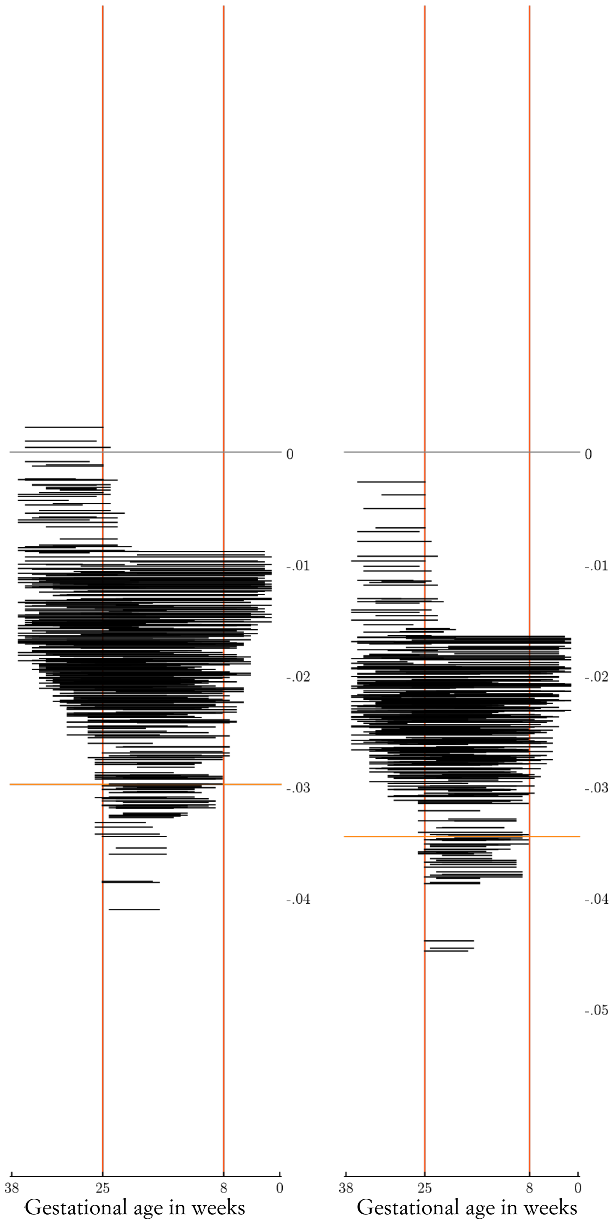
Notes: The graph illustrates how the examination performance varies over time. Upper panel reports the average matriculation performance by month of birth. The average performance is calculated as a mean of standardized subject-specific examination scores. Standardization is performed at examination level. The lower panels reports average matriculation performance for using regional classification based on the degree of ^{137}Cs contamination received. Classification of the contamination: low (1–25^{137}Cs), medium (25–48^{137}Cs) to high (48–72^{137}Cs). The vertical lines represent the beginning and the end of the birth cohort exposed to the radiation spike during the critical phase of prenatal development.

Figure 4: *Differences in matriculation performance by degree of contamination*



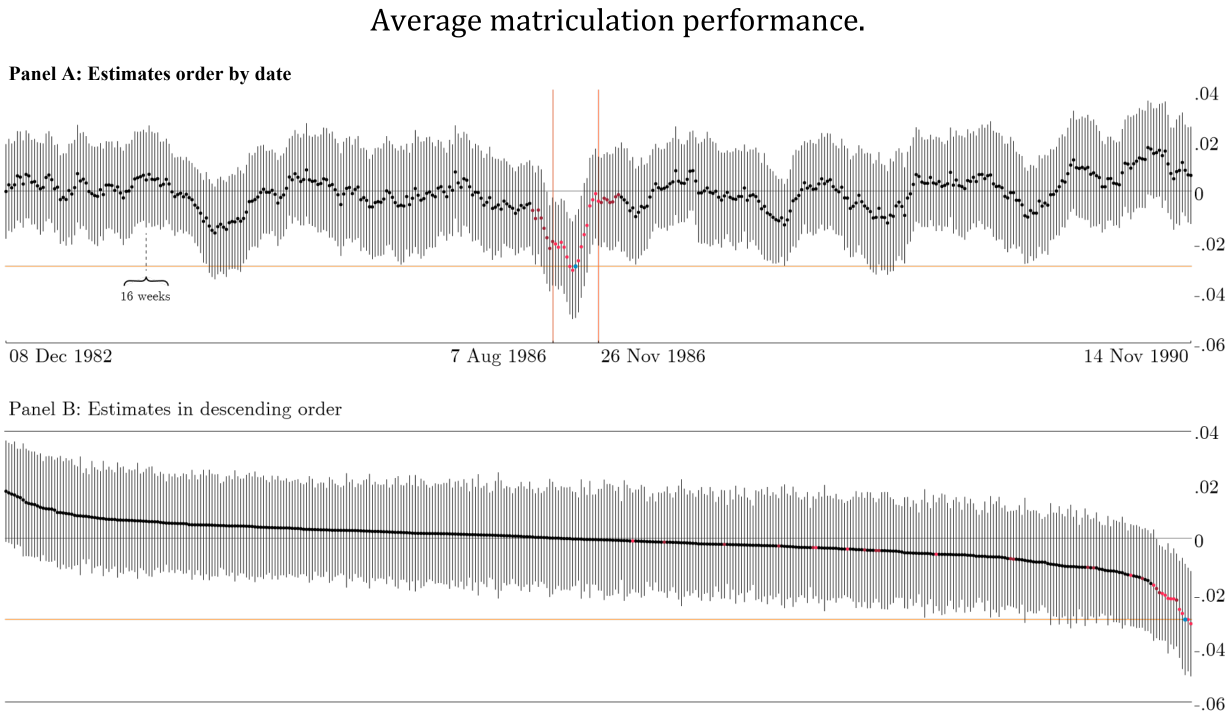
Notes: The graph illustrates how the matriculation examination performance is affected as the level of potential exposure to irradiation increases. vertical axis reports average performance in matriculation examination in standard deviations. Measurements are standardized at examination level. Average performance (left side) is an arithmetic mean of individual subject-specific standardized examination scores. Estimates are based on the non-linear specification (Model 3) using classified measure of Log ^{137}Cs*. Each group is compared against the reference area, in this case the municipalities reporting* ^{137}Cs *measurements in logarithmic form of less than 1.*

Figure 5: *Variation in radiosensitivity during gestation.*



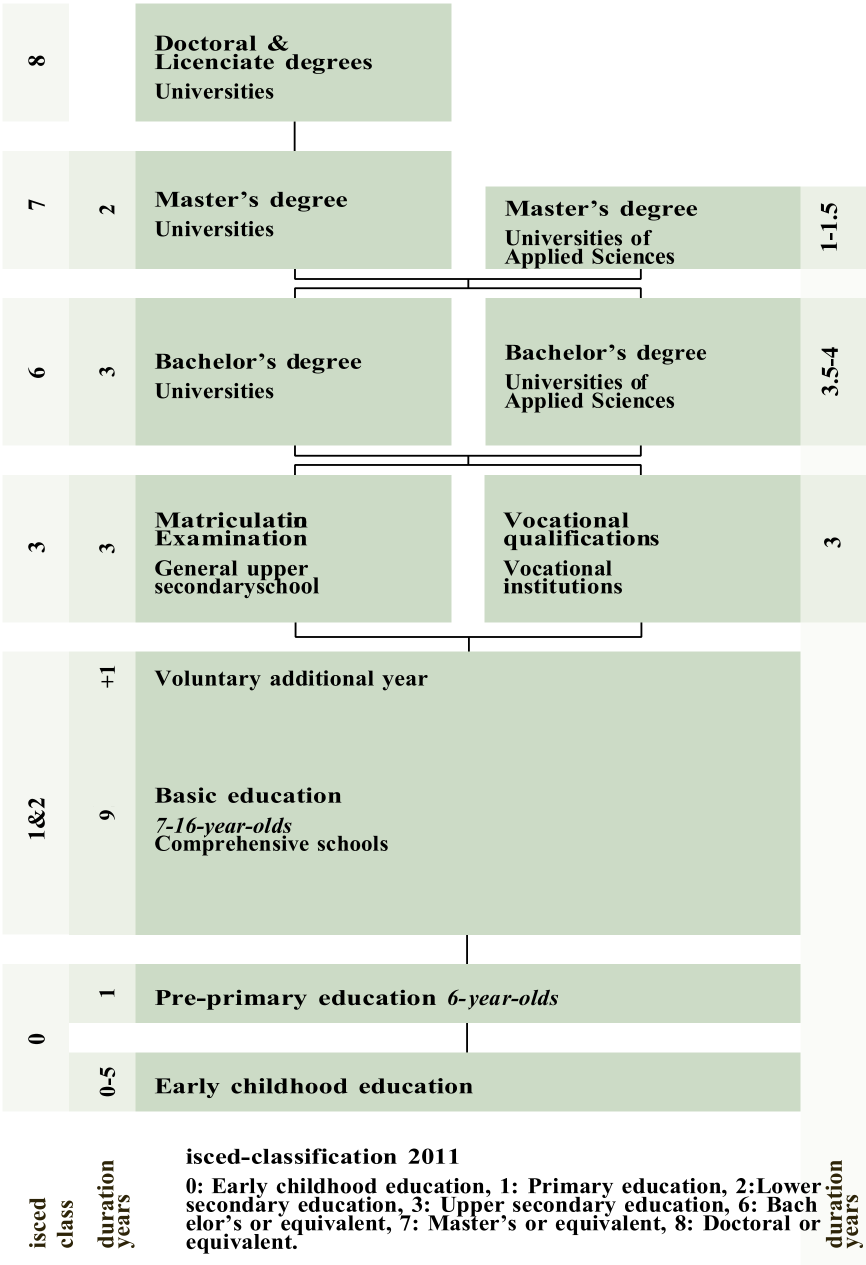
Notes: The graph illustrates the relationship between the temporal definition of critical part of the fetal period and the observed impact of irradiation. The purpose of the graph is to understand how altering the boundaries of the inutero cohort affects the estimates, how radiosensitivity changes over fetal period and to confirm previous finding regarding the presumably critical phase of fetal development in regard to cognition. The graphs report the estimated impact for arbitrary definitions of the critical parts of the fetal period. Horizontal black lines represent different definitions of the inutero cohort: the beginning and the ending of the presumably critical phase of prenatal development. The estimated impact on matriculation examination performance for a corresponding definition of the inutero cohort can be read from the vertical axis. The performance is measured in standard points. Gestational age is mapped on the horizontal axis. The impacts are estimated using the model for continuous measure of ^{137}Cs contamination (Model 1).
Vertical red lines define the weeks during which the mitotic activity in the developing brain is the highest (pregnancy weeks 8–25). The horizontal orange lines represent the estimated impacts while defining the weeks 8–25 as the inutero cohort.

Figure 6: *Placebo estimates: Average matriculation performance.*



Notes: The figure reports the estimates for a series of placebo treatments. The estimated impacts are calculated for arbitrary definitions of the inutero cohort over time. Each estimate is calculated for 16 weeks long definition of the inuitero cohort. The placebo treatments take place every week from 1982 to 1990. For estimating the impact, I use the model for continuous measure of the fallout (Model 1). Average matriculation performance is the mean of standardized individual level subject-specific matriculation examination scores. Estimates for the placebo treatments consisting of individuals born outside the presumably critical time window of fall 1986 are marked with black markers. Red markers represent estimates for placebo treatments that are partly overlapping the presumably critical birth cohort of 1986 (Marked with vertical red lines). The vertical black lines represent 95 percent confidence interval for corresponding estimates. Panel B reports the same estimates in descending order.

Figure 7: *Finnish Education system*



OPH, Finnish National Agency for Education and OKM, Ministry of Education and Culture (2017)

References

Aaltonen, H., Arvela, H., Asikainen, M., and al. Väliaikainen raportti, säteilytilanne Suomessa 26.4.-4-5-1986. *STUK Valvontaraportti (STUK-B)*, 44, 1986.

Ackerman, S. *Discovering the brain*. National Academies Press, 1992.

Alderman, H., Hoddinott, J., and Kinsey, B. Long term consequences of early childhood malnutrition. *Oxford economic papers*, 58(3), pp. 450–474, 2006.

Almond, D., Edlund, L., and Palme, M. Chernobyl's subclinical legacy: prenatal exposure to radioactive fallout and school outcomes in Sweden. *The Quarterly journal of economics*, 124(4), pp. 1729–1772, 2009.

Arvela, H., Markkanen, M., and Lemmelä, H. Mobile Survey of Environmental Gamma Radiation and Fall-Out Levels in Finland After the Chernobyl Accident. *Radiation Protection Dosimetry*, 32(3), pp. 177–184, 1990.

Banzhaf, H. S. and Walsh, R. P. Do people vote with their feet? an empirical test of tiebout. *American Economic Review*, 98(3), pp. 843–63, 2008.

Bergman, K., Sarkar, P., O'CONNOR, T. G., Modi, N., and Glover, V. Maternal stress during pregnancy predicts cognitive ability and fearfulness in infancy. *Journal of the American Academy of Child & Adolescent Psychiatry*, 46(11), pp. 1454–1463, 2007.

Black, S. E., Bütikofer, A., Devereux, P. J., and Salvanes, K. G. This is only a test? long-run and intergenerational impacts of prenatal exposure to radioactive fallout. *The Review of Economics and Statistics*, 101(3), pp. 531–546, 2019.

Cort, M. d. Atlas of caesium deposition on Europe after the Chernobyl accident, 1998.

Currie, J. and Almond, D. Human capital development before age five. In *Handbook of labor economics*, volume 4 pp. 1315–1486. Elsevier, 2011.

Currie, J. and Hyson, R. Is the impact of health shocks cushioned by socioeconomic status? the case of low birthweight. *American Economic Review*, 89(2), pp. 245–250, 1999.

De Santis, M., Di Gianantonio, E., Straface, G., Cavaliere, A. F., Caruso, A., Schiavon, F., Berletti, R., and Clementi, M. Ionizing radiations in pregnancy and teratogenesis: a review of literature. *Reproductive Toxicology*, 20(3), pp. 323–329, 2005.

Eleveld, H. Ionising radiation exposure in the Netherlands, 2003.

Hirose, K., Takatani, S., and Aoyama, M. Wet deposition of radionuclides derived from the Chernobyl accident. *Journal of Atmospheric Chemistry*, 17(1), pp. 61–71, 1993.

Jukic, A. M., Baird, D. D., Weinberg, C. R., McConnaughey, D. R., and Wilcox, A. J. Length of human pregnancy and contributors to its natural variation. *Human reproduction*, 28(10), pp. 2848–2855, 2013.

Kinly III, D. Chernobyl's legacy: Health, environmental and socio-economic impacts and recommendations to the governments of Belarus, the Russian federation and Ukraine. the chernobyl forum 2003-2005. second revised version, 2006.

Martin, J. H. *Neuroanatomia-: Texto e Atlas*. AMGH Editora, 2014.

Nowakowski, R. S. and Hayes, N. L. Radiation, retardation and the developing brain: time is the crucial variable. *Acta Paediatrica*, 97(5), pp. 527–531, 2008.

OPH, Finnish National Agency for Education and OKM, Ministry of Education and Culture. Finnish education in a nutshel, 2017.

Otake, M. Radiation-related brain damage and growth retardation among the prenatally exposed atomic bomb survivors. *International journal of radiation biology*, 74(2), pp. 159–171, 1998.

Paatero, J., Hämeri, K., Jaakkola, T., Jantunen, M., Koivukoski, J., and Sax´en, R. Airborne and deposited radioactivity from the chernobyl accident—a review of investigations in Finland, 2010.

Pilaz, L.-J., McMahon, J. J., Miller, E. E., Lennox, A. L., Suzuki, A., Salmon, E., and Silver, D. L. Prolonged mitosis of neural progenitors alters cell fate in the developing brain. *Neuron*, 89(1), pp. 83–99, 2016.

Pöllänen, R., Valkama, I., and Toivonen, H. Transport of radioactive particles from the chernobyl accident. *Atmospheric Environment*, 31(21), pp. 3575–3590, 1997.

Saxen, R., Taipale, T. K., and Aaltonen, H. Radioactivity of wet and dry deposition and soil in Finland after the Chernobyl accident in 1986. Technical report, Finnish Centre for Radiation and Nuclear Safety, 1987.

Shaw, P., Duncan, A., Vouyouka, A., and Ozsvath, K. Radiation exposure and pregnancy, 2011.

UNSCEAR, U. N. S. C. o. t. E. o. A. R. *Sources and effects of ionizing radiation*, volume 1. United Nations Publications, 2000.

Ylioppilastutkintolautakunta. Matematiikan kokeen määräykset, 2017.

Ylioppilastutkintolautakunta. Äidinkielen kokeen määräykset, 2017.

8. Appendix A.

8.1 Education system in Finland

Figure 7 illustrates the Finnish educational system. After nine years of mandatory basic education, students can enroll in General Upper Secondary School or in vocational qualifications.

Finnish Matriculation Examination

To participate in the matriculation examination in a given subject, the student must complete the mandatory studies required for the given subject. The matriculation examination consists of grades of at least four subjects. Students are free to choose subjects from an array of subjects, where the mother tongue is the only mandatory for all subjects. This freedom of choice imposes certain limitations on the outcome variables used to measure the endowment of education. For one, observing the variation in total grade points would be more insightful if the number of mandatory subjects was higher. Having said this, I assume that any cognitive impairment arising from prenatal irradiation would most likely affect all matriculation examinations, regardless of the subject, in a similar fashion.

8.2 Fallout

Classification of ^{137}Cs fallout

Duplicating the classification of the ^{137}Cs using the boundaries presented in Almond et al. (2009) is neither justified nor reasonable in the Finnish context. Doing so would result in a seemingly unbalanced grouping of the sample, as can be seen from tables 9 and from panel 2B of figure 1.

Timing of the presumed exposure

For the purpose of understanding how the presumed timing of potential exposure to irradiation affects estimates, I run several regressions while manipulating the boundaries for the *inutero* cohort. Using the model 1, the estimates are calculated for all combinations where the arbitrary *inutero* cohort take course of 7 to 17 weeks, using a one-week interval, for all weeks of birth where the foetus was exposed to irradiation. This allows me to observe all the reasonable definitions of the *inutero* cohor. The results are reported in figure 5. For comparability, I also estimate the impact using the definition of the *inutero* cohort defined in Almond et al. (2009). The estimates are reported in Table 7 panel B. The results seem to suggest that the estimates presented in Almond et al. (2009) could be diluted by including people who were exposed to irradiation outside the critical window.

8.3 Summary statistics

Table 8: *Regional Classification of the Fallout*

	Observations			Caesium-137 kBq/m	
	1.1.1980	30.7.1986	26.11.1986		
Fallout	to	to	to		
Classification	30.7.1986	26.11.1986	31.1.1990	Mean	Std. Dev.
R0	46575	2124	27712	1.76	0.23
R1	108185	5131	70987	4.06	1.27
R2	116155	5380	70987	11.50	3.77
R3	121311	5520	74812	36.50	11.43
Total	392216	18155	242500	15.57	15.41

First three columns report the number of observations based on the dates of birth and the regional classification based on the degree of contamination. Mean is calculated using even weights for the municipalities.

Table 9: *Regional classification motivated by Almond et al. (2009)*

	Number of Observations			^{137}Cs contamination	
	1.1.1980	1.8.1986	31.12.1986		
Fallout	to	to	to		
Classification	1.8.1986	31.12.1986	31.1.1990	Mean	Std. Dev.
AEP-R0	11706	666	6949	1.42	0.20
AEP-R1	43514	2492	25388	1.92	0.11
AEP-R2	253221	14807	154282	10.60	7.43
AEP-R3	84172	4771	51101	42.23	9.75
Total	392736	22736	237717	15.54	15.54

First three columns report the number of observations based on the dates of birth and the regional classification based on the degree of contamination. Class boundaries and the definition of the inutero cohort mimic boundaries defined in Almond et al. (2009).

Table 10: *Summary statistics: Measure of contamination.*

	Caesium-137 deposition					
	mean	sd	p10	p25	p75	p90
^{137}Cs	15.18	15.32	1.96	3.88	23.58	41.25
Log ^{137}Cs	2.19	1.06	0.67	1.36	3.16	3.72

Measurement of caesium-137 is used as a measure of radioactivity on municipality level. The measurements have been corrected for decay and washout effects.

Table 11: *Summary statistics: Outcome Variables*

	Born 1980–1991			Born 1986		
	Examination points					
	Mean	Sd	n	Mean	Sd	n
Finnish	67.15	18.84	330327	74.89	11.12	28838
Extended mathematics	28.97	14.51	124431	25.75	13.95	11134
Basic mathematics	27.83	13.01	158137	29.90	13.33	14511
English A	199.18	48.33	340204	213.40	45.18	29773
Swedish B	178.27	54.73	268389	188.42	51.06	23157
	Standardized examination points					
Finnish	0.00914	0.99898	330326	0.02365	0.99746	28838
Extended mathematics	0.00302	0.99969	124431	0.00150	0.99702	11134
Basic mathematics	0.00487	0.99896	158137	0.00100	0.99854	14511
English A	-0.00022	0.99965	340204	0.00179	1.00440	29773
Swedish B	0.00101	0.99938	268387	0.05578	0.98804	23157
Higher education	0.689	0.463	349729	0.696	0.460	30545
Female	-	-	-	-	-	-
Income at 25	15422	12572	349400	16087	12202	30558
Income at 26	18650	14011	349445	19695	14226	30557
Income at 27	21535	15932	349569	22283	17916	30542
Income at 28	23766	17209	318601	24285	17943	30554
Income at 29	25408	18682	287770	25669	19950	30601
Income at 30	26841	19706	256297	27289	21774	30669
Income at 31	28137	23560	226166	29282	35954	30774
Income at 32	29238	23886	195640	.	.	0
Income at 33	30488	25673	164049	.	.	0
Income at 34	31825	27005	131660	.	.	0
Income at 35	33243	29772	98136	.	.	0

The table reports descriptive statistics regarding matriculation examination. The means are calculated using the raw scores and standardized scores. Higher education is an indicator variable taking value of one for the individuals with ISCED classified educational degree of 6 or greater and zero otherwise. Annual income in euros.

Table 12: *Summary statistics*

Control variables: Parental education						
		Father			Mother	
ISCED	**Mean**	**Sd**	**n**	**Mean**	**Sd**	**n**
Class 1	0.256	0.437	353210	0.279	0.448	353210
Class 2	0.008	0.087	353210	0.010	0.097	353210
Class 3	0.132	0.338	353210	0.226	0.418	353210
Class 4	0.091	0.288	353210	0.088	0.283	353210
Class 5	0.114	0.318	353210	0.122	0.327	353210
Class 6	0.023	0.151	353210	0.015	0.123	353210
Class 7	0.375	0.484	353210	0.261	0.439	353210

Parental education is an indicator variable with a value of one for individuals with an ISCED classified degree of 6 or higher and zero otherwise. The Finnish education system and the ISCED classification is described in detail in figure 7.