CHERNOBYL'S SUBCLINICAL LEGACY: PRENATAL EXPOSURE TO RADIOACTIVE FALLOUT AND SCHOOL OUTCOMES IN SWEDEN*

DOUGLAS ALMOND
LENA EDLUND
MÅRTEN PALME

We use prenatal exposure to Chernobyl fallout in Sweden as a natural experiment inducing variation in cognitive ability. Students born in regions of Sweden with higher fallout performed worse in secondary school, in mathematics in particular. Damage is accentuated within families (i.e., siblings comparison) and among children born to parents with low education. In contrast, we detect no corresponding damage to health outcomes. To the extent that parents responded to the cognitive endowment, we infer that parental investments reinforced the initial Chernobyl damage. From a public health perspective, our findings suggest that cognitive ability is compromised at radiation doses currently considered harmless.

I. INTRODUCTION

Empirical studies in the human capital tradition have sought to isolate the role of latent variables—such as ability or family background—from differences in other inputs or production technologies. An obvious challenge for such studies is the lack of exogenous variation in the latent variables, which, in turn, may be highly interrelated. For example, children's cognitive ability may be positively related to family background and this background may affect other human capital investments or their return (or both). Furthermore, parents or education policies may respond to realizations of a latent variable, such as compensating for children with low innate ability.

A natural experiment in a specific latent factor could help disentangle some of these relationships. First, the magnitude of the reduced form impact on human capital formation could be assessed—for example, how much does cognitive ability matter?

---

*We would like to thank Leif Moberg (Swedish Radiation Protection Authority) for providing the radiation data and key references. We also thank Johanna Adami, Hoyt Bleakley, David Brenner, Janet Currie, Lucas Davis, Avraham Ebenstein, Tore Ellingsen, Bill Evans, Raquel Fernandez, Andrew Foster, Michael Greenstone, Eric Hall, Per Hall, Ethan Kaplan, Wojciech Kopczuk, Wilbert van der Klaauw, David Lee, Bhashkar Mazumder, Costas Meghir, Mark Peplow, Torsten Persson, Per Pettersson-Lidbom, Cristian Pop-Eleches, Heather Royer, William Schull, David Strömberg, Ezra Susser, Miguel Urquiola, Simon Wright, and Lydia Zablotska for valuable comments. Financial support from the National Science Foundation (Grant 0721155) and the Russell Sage Foundation is gratefully acknowledged. *da2152@columbia.edu, le93@columbia.edu, marten.palme@ne.su.se.*

The Quarterly Journal of Economics, November 2009

Second, with data on baseline characteristics (e.g., family background), we could observe how predetermined factors interact with the latent input in producing human capital.

The physical environment can provide exogenous variation in latent human capital inputs. Cunha and Heckman (2007) observed that "abilities are susceptible to environmental influences, including *in utero* experiences." But Tiebout sorting implies that proximity to environmental hazards may be endogenous (Banzhaf and Walsh 2008). Therefore, changes in the local environment caused by accidents or pollution might be more compelling empirically, especially when the environmental damage is physically removed from its source. Finally, environmental epidemiology can specify pathways by which the environment affects specific latent inputs, such as, prenatal famine exposure and adult schizophrenia (St. Clair et al. 2005).

In this paper, we argue that radioactive fallout from the 1986 Chernobyl accident in Sweden offers a natural experiment in cognitive ability. Although Sweden is more than 500 miles away from Chernobyl, weather conditions caused it to receive about 5% of the accident's cesium fallout. Due to variation in rainfall levels while the radioactive plume was over Sweden, there was stark geographic variation in the levels of fallout. Chernobyl fallout is of interest because cognitive development is sensitive to prenatal radiation exposure (Otake and Schull 1998; Nowakowski and Hayes 2008).[1] Despite targeting cognitive ability, empirical studies of human capital formation have not previously assessed radiation damage. Epidemiological studies have focused on radiation exposure where either (i) the estimated dose was an order of magnitude higher, or (ii) doses were low but exposures were unlikely to be exogenous, for example, radiation from radon or medical procedures.

Following the findings from studies of A-bomb survivors, we focus on the cohort between weeks 8 and 25 of gestation at the time of the accident, and thus born in the fall of 1986.

We evaluate Chernobyl's impact using administrative data on the universe of birth, hospital discharge, and schooling outcomes in Sweden for cohorts born 1983–1988 (it is too early to assess labor market outcomes). In particular, we evaluate (1) health status

---

[1] The link made between prenatal medical radiation and microcephaly (small head circumference) in 1929 was the "first indication of malformations induced by an iatrogenic agent in human beings" (DeSantis et al. 2005).

as recorded by natality data and the inpatient registry, which includes all hospitalizations between 1987 and 2006; (2) performance in the final year of compulsory school (age 16); and (3) performance in high school (age 19). Importantly, we observe both place of birth and parental education. This enables us to compare impact estimates by parental education, as suggested by Currie and Hyson (1999), Case, Lubotsky, and Paxson (2002), and Currie and Moretti (2007).

We find that the fall 1986 birth cohort performed substantially worse in the final year of compulsory schooling (i.e., middle school). Grades in mathematics were particularly affected. This cohort was also less likely to have graduated from high school (as of 2006) and had worse grades conditional on graduating. Furthermore, the magnitude of damage to the fall 1986 cohort corresponds to regional differences in fallout. Projecting forward, we estimate that Chernobyl will cause a 3% reduction in annual earnings for the most-exposed Swedes. In contrast, we do not detect corresponding health damage. Neither the birth outcomes (including birth weight) nor the hospital discharge records reveal damage. Thus, we believe Chernobyl fallout in Sweden isolated a latent factor: cognitive ability.

Interestingly, the damage to human capital is highly concentrated in families with low-education parents. This pattern exists both across and within families, that is, when we compare exclusively among siblings where one was exposed to Chernobyl while *in utero*. This pattern—together with the fact that sibling fixed effects estimates are generally stronger than simple difference-in-differences estimates—suggests that if parents responded with postnatal investments, they were most likely reinforcing, that is, accentuating differences in birth endowments (Rosenzweig and Schultz 1982; Rosenzweig and Zhang 2009; Datar, Kilburn, and Loughran forthcoming). Finally, our impact estimates are strengthened when we instrument for measurement error in fallout deposition with rainfall, suggesting that our OLS estimates are conservative.

The remainder of our paper is organized as follows. Section II describes the Chernobyl accident, summarizes the literature on prenatal exposure to ionizing radiation, and then describes the Swedish school system. Section III describes the radiation, schooling, and health data that we analyze. Section IV presents our main results, followed by an instrumental variables approach to address bias from possible measurement error using rainfall; we then provide a back-of-the-envelope calculation of the accident's costs. Section V considers whether human capital investments may have responded to Chernobyl damage and interprets the concentration of damage among families with low-education parents. Finally, Section VI discusses the external validity of our results for various other sources of ionizing radiation.

II. BACKGROUND

II.A. The Chernobyl Accident

The core meltdown at Chernobyl occurred at 1:24 A.M. on April 26, 1986, in Ukraine. The world first learned of the accident the next day, when the cloud reached Sweden. Heightened levels of radioactivity had set off alarm bells at the Swedish nuclear plant Forsmark, some 680 miles away. During the ten days it took to control the fire, large quantities of radioactive material were released. Europe received the bulk of the fallout, but measurable levels of ground deposition have been detected in all countries in the northern hemisphere (UNSCEAR 2000).

The Chernobyl accident provides a nearly ideal natural experiment in radiation exposure. Meteorological conditions resulted in Sweden receiving about 5% of the cesium fallout, creating a pronounced spike in radiation levels (Moberg 1991). Figure I shows measured gamma radiation in Njurunda in Sundsvall municipality (about 1,000 miles from Chernobyl). Gamma radiation in Njurunda peaked on April 29 at over ten times background levels.

There was also substantial geographic variation in deposition due primarily to differences in rainfall at the time of the accident (Holmberg, Edvarson, and Finck 1988).[2] Njurunda registered the highest radiation level among Sweden's fixed gamma monitoring stations (Kjelle 1987). Ground deposition in the worst-affected areas (around Gävle and Sundsvall) equaled that found just outside Chernobyl's 30-km (19-mile) radius exclusion zone, whereas the northernmost parts of Sweden were virtually spared (see Figure II). In addition to the distinct time and geographic variation, this natural experiment exposed a large number of people, thereby overcoming an important challenge to evaluating effects

---

[2] Daily rainfall data for about 100 weather stations in Sweden 1985–1986 (from the U.S. Department of Commerce) reveal that between April 27 and May 30, it rained substantially more near Gävle and Sundsvall. Also, rainfall during this period was uncorrelated with rainfall during the rest of the year (see Section IV.D).

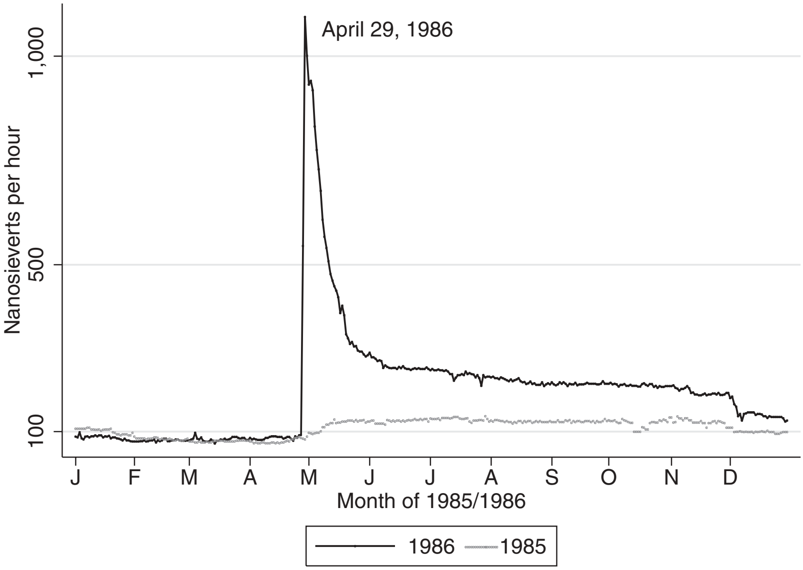


FIGURE I
Daily Gamma Radiation in Njurunda, Sweden
Source. Kjelle (1987).

of low-dose radiation (because effect sizes are also presumably small (Brenner et al. 2003)).

II.B. Prenatal Radiation and Cognitive Damage

It is generally accepted that prenatal radiation exposure causes cognitive damage. However, the best-regarded epidemiological studies considered radiation doses an order of magnitude higher than the maximum dose for Swedes following Chernobyl, estimated at 4 mSv in the first year (Edvarson 1991a).[3] While exposure to low-dose ionizing radiation is common, the low-dose question remains unresolved (DeSantis et al. 2005; Peplow 2006). The pathophysiologic mechanism for cognitive effects is summarized below, followed by the epidemiological studies of medical radiation and the 1945 atomic bombings of Hiroshima and Nagasaki.

Damage to neural development from prenatal irradiation is biologically plausible. Ionizing radiation ejects electrons capable

---

[3] See Section III.A and Online Appendix D for a summary of radiation measurements and magnitudes.

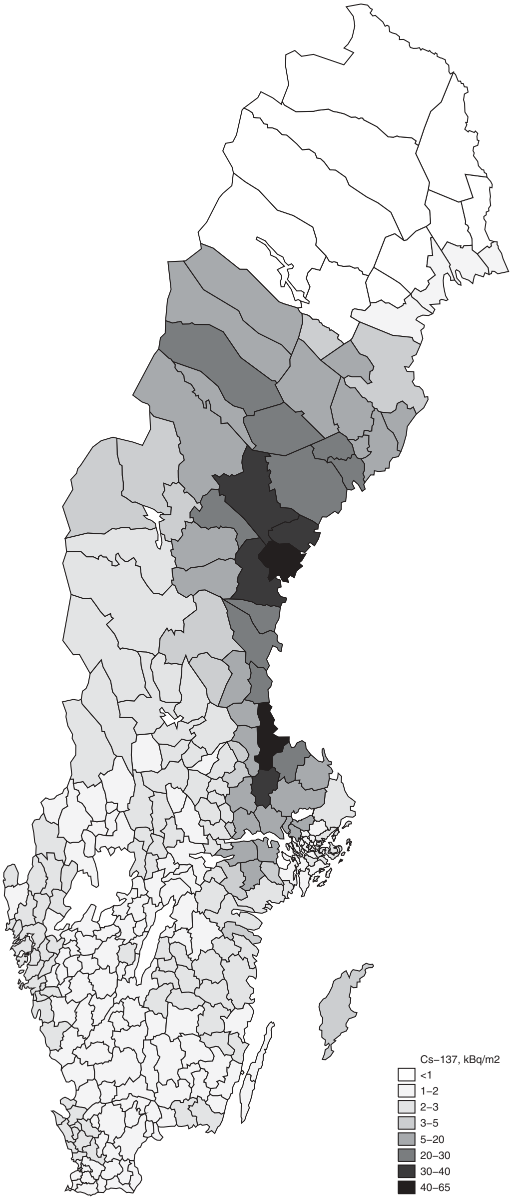


FIGURE II
Cesium-137 Ground Deposition in kBq/m^2 by Municipality

Source. From the Swedish Radiation Protection Authority.

Aerial measurements are corrected according to Edvarson (1991b) and are population-weighted.

of breaking chemical bonds, those in DNA strands in particular. Although there is some ability to repair, improper repair may lead to mutations or cell death.[4] DNA is particularly vulnerable during cell cycling and division, which are more rapid early in life.[5] The brain differs from other epithelial organs in that there is little cell proliferation in the adult brain. This limited renewal means that insults to the developing brain are likely to have permanent effects. Nowakowski and Hayes (2008, p. 527) state that "any neural loss sustained during the developmental period is retained for life." Weeks 8–25 postconception mark a major neuronogenetic period for the neocortex. During this period, the neocortex expands more than 100-fold (Nowakowski and Hayes 2008), and the normal number of neurons in the neocortex in an adult may already have been achieved by week 16 (Otake and Schull 1998). Except in the hippocampus, no neuronal stem cell proliferation takes place after birth (Gluckman and Hanson 2005).[6] Radiation interferes with the two main processes of proliferation and migration to the cortex and results in fewer and/or improperly wired neurons (the migration is guided by specialized neurons that later self-destruct).

The first indication that *in utereo* radiation exposure caused cognitive damage (microcephaly and mental retardation) came from case studies of children born to women who had been treated with high doses of medical radiation while pregnant (DeSantis et al. 2005). It was the larger-sample studies of atomic bomb survivors that permitted a finer analysis of when during pregnancy radiation was most damaging; see Otake and Schull (1998). The sample used in these studies contains 1,566 individuals (1,242 in Hiroshima and 324 in Nagasaki) who prenatally were closer than 2,000 meters to the hypocenter of the atomic bomb explosion. Two control groups from the same areas were matched to the sample on the basis of age and sex: one of distally exposed survivors (3,000–4,000 meters from the hypocenter) and one of nonexposed survivors ($>$10,000 meters). In addition to some anthropometric measures (e.g., weight, height, and head size), these studies also analyzed cognitive ability (IQ) and school

---

[4] Although cell death is believed to be roughly proportional to dose rate, the ability to repair and compensate is unknown.

[5] The effect of radiation on DNA and DNA's vulnerability during cell division is a reason radiation can both cause and treat cancers—cancer cells not showing the slowdown in growth typical of normal cells.

[6] The brain continues to grow after birth, but this growth is largely that of myelin, not neurons.

records. The effect on IQ was estimated to be a reduction by 25–30 points per Gy (1,000 mGy) for those exposed at postovulatory ages 8–15 weeks. A smaller reduction was estimated for those aged 16–25 weeks. For children exposed earlier or later, no significant effect was found.

Irradiation outside the window at 8–25 weeks was not associated with lower cognitive performance among the A-bomb survivors. That is not to say that radiation does not have effects outside those ages. In the preimplantation period (the first two weeks after conception), radiation is believed to result in embryonic death, but conditional on survival, there are no developmental effects. During organogenesis, 2–7 weeks postconception, the internal organs are developed, and radiation during this period can lead to malformations and growth retardation, including small head size (but without mental retardation). Radiation in the third trimester can heighten the risk of cancer (Hall and Giaccia 2005). But so far as the central nervous system is concerned, the period after the 25th week of pregnancy is "relatively radioresistent" (DeSantis et al. 2005).

Median exposure for A-bomb survivors was estimated to be 40 mGy (Otake and Schull 1984). Whether the findings from the A-bomb survivors generalize to doses less than 10 mGy has not been established (Hall and Giaccia 2005; BEIR 2006).

In light of the effects documented above, both ethical and cost considerations preclude controlled experiments with low radiation doses.

II.C. Chernobyl Studies

A number of previous studies have found reduced cognitive function due to prenatal radiation in high-fallout areas of Ukraine, Belarus, and Russia, such as Nyahu, Loganovsky, and Loganovskaja (1998), Kolominsky, Igumnov, and Drozdovitch (1999), and Loganovskaja and Loganovsky (1999). These studies have focused on populations born near the reactor. As a consequence, they were exposed to much higher levels of radiation than considered here, and sample sizes were relatively small.

Perinatal impacts have been evaluated in areas of Europe with substantially lower levels of Chernobyl fallout. Outcomes including conception, spontaneous abortion, induced abortion, stillbirth, gestation length, birth weight, and neonatal mortality have been studied (Lüning et al. 1989; Ericson and Källén 1994; Sperling et al. 1994; Scherb, Weigelt, and Brüske-Hohlfeld 1999;

Auvinen et al. 2001; Laziuk et al. 2002). For each outcome, studies can be found on either side: some find effects and others do not, and generally the effects have been small.

In the interest of space, we refer the reader to our working paper (Almond, Edlund, and Palme 2007) for a more thorough discussion of these studies.

II.D. The Swedish School System

Primary and middle schooling (*Grundskola*), grades one through nine, is compulsory in Sweden (unlike in the United States, where compulsory schooling relates to age, typically the sixteenth birthday). The school year begins in August, and typically, pupils enroll in first grade the calendar year they turn seven.[7] Although some specialization is allowed after sixth grade, students are kept in common classes and the final-year grades are set on the basis of the outcomes from national tests.

Pupils are graded in sixteen individual subjects. The grades are set in two stages. In the first stage, each school's average grade is set on the basis of how the school's pupils did in national tests. The specific subject grades we will analyze—mathematics and Swedish—are both set according to nationally standardized tests. (This national benchmarking would tend to attenuate the cohort main effect below, but not the difference-in-differences estimator.) In the second stage, the individual pupil's grades are set. In addition to his or her performance on the national test, performance on local tests and in the classroom are factored in (which are not nationally standardized). Grades are assigned according to a four-point scale:

- "Failed" (0 points)
- "Passed" (10 points)
- "Passed with distinction" (15 points)
- "Passed with special distinction" (20 points)

The grades from the last year in compulsory school (in the spring after the pupil turns sixteen years old) are used for admission to secondary education. In particular, passing grades in the three "core" subjects—English, Swedish, and mathematics—are required for matriculation.

---

[7] Public, or free, education (all levels) dominates schooling in Sweden. Recently, there has been a growth in private schools that are state-financed and do not charge tuition. Only a handful of tuition-charging schools exist.

Roughly 90% continue to secondary school (*Gymnasieskola*), which is elective and divided into two basic tracks: vocational and academic. Within these tracks, there are different programs, most of which last three years. The main programs in the academic tracks are science, social sciences, and business administration. Each program consists of separate courses. Some of these courses are common even between different programs and graded on the basis of results on national tests, using the same grading system as in compulsory school. The grades from secondary school are used for admission to higher education (colleges and universities).

Beginning in 1989, municipalities assumed responsibility for providing compulsory and secondary education (prior to 1989, school administration was at the county level). Although the schools are regulated by a national curriculum, the political majority in the individual municipalities has discretion over the management of the schools and resources allocated to education. This, in turn, may generate correlation of school performance between individuals within municipalities as well as autocorrelation over time. Our cohorts entered primary education in 1990 and therefore we will cluster standard errors at the municipality level.[8]

III. DATA

Below, we describe the radiation, schooling, and health data that we will analyze. Outcomes data are available for cohorts born 1983–1988. Assuming that the radioactive cloud swept Sweden April 27–May 10, and a 38-week postconception gestation, this implies that those between 8 and 25 weeks gestation are those born between July 27 and December 13, 1986. Thus, we will consider the cohort born between August and December of 1986 the *in utero* cohort.

III.A. Radiation Data

Following Chernobyl, ground deposition of Cs-137 fallout (half-life of 30.2 years) was mapped for most of Europe; see UNSCEAR (2000).[9] For Sweden, the Swedish Geological Co. (SGAB)

---

[8] The number of clusters—286—is sufficient to avoid downward bias in the estimated standard errors (Angrist and Pischke 2009). Furthermore, the most conservative approach, suggested by Donald and Lang (2007), is to use the treatment and control group averages. Our effects estimated using this method are still highly significant (results available from the authors).

[9] “From the radiological point of view, ^{131}I and ^{137}Cs are the most important radionuclides to consider, because they are responsible for most of the radiation

(commissioned by the Swedish Radiation Protection Authority, *Statens Strålskyddsinstitut*) conducted aerial measurements of ground-deposition gamma radiation from cesium-137 over the period May–October 1986 and decay-corrected to May 1986.[10]

We have obtained these aerial measurements for 2,380 parishes (out of 2,517). A parish is a rather small geographic unit, and for most people, everyday activities would involve crossing parish boundaries. Therefore we aggregate to the municipality or county level.[11] The aerial measurements of deposition were calibrated against *in situ* gammaspectrometric measurements using high-resolution germanium detectors at 61 locations covering 48 municipalities (Holmberg, Edvarson, and Finck 1988; Edvarson 1991b). Because of their importance, we focus on cesium and iodine-131 (half-life of 8 days).

We consider two basic types of radiation measures in this paper. First, there are measures of ground deposition of radioactive cesium. Second, there are measures of dose, which reflect the energy absorbed by matter. Deposition is more easily measured than dose. Deposition estimates are measured in kilobecquerels (kBq) per appropriate unit (e.g., per square meter) and doses in millisieverts (mSv), where the sievert refers to the dose equivalent (which for gamma radiation is the numerical equivalent to absorbed dose, denoted in units of gray (Gy)). To give a rough sense of magnitudes, regions with kBq/m^2 above 37 were considered "contaminated," whereas 6 mSv is a common estimate of annual dose due to background radiation. These measures are described in greater detail in the Online Appendix D.

Regional Groups. Based on information from the aerial measurements and *in situ* measurements, we classify Sweden into four regional groups as detailed in Table I and mapped in Figure III. Classification at the measured extremes is straightforward. The areas around Gävle and Sundsvall were particularly hard hit,

---

exposure received by the general population" UNSCEAR (2000, para. 21). The release of ^{131}I and ^{137}Cs has been estimated at 1,760 and 85 pBq, respectively (UNSCEAR 2000).

[10] In fact, cesium-134 (half-life of 2.1 years) was measured because of its known relationship to cesium-137 (a Cs-137/Cs-134 ratio of 1.7) and the fact that radiation from atmospheric nuclear weapons tests stemmed almost exclusively from cesium-137, rendering the Cs-134 isotope a more accurate indicator of Chernobyl-related cesium fallout.

[11] The county (*län*) is the first-level administrative and political subdivision. There are 21 counties. The second level is the municipality (*kommun*), and there are some 286 municipalities. The parish (*församling*) is the third and lowest level.

TABLE I
GEOGRAPHIC CLASSIFICATION BY FALLOUT—MAPPED IN FIGURE III

Area	Description	*N* born 1983–1988	*N* born Aug.–Dec. 1986	Cs-137 kBq/m^{2a}
R3	"Gävle and Sundsvall": Älvkarleby, Heby, Gävle, Timrå, Härnösand, Sundsvall, Kramfors, and Sollefteå (municipalities)	18,253	1,139	44.1
R2	Not R0, R1, or R3	375,556	24,094	4.74
R1	Värmland, Örebro, and Stockholm (counties)	140,143	9,540	1.93
R0	Norrbotten (county)	17,678	1,061	0.96[b]
	All Sweden	551,630	35,834	5.7

Note. The radiation values are population weighted. Areas R0–R3 are mutually exclusive and collectively exhaustive.

[a] All value from the Swedish Radiation Protection Authority, except *b*, see below.

[b] From Edvarson (1991b).

whereas Norrbotten county was virtually spared. Consequently, we include in the top group Gävle and Sundsvall and six contiguous municipalities. Together, these eight municipalities registered the eight highest levels of ground deposition of cesium-137. As for the control group, the choice of R0 (Norrbotten county) is dictated by Edvarson (1991b, Table 2) and UNSCEAR (2000, Figure X), where Norrbotten shows the lowest values of cesium-137.

Norrbotten is, however, a sparsely populated county. Therefore, we also present results from using a broader control group. Based on Holmberg, Edvarson, and Finck (1988, Figure 2) as replicated in our working paper (Almond, Edlund, and Palme 2007, Figure 4), we extend the control group to also include the counties denoted by R1 (in Table I): Stockholm, Örebro, and Värmland.[12]

In sum, although data clearly single out our two extreme areas—R0 and R3—the division of the "middle" into R1 and R2 may be viewed as exploratory. However, this categorization will allow us to present results in both figures and regression tables with more than one comparison group.

---

[12] The authors spent the summer of 1986 in R1 and R2, but avoided R3.

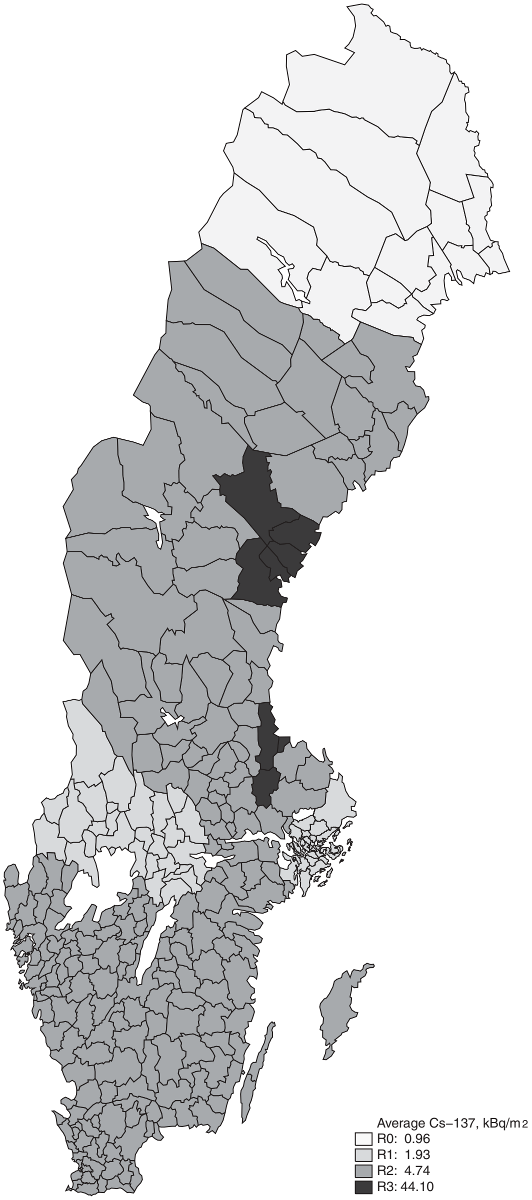


FIGURE III
Cesium-137 Ground Deposition in kBq/m^2 by Area (cf. Table I)

Source. From the Swedish Radiation Protection Authority.

Aerial measurements are corrected according to Edvarson (1991b) and are population-weighted.

Continuous Measures. We also consider four continuous measures of radiation exposure:

I-131, *in situ*, municipality. In the 43 municipalities with data, I-131 ranged from 3.3 to 627 kBq/m^2.

Cs-134, *in situ*, municipality. In the 48 municipalities with data, the range is 0.12–54 kBq/m^2. These values were used to calibrate the aerial measurements, and therefore should coincide (by a factor of 1.7) with the aerial measures for the location in question. We include this measure to allow comparison with the I-131 measures. While there was variation in the nuclide composition, these two radionuclides were highly correlated (correlation .97).

Cs-137, aerial, municipality. Here we have full coverage. Municipality averages range from 0.3 to 64 kBq/m^2. We have made the following substitutions. In accordance with Edvarson (1991b, Table 2), we assign value 0.3 kBq/m^2 to all but four coastal municipalities in Norrbotten county, and a value of 4.1 kBq/m^2 to Gotland county. The geographic variation at the municipality level is shown in Figure II.

Cs-137, aerial, county. These are the municipality values aggregated to the county level. County averages range from 1 to 32 kBq/m^2.

The *in situ* measurements come from Edvarson (1991b, Table 7) where we assign the measured value to the municipality of the measuring station. There were 61 stations, covering 48 municipalities.[13] Iodine (I-131) readings were missing from some stations, so for iodine we only have readings for 43 municipalities. Although the *in situ* readings may be more reliable than the aerial measurements, there is a steep trade-off in power, as we can match these monitors to less than one-third of the student sample.[14]

III.B. School Outcomes

Below we describe the schooling data. These data are matched to the radiation measures above based on the mother's parish of residence at the time of birth. As a result, we have a fairly

---

[13] For three stations, we could not locate the position with enough precision to identify a unique municipality and we resorted to assigning the measured radiation readings to adjacent municipalities.

[14] As the aerial measurements were calibrated using the *in situ* readings, an instrumental variables approach to correct for measurement error is not feasible. See Section IV.D.

good measure of the mother's likely location in Sweden during pregnancy.

Compulsory Schooling. Compulsory school records for cohorts born 1983–1988 come from two sources. The first data set consists of all persons who were either born between 1983 and 1985 or the children of Swedish-born parents born between 1940 and 1985. As a result, this data set has almost universal coverage of the cohort born 1983–1985. For the 1986 birth cohort, we capture everybody who had at least one Swedish-born parent younger than age 46 (in 1986), and for 1987 and 1988 this age is 47 and 48, respectively. Because fertility is nearly complete for women by age 45, this means that coverage for the later cohort is also almost universal.

To this data set we have matched final grades from the last year of compulsory school (typically obtained at age sixteen), as well as individual information from the National Birth Register and from the National Inpatient Register, containing diagnosis codes for all admissions to Swedish hospitals. Altogether, we have 551,630 complete observations. Online Appendix Table A.1 contains descriptive statistics.

In addition to the individual grades in the subjects mathematics and Swedish, we focus on the following outcome variables:

Qualify for High School. As noted in Section II.D, one must pass English, Swedish, and mathematics in the ninth grade to be eligible to attend high school.

Average Grade. The average grade in sixteen subjects, with a maximum of 20 points. It is used for application for secondary education.

High School. We obtained high school records through 2006 for all students born in Sweden. Students typically graduate the year they turn nineteen, and therefore we restrict our sample to those born between 1983 and 1987. For this data set we have 444,583 complete observations. Descriptive statistics are provided in Online Appendix Table A.2.

We focus on whether the person has graduated from high school (73%), average grades, and individual grades in mathematics and Swedish.

III.C. Control Variables

Parental education. We obtained information on parental education as of 1990, the earliest year available. Parental education comes from the National Education Register, obtained from the Longitudinell integrationsdatabas för sjuktörsäkrings-och arbetsmarknads studier (LISA) database, which we merged with the schooling records using a unique person identifier. We will include dummy variables for the education level (two sets, one for each parent). These variables indicate the highest schooling attained: compulsory education (old system), 9-year compulsory education (new system), vocational high school, academic high school, some college (but not graduated from a three-year program), college graduate (three-year program or more), or graduate degree. Ideally, we should have parental education before the Chernobyl accident in 1986, but we note that average age at first birth was 26 years in 1985, an age at which we expect education to be completed or close to completed.

Local labor market conditions. Employment and unemployment rates are available from Statistics Sweden by quarter and county for those aged 16–64 years. Dehejia and Lleras-Muney (2004) highlighted the effect of the business cycle on the average characteristics of parents who conceived children. We therefore consider labor market conditions lagged three quarters. For example, if a student was born in the fourth quarter, the unemployment rate in her county of birth during the first quarter is applied.

Means of the control variables (by region) are reported in Online Appendix Table A.3.

III.D. Birth Outcomes

The Swedish Birth Register contains information on pregnancies and deliveries for all births in Swedish hospitals since 1973. This register provides date of delivery, information on previous pregnancies, gestation length, clinic, mode of birth, length, and weight, as well as diagnoses of the mother and the child (ICD-7 codes). There are between 85,000 and 120,000 births per year in Sweden. The annual information loss ranges from 0.5% to 3%.

We focus on the following outcome variables:

Birth weight. Weight immediately after birth measured in grams.

Gestation length. Gestation length in days measured on the basis of last menstrual period or clinical estimates (using ultrasound exam during pregnancy).

Apgar score. Apgar score from test conducted five minutes after birth. The Apgar score is the sum of the scores 0, 1, or 2 for five criteria (heart rate, respiratory effort, muscle tone, reflex irritability, and color). The minimum score is 0 and the maximum (indicating no problems) is 10.

III.E. Hospitalizations during Childhood

Sweden's inpatient hospital register contains one record for each hospital admission. The register was started in 1964 and has full coverage of Swedish hospitals since 1987. The register includes ICD-7 codes for up to eight diagnoses, the date of admission, number of days in hospital care, and mode of discharge. Coverage is very close to universal.[15]

Using a unique person identifier, we matched these data to our compulsory schooling data set, and thereby assign likely exposure to Chernobyl radiation (based on parish and month of birth). Because we are interested in evidence of radiation damage, we focus on the following outcomes:

Malformations. Hospital care caused by congenital malformations is identified by ICD-7 diagnosis codes 750–759 (these include congenital malformations of various organs, monstrosity, congenital hydrocephalus, cleft palate, and harelip). Because our cohort of interest was likely exposed during the fetal period, and thus past the organogenesis period, when radiation has been showed to cause malformations, we do not expect to detect effects. Cohorts at greater risk are part of our reference group (born in January and February 1987), and to the extent that there were teratogenic effects, this would tend to attenuate our results. Still, the fact that Ericson and Källén (1994) did not find increases in malformations suggests that such effects are minimal.

Mental, nervous, and sensory disorders. We consider hospitalizations with diagnoses related to mental health, diseases of the nervous system, and diseases of the sensory organs (ICD-7 codes 300–398). These conditions may be related to development of the brain and nervous system.

Neoplasms. Most research on the health effects of ionizing radiation focuses on cancer. We consider cancers

---

[15] The annual loss of information is estimated to be less than 1%; the information loss on main diagnosis and person identifier is about 1% each.

such as cancer of the thyroid and leukemia, as well as nonmalignant tumors (ICD-7 codes 140–239).

Days hospitalized. This is a summary measure that may proxy for aggregate health care expenditures.

IV. RESULTS

Our analysis exploits variation in the timing (Figure I) and geography (Figures II and III) of radioactivity from Chernobyl. We estimate three basic specifications, described below.

IV.A. Econometric Specification

We begin by grouping regions of Sweden into four areas according to fallout—R0 (lowest) through R3 (highest)—as detailed in Table I and Figure III:

$$y_i = \alpha_0 \times \mathtt{I(inutero)}_i + \sum_{j=1}^{3} \alpha_j \times R_j \times \mathtt{I(inutero)}_i + \beta X_i + \tau_{\text{yob}} + \gamma_{\text{mob}} + \lambda_{\text{muni}} + \epsilon_i, \tag{1}$$

where y_i is the dependent variable of interest. `I(inutero)` is an indicator variable that takes the value 1 for the cohort born August–December 1986 and 0 otherwise. α_0 is the main effect, and we expect that $\alpha_0 < 0$. If Chernobyl fallout affected the developing brain, we also expect lower performance in areas that received more fallout. Therefore, we interact the `inutero` indicator variable with the indicator variables R_1, R_2, and R_3 for the three areas R1, R2, and R3 exposed to fallout to varying degrees. X_i is a vector of controls for gender, parental education (seven education levels, mother and father separately), and county labor market conditions around the time of conception (employment and unemployment rates) to control for selection into fertility. τ_{yob} is a vector of year of birth indicators. γ_{mob} is a vector of month of birth indicators. λ_{muni} is a vector of municipality of birth indicators.

Parameters $\alpha_j, j = 1, 2, 3$ allow for differential effects by region and we hypothesize that $\hat{\alpha}_3 \leq \hat{\alpha}_2 \leq \hat{\alpha}_1 < 0$.

These parameters measure the extent to which the outcomes for the `inutero` children born in the corresponding areas at the time of the accident differ from the `inutero` children born in the reference area, controlling for all permanent differences between areas; i.e., we assume that

$$\mathtt{cov}(\epsilon_i, R_j \times \mathtt{I(inutero)} | X_i, \tau_{\text{yob}}, \gamma_{\text{mob}}, \lambda_{\text{muni}}) = 0, j = 1, 2, 3.$$

To the extent that parents or schools responded to cognitive damage, this would tend to attenuate the observed damage if the response was compensatory. (We discuss this issue in greater detail in Section V.)

Our second strategy uses the continuous measures of radioactive fallout at the municipality or county level in place of the regional grouping to estimate a model of the form

$$\begin{aligned} y_i &= \alpha_0 \times \mathtt{I(inutero)}_i + \alpha_1 \times \mathtt{log}(\mathrm{FALLOUT}_r) \times \mathtt{I(inutero)}_i \\ &\quad + \beta X_i + \tau_{\text{yob}} + \gamma_{\text{mob}} + \lambda_{\text{region}} + \epsilon_i, \end{aligned} \tag{2}$$

where $\mathrm{FALLOUT}_r$ measures average fallout in region (municipality or county) r—for example, municipality-level Cs-137 kBq/m^2. An advantage of this method is that it avoids recategorizing municipalities into regional groups. However, functional form assumptions become more important.[16] Again, our identifying assumption is independence between the disturbances and the measure of exposure conditional on permanent differences between the areas with different exposure and the other control variables.

Our third empirical strategy is to apply the difference-in-differences approach to a sample restricted to siblings (using the unique mother and father identifiers) and compare those *in utero* during Chernobyl to their siblings.

That is, we estimate equation (1) with family fixed effects,

$$\begin{aligned} y_i &= \alpha_0 \times \mathtt{I(inutero)}_i + \sum_{j=1}^{3} \alpha_j \times R_j \times \mathtt{I(inutero)}_i \\ &\quad + \beta P_i + \pi_{\text{family}} + \tau_{\text{yob}} + \gamma_{\text{mob}} + \lambda_{\text{muni}} + \epsilon_i, \end{aligned} \tag{3}$$

where P_i is the subset of variables in X_i that vary within siblings (local labor market conditions) and π_{family} is a vector of indicator variables, one for each family (5,547 in total). Municipality fixed effects are identified by families that report different municipalities of birth for their children. We restrict the sample to families with two same-sex full siblings and a married father (to reduce the likelihood that the parents had separated, an event likely to have differential effects on siblings depending on age), where one sibling belonged to the exposed cohort and the other one did not (but was born between 1983 and 1988).

---

[16] Although similar results are obtained when $\mathrm{FALLOUT}_r$ is not logged.

Including these fixed effects is equivalent to differencing the outcomes and regressors of the sibling *in utero* during Chernobyl fallout from those of his/her sibling (because we retain only sibling pairs). Therefore, comparisons identifying the Chernobyl effect are only made within (and not across) families. As before, if school performance is affected by Chernobyl fallout, we would expect those born between August and December 1986 to perform worse than their siblings, and this difference to be greater for those born in areas that received more fallout. This approach controls for all unobserved heterogeneity at the family level.

IV.B. Health

Before considering school performance, we evaluate health in the universe of birth records and hospitalizations through 2006. Sweden has universal health insurance, and fees, when charged, are nominal and therefore unlikely to deter low-income families from using health care.[17]

Table II reports results from estimating equation (1) on our birth register and in-patient data. Estimates in column (1) reveal no significant effects for birth weight; nor do the magnitudes of point estimates correspond to geographic variation in fallout levels. The largest difference (for R2) indicates a less than 0.3% mean difference in birth weight. Nor do we detect significant differences in APGAR score (column (2)) or gestation length (column (3)). And again, the ordering of the point estimates does not correspond to variation in fallout.

Turning to the universe of hospitalizations through 2006 (i.e., during the twenty years after the accident), we again find no systematic pattern or statistically significant differences for the cohort born in fall 1986. This cohort was no more likely to be diagnosed with congenital malformations (column (4)), or mental or nervous system problems (column (5)), or to be hospitalized more days (column (6)). There is no systematic ordering of the magnitude of point estimates.

We also studied the occurrence of neoplasms and diseases of the blood. However, the low risk of these diseases made them unsuitable for regression analysis, and we report instead the actual occurrence and the predicted occurrence based on the sample means. For neoplasms (tumors), we found six cases for those born in R3, August–December 1986, against a predicted number of 6.82

---

[17] Private health care is rare in Sweden.

TABLE II

HEALTH OUTCOMES, COHORTS 1983–1988

	Natality data, years 1983–1988			Inpatient data, years 1987–2006		
	Birth weight	Apgar<10[a]	Gestation	Malformation[b]	Mental[c]	Hospitalization[d]
Mean	3,484 (grams)	0.175	280 (days)	0.021	0.068	5.6 (days)
	(1)	(2)	(3)	(4)	(5)	(6)
`inutero` × area:						
R3	−4.32	−0.015	−0.371	−0.0071	−0.012	−0.143
	[15.85]	[0.014]	[0.318]	[0.0047]	[0.011]	[0.853]
R2	−9.37	−0.021	−0.284	−0.0015	−0.0019	0.025
	[15.79]	[0.014]	[0.322]	[0.0014]	[0.0021]	[0.656]
R1	−0.057	−0.015	−0.343	0.0022	−0.0021	−0.328
	[19.10]	[0.022]	[0.383]	[0.0015]	[0.0017]	[0.670]
N	584,014	595,354	586,139	551,631	551,631	551,632
R^2	.0010	.011	.0010	.0047	.0043	.0019

Notes. Standard errors clustered at the county level in brackets. `inutero` – Indicator variable, 1 if date of birth between August and December 1986. The table reports estimates of $\alpha_i, i = 1, 2, 3$, in equation (1) (with the modification that a vector of county dummies substitutes for the vector of municipality dummies because health care in Sweden is organized at the county level). All regressions include indicator variables for year of birth, month of birth, county of birth, mother's and father's level of education (seven levels), sex, the employment and unemployment rates in the county of birth three quarters prior to the quarter of birth, and an `inutero` main effect.

[a] Apgar<10, dummy, equals 1 if the five-minute Apgar score was below 10.

[b] Malformation, dummy, equals 1 if any of the diagnosis codes (up to eight for each inpatient record) indicated congenital malformations (ICD-7 codes 750–759).

[c] Mental, dummy, equals 1 if any of the diagnosis codes (up to eight for each inpatient record) indicated mental, psychoneurotic, or personality disorders or disease of the nervous system and sense organs (ICD-7 codes 300–398) in any of the inpatient records for a person.

[d] Hospitalization, sum of days in hospital, median = 1.

*Significant at 10%; **significant at 5%; ***significant at 1%.

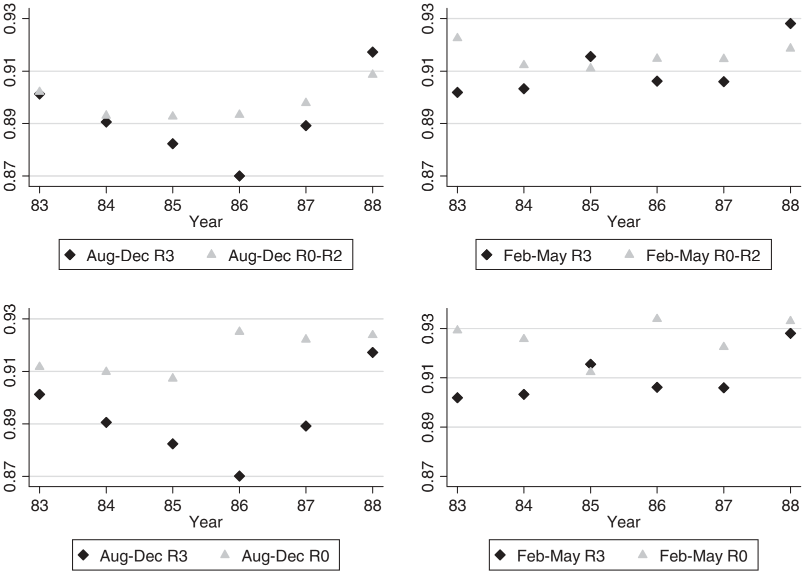


FIGURE IV

Fraction Qualified to Enter High School by Year and Season of Birth

Treatment group: R3 (eight most exposed municipalities). Control groups: R0–R2 (rest of Sweden; top panels); R0 (Norbotten; bottom panels).

(1154 × 0.0059175). For diseases of the blood and blood-forming organs, the corresponding figure was 0 actual cases, against a predicted number of 0.32.

In summary, we can detect no significant aberration in the universe of births and hospitalizations for those born in August–December 1986.

IV.C. School Performance

Graphical Results. We begin by presenting the share qualifying to enter high school, average grades, and average mathematics grades in a series of figures.

Figure IV shows the fraction of each birth cohort qualifying to high school. Because there is substantial seasonality in school performance by birth month, we compare those born August–December 1986 to those born August–December in adjacent years in the two left-hand panels. In the upper left-hand panel, we compare annual qualification rates for those born in R3 (highest fallout) to rates for those born in the rest of Sweden (R0–R2). The two series track each other fairly closely until 1986, when the share qualifying from R3 drops substantially to produce a three–percentage-point gap. The lower left-hand panel again plots the R3 means, but now against the lowest fallout region of Sweden: Norrbotten (R0). The gap is now larger, at about five percentage points, and it is noteworthy that the difference is in part driven by the control group doing better for this particular birth year.[18] This is consistent with grades in the core subjects (and thus qualification to enter high school) being assigned in part based on nationally standardized tests (see Section II.D) where the national standard was temporarily relaxed.

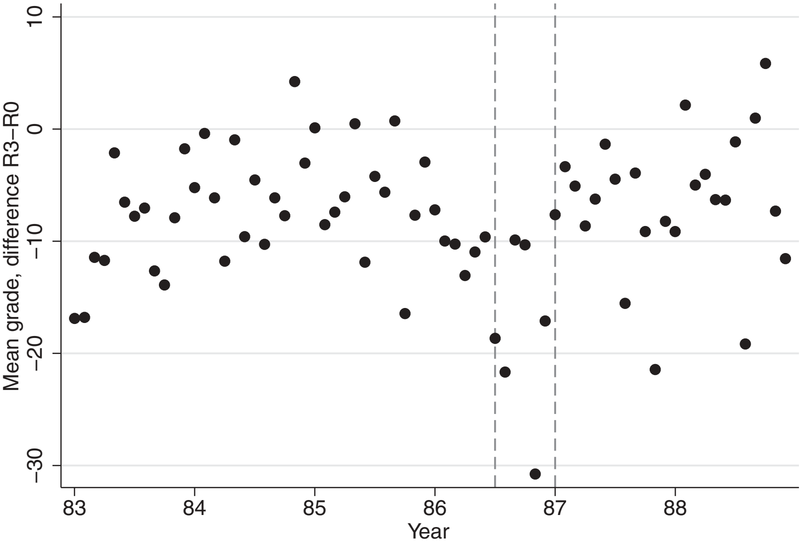
As a falsification exercise, the right-hand panels of Figure IV make the same regional comparisons for those born between February and May, that is, cohorts for which the studies of A-bomb survivors do not predict effects attributable to radiation. Clearly, the poor performance of the R3 cohort does not extend to those born just prior to the accident and exposed to the radiation spike in Figure I as neonates. This finding reduces the likelihood that geographically varying effects unrelated to Chernobyl account for the pattern observed for the cohorts most likely exposed between weeks 8 and 25 of gestation.

Next, we present grades by month of birth. Figure V plots the difference between the mean grade sums in R3 and R0, and Figure VI does the same for the mean mathematics grade. Although generally slightly negative, there is a pronounced dip in this difference for the cohort born in the fall of 1986. We do not observe larger regional gaps for those born before Chernobyl (e.g., aged two years during the accident) than for those conceived after the radiation spike. This suggests not only that cohorts exposed at weeks 8 to 25 were more affected, but also that children exposed postnatally were not particularly affected (consistent with Otake and Schull (1998)).

Regression Results. Tables III–VI present our primary regression estimates, where standard errors are clustered at the municipality level (as discussed in Section II.D). With the exception of Table VI, outcomes in compulsory school are reported. (As described above, for compulsory schooling we analyze cohorts born

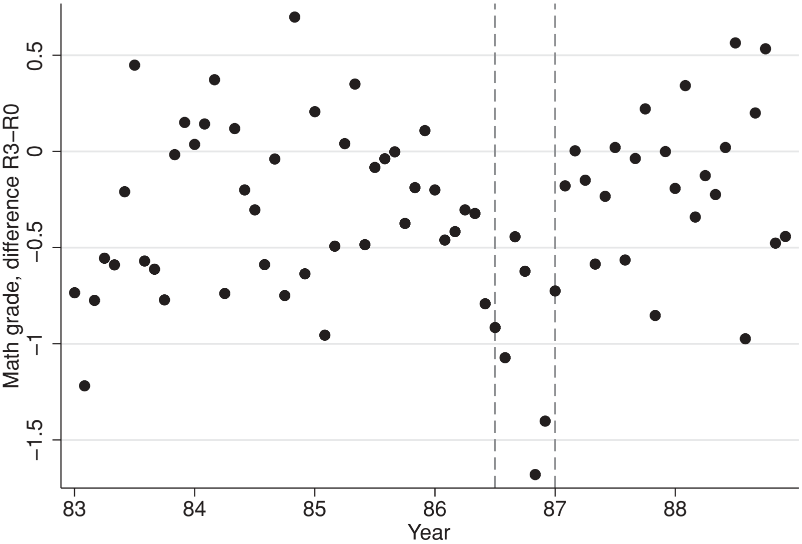
---

[18] The pretreatment gap in qualification rates in the bottom left-hand panel of Figure IV is consistent with effects on children born prior to Chernobyl and therefore exposed postnatally. To the extent that this cohort gap is due to Chernobyl, our regression estimates may be interpreted as the *additional* effect attributable to prenatal exposure. However, corresponding pretreatment gaps are not apparent in Figures V and VI.



Vertical lines at July 1986 and January 1987

FIGURE V
Difference in Mean Grade Sums by Calendar Month of Birth: R3 (Eight Most Exposed Municipalities) Relative to R0 ("Norrbotten")



Vertical lines at July 1986 and January 1987

FIGURE VI
Difference in Mean Mathematics Grades by Calendar Month of Birth: R3 (Eight Most Exposed Municipalities) Relative to R0 ("Norrbotten")

1983–1988, and for high school outcomes we consider cohorts born 1983–1987, because the 1988 cohort would only have completed two years of high school in 2006, the last year of our high school data.)

First, we present results from estimating (1) without the region interaction terms. This approach amounts to only exploiting the time variation, and the estimated effect is negative for all of the four outcomes, albeit not statistically significant—Table III, columns (1) and (5). Next, we turn to our difference-in-differences estimates where we exploit both the time and the regional variation. The regional interaction terms are entered sequentially to allow for different base groups in the regressions—Table III, columns (2)–(4) and (6)–(8). First, the worst affected area (R3) is compared to the rest of Sweden; then to R0 and R1; and finally to R0. Consistent with radiation-related damage, the estimated effect is negative, the magnitude increases with the difference in fallout, and the ordering corresponds to the ordering of fallout. For the average grade, we estimate a reduction of 0.54 points, or a roughly 2.5–percentile point drop in the grade distribution for the `inutero` cohort from R3.[19,20] We also find this group to be 3% less likely to qualify to enter high school. As for mathematics, the `inutero` cohort in the most exposed area is estimated to have a 0.67-point lower grade, or a 6% reduction (0.67/11.9). The effect size is comparable to the estimated effect of a full year's delay in school entry (from month of birth dummies, not reported, available on request). The results for Swedish are qualitatively similar, albeit smaller in magnitude.

Table IV repeats the analysis using four different continuous measures of fallout (in logs). The first two are the *in situ* measures of Cs-134 and I-131, which were aggregated to the municipality level as described above. Because there were only 61 monitoring sites, our sample size is reduced accordingly. The last two regressions use aerial measurements of Cs-137 at the municipality and the county level, respectively, and here we have full coverage. The reduction in mathematics grades is statistically significant for all radiation measures, and for qualification to enter HS, the

---

[19] For average grades, qualification, and mathematics, the estimated α_js in (1) are significantly different for R3 versus R2 and R3 versus R1, at the 5% level at least.

[20] Excess damage for the R3 cohort is mild compared to the fallout difference, suggesting a concave relationship. As rainfall differences explain most of the variation in fallout (see Section IV.D), rain may have caused people to stay indoors and thus reduced exposure.

TABLE III

COMPULSORY SCHOOL GRADES, COHORTS 1983–1988—EFFECT BY GEOGRAPHIC AREA

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Grade average (mean = 12.78)				Qualify to enter HS (mean = 0.912)			
`inutero`	−0.028	−0.023	0.125**	0.367***	−0.0034	−0.0030	0.0030	0.015**
	[0.026]	[0.037]	[0.053]	[0.139]	[0.0021]	[0.0021]	[0.0028]	[0.0073]
`inutero` × area:								
R3		−0.153	−0.301**	−0.543***		−0.012	−0.018**	−0.030***
		[0.113]	[0.119]	[0.176]		[0.008]	[0.008]	[0.010]
R2			−0.213***	−0.456***			−0.009***	−0.020***
			[0.054]	[0.140]			[0.003]	[0.007]
R1				−0.269*				−0.013*
				[0.147]				[0.007]
N	551,630	551,630	551,630	551,630	551,630	551,630	551,630	551,630
R^2	.19	.19	.19	.19	.047	.047	.047	.047
	Mathematics (mean = 11.96)				Swedish (mean = 12.73)			
`inutero`	−0.026	−0.020	0.128***	0.470***	−0.034	−0.031	0.082	0.303**
	[0.032]	[0.040]	[0.046]	[0.104]	[0.031]	[0.035]	[0.055]	[0.141]
`inutero` × area:								
R3		−0.184**	−0.333***	−0.674***		−0.084	−0.198	−0.418**
		[0.093]	[0.097]	[0.133]		[0.158]	[0.164]	[0.209]
R2			−0.214***	−0.555***			−0.163***	−0.384***
			[0.047]	[0.103]			[0.059]	[0.142]
R1				−0.380***				−0.245
				[0.106]				[0.151]
N	551,630	551,630	551,630	551,630	551,630	551,630	551,630	551,630
R^2	.13	.13	.13	.13	.20	.20	.20	.20

Notes. Standard errors clustered at the municipality level in brackets. `inutero`—Indicator variable, 1 if date of birth between August and December 1986. The table reports estimates of $\alpha_i, i = 1, 2, 3$, in equation (1). All regressions include indicator variables for year of birth, month of birth, municipality of birth, mother's and father's level of education (seven levels), sex, and the employment and unemployment rates in the county of birth three quarters prior to the quarter of birth.

*Significant at 10%; **significant at 5%; ***significant at 1%.

TABLE IV
COMPULSORY SCHOOL GRADES, COHORTS 1983–1988—CONTINUOUS MEASURE OF EXPOSURE

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Grade average				Qualify to enter HS			
Cs-134	−3.400				−0.053			
(*In situ*, municipality)	[2.548]				[0.125]			
I-131		−0.249				−0.0031		
(*In situ*, municipality)		[0.254]				[0.016]		
Cs-137			−2.740				−0.241	
(Aerial, municipality)			[2.483]				[0.182]	
Cs-137				−2.921				−0.522***
(Aerial, county)				[2.781]				[0.171]
N	181,258	169,659	551,630	551,630	181,258	169,659	551,630	551,630
R^2	.20	.20	.19	.19	.050	.050	.047	.044
	Mathematics				Swedish			
Cs-134	−4.087**				−1.306			
(*In situ*, municipality)	[1.949]				[3.693]			
I-131		−0.540***				0.190		
(*In situ*, municipality)		[0.190]				[0.252]		
Cs-137			−4.491*				−2.436	
(Aerial, municipality)			[2.354]				[3.466]	
Cs-137				−6.185*				−2.369
(Aerial, county)				[2.968]				[2.830]
N	181,258	169,659	551,630	551,630	181,258	169,659	551,630	551,630
R^2	.14	.14	.13	.13	.20	.20	.19	.20

Notes. Standard errors clustered at the level of the treatment aggregation (the municipality in columns (1)–(3) and (5)–(7) and the county in columns (4) and (8)) in brackets. The table reports estimates of α_1 in equation (2), that is, the coefficient on the logged value of the respective measure of fallout interacted with a dummy variable that is 1 for individuals born between August and December 1986. All regressions include indicator variables for year of birth, month of birth, municipality or county of birth, mother's and father's level of education (seven levels), sex, the employment and unemployment rates in the county of birth three quarters prior to the quarter of birth, and an `inutero` main effect.

*Significant at 10%; **significant at 5%; ***significant at 1%.

TABLE V
COMPULSORY SCHOOL GRADES, COHORTS 1983–1988—SIBLING FIXED EFFECTS

	Grade average (1)	Qualify HS (2)	Math (3)	Swedish (4)
`inutero` × area:				
R3	−0.935**	−0.049	−1.439***	−0.733
	[0.427]	[0.044]	[0.503]	[0.541]
R2	−0.795**	−0.028	−1.417***	−0.843*
	[0.374]	[0.041]	[0.472]	[0.434]
R1	−0.617	−0.009	−1.215**	−0.679
	[0.382]	[0.044]	[0.486]	[0.435]
N	11,094	11,094	11,094	11,094
R^2	.80	.66	.73	.76

Notes. Standard errors clustered at the municipality level in brackets. `inutero`—indicator variable, 1 if date of birth between August and December 1986. The table reports estimates of $\alpha_i, i = 1, 2, 3,$ in equation (3). In addition to the vector of (5,547) indicator variables, one for each family, all regressions include indicator variables for year of birth, month of birth, municipality of birth, the employment and unemployment rates in the county of birth three quarters prior to the quarter of birth, and an `inutero` main effect.

*Significant at 10%; **significant at 5%; ***significant at 1%.

county-level aerial measurement is significant. The estimated relationship between grades and exposure is negative in ten out of the eleven remaining cases, but fails to be statistically significant.

A violation of our identifying assumption for equations (1) and (2) would occur if the unobservable characteristics of families from high-radiation areas of Sweden with children born in the fall of 1986 deteriorated.[21] This possibility motivates our sibling fixed-effects estimation, the strongest test of our hypothesis. Table V presents the results. The within-sibling comparison confirms the findings in the cross section, reducing the likelihood that the found evidence of damage is driven by systematic heterogeneity across families. Moreover, the effect sizes are larger than in the cross section. For example, the effect of prenatal exposure on mathematics scores is over 10%. The strengthening of damage estimates suggests that to the extent that parents responded to the cognitive endowment, such responses may have been reinforcing (Rosenzweig and Schultz 1982; Rosenzweig and Zhang 2009; Datar, Kilburn, and Loughran forthcoming).

Finally, we repeat the basic analysis for those who graduated from high school. Table VI presents results from estimating

---

[21] However, controlling for observable background characteristics, such as parental education, does not substantially change our damage estimates; see the unadjusted estimates for qualification in Table 4 of Almond, Edlund, and Palme (2007).

TABLE VI

HIGH SCHOOL OUTCOMES (AS OF 2006), COHORTS 1983–1987—EFFECT BY GEOGRAPHIC AREA

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Graduate (mean = 0.732)				Grade average (mean = 14.2)			
`inutero`	−0.0039	−0.0034	0.006	0.015	−0.025	−0.021	0.014	0.132***
	[0.003]	[0.003]	[0.005]	[0.020]	[0.024]	[0.024]	[0.029]	[0.048]
`inutero` × area:								
R3		−0.016	−0.026*	−0.035		−0.138	−0.173	−0.291*
		[0.014]	[0.014]	[0.024]		[0.165]	[0.166]	[0.169]
R2			−0.014***	−0.023			−0.05	−0.168***
			[0.005]	[0.020]			[0.033]	[0.049]
R1				−0.01				−0.131**
				[0.020]				[0.052]
N	444,583	444,583	444,583	444,583	325,255	325,255	325,255	325,255
R^2	.060	.060	.060	.060	.18	.18	.18	.18
	Mathematics (mean = 13.3)				Swedish (mean = 13.9)			
`inutero`	−0.034	−0.03	0.054	0.173	−0.024	−0.024	−0.075	0.057
	[0.040]	[0.041]	[0.051]	[0.160]	[0.031]	[0.032]	[0.048]	[0.137]
`inutero` × area:								
R3		−0.108	−0.193	−0.312		0.019	0.07	−0.062
		[0.164]	[0.168]	[0.225]		[0.232]	[0.235]	[0.268]
R2			−0.120**	−0.24			0.072	−0.059
			[0.061]	[0.161]			[0.054]	[0.138]
R1				−0.133				−0.147
				[0.165]				[0.143]
N	324,285	324,285	324,285	324,285	323,879	323,879	323,879	323,879
R^2	.11	.11	.11	.11	.17	.17	.17	.17

Notes. Standard errors clustered at the municipality level in brackets. `inutero`—indicator variable, 1 if date of birth between August and December 1986. The table reports estimates of $\alpha_i, i = 1, 2, 3$, in equation (1). All regressions include indicator variables for year of birth, month of birth, municipality of birth, mother's and father's level of education (seven levels), sex, and the employment and unemployment rates in the county of birth three quarters prior to the quarter of birth.

*Significant at 10%; **significant at 5%; ***significant at 1%.

(1) for graduation, average grades, mathematics, and Swedish. Significant effects are found for average grades, with the expected ordering of point estimates for other outcomes. With the exception of graduation, however, the estimated effect size is smaller than those we found for compulsory schooling. This is presumably due to the fact that high school students are positively selected (high school is not compulsory).

IV.D. Measurement Error

The aerial measurement of cesium deposition over Sweden did not begin until May 9, 1986 (Isaksson, Erlandsson, and Linderson 2000), two weeks after the accident. Iodine is believed to be the largest initial single contributor to radiation doses. Due to its relatively short half-life (eight days), it was soon dominated by longer-lived radionuclides. For example, as shown in Figure I, gamma radiation levels in Njurunda had already dropped to half their April 29 peak when flights began on May 9 (Kjelle 1987). Although our *in situ* data indicate that the correspondence between iodine and cesium was high, this relationship weakens over time. Thus, we expect some slippage between the magnitude of the initial radiation spike and subsequent aerial measurement of cesium (measurement error).

We may be able to improve measurement of geographic differences in the initial radiation spike by using rainfall patterns. As noted above, the Chernobyl accident generated "a highly nonuniform distribution of ground deposition produced by rainout" (Hohenemser 1988). Devell (1991) noted,

> Rainfall at locations which were passed by the plume washed-out significant amounts of the radioactive materials, where were deposited on the ground. The wash-out is dependent on total rainfall or rainfall intensity.

One study of Chernobyl fallout in Göteborg (in western Sweden) found that 99% of Chernobyl deposition was due to rainfall (Mattsson and Vesanen 1988).

Daily precipitation data from 94 weather stations across Sweden are available from the National Climactic Data Center of the U.S. Department of Commerce.[22] Rainfall in the ten days after the Chernobyl accident (when the plume was over Sweden)

---

[22] Available at www.ncdc.noaa.gov/oa/ncdc.html.

is indeed strongly predictive of deposition—R^2 of .77.[23] As wet deposition is a well-known physical process (Holmberg, Edvarson, and Finck 1988), a strong first stage is to be expected. Rainfall in the Chernobyl aftermath is only weakly (and negatively) correlated with rainfall during the rest of the year.[24] Thus, deposition was not in the "rainy" parts of Sweden. As aerial measurement of deposition did not begin until May, 9, 1986, that is, four days after the end of the ten-day rainfall window, confounding of radiation measures by weather conditions is unlikely.

We instrument for measurement error in cesium deposition using a well-specified physical process. Unfortunately, few of the *in situ* radiation monitoring stations were located near the separate set of rainfall monitors. Therefore, we instrument for the *aerial* radiation measurements (at the county level).

Table VII reports OLS and IV coefficient estimates for county-level measures of cesium deposition (logged) interacted with weeks 8 to 25 gestation during Chernobyl. Because we do not have rainfall measures for Södermanland county, we begin with OLS estimates for the sample with this county dropped; these are trivially different from Table IV estimates.[25] Instrumenting for deposition with rainfall in the 10 days following Chernobyl, we find larger point estimates—roughly double the OLS estimates. The pattern of increased point estimates suggests that we indeed had a measurement error problem. Standard errors are also substantially larger, but the IV estimate for qualifying to enter high school is significant at the 5% level.[26] Finally, we report the IV estimates for the sibling comparisons—that is, where sibling differences are identified by county-level rainfall differences. These point estimates are substantially larger than the basic IV results (with the exception of mathematics). Standard errors are again larger, but qualification remains significant at the 10% level. Thus, the consistent increase in point estimates suggests that our results are robust to improvements in measurement of radiation exposure where the source of variation is plausible and clearly defined.

---

[23] The first-stage specification is a population-weighted county-level regression of cesium deposition on precipitation, precipitation squared, and a constant.

[24] For the 84 individual rainfall monitors, the slope coefficient on the coefficient on rainfall during the rest of the year is -0.0017 with a standard error of 0.033 (t-stat $= -.51$). Similar results are obtained in a county-level specification (as in footnote 23).

[25] $N = 535{,}954$, or 97% of the Table IV sample.

[26] Here, we cluster standard errors at the county level because the rainfall instrument only varies at this level.

TABLE VII
OLS VERSUS IV ESTIMATES

Outcome	Grade (1)	Qualify (2)	Math (3)	Swedish (4)
Cs-137	−2.92	−0.526***	−6.19**	−2.63
OLS	[2.78]	[0.171]	[2.95]	[2.87]
Cs-137	−14.0	−0.909**	−10.9	−11.2
IV	[10.3]	[0.389]	[7.76]	[9.72]
Cs-137	−25.0	−1.86*	−10.9	−25.1
IV, sibling fixed effect	[22.4]	[0.946]	[19.9]	[25.4]

Notes. Standard errors clustered at the county level (the aggregation level required for instrumenting). The first row reports estimates of α_1 in equation (2), that is, the coefficient on the logged value of the county-level fallout interacted with a dummy variable that is one for individuals born between August and December 1986. The second row of point estimates instruments for fallout with precipitation and precipitation squared, measured over the 10 days from April 26 to May 5, 1986. Births for Söodermanland are dropped because rainfall data are missing, resulting in $N = 535{,}954$. Regressions in both first and second rows include indicator variables for year of birth, month of birth, county of birth, mother's and father's level of education (seven levels), sex, the employment and unemployment rates in the county of birth three quarters prior to the quarter of birth, and a dummy variable for birth between August and December 1986 (i.e., the main effect). The final row of results adds sibling fixed effects to the instrumental variables version of 2. The sibling FE regressions include indicator variables for year of birth, month of birth, county of birth, the employment and unemployment rates in the county of birth three quarters prior to the quarter of birth, and a dummy variable indicating birth between August and December 1986. $N = 10{,}738$.

*Significant at 10%; **significant at 5%; ***significant at 1%.

IV.E. Projected Wage Effects[27]

Sweden. It is too early to assess directly the labor market damage suffered by the studied cohorts. However, the relationship between school performance and labor market outcomes can be evaluated using older cohorts. To that end, we study those born in 1972, the oldest cohort for which we can match individual school and earnings records (the latter from the LISA data base). The earnings data are pretax labor incomes in 2003 (when 31 years old). The 1972 cohort was graded on a different scale. For comparability, we convert the grades to grade percentiles.

In Table VIII, we regress log earnings (top panel) or percentile in the earnings distribution of this cohort (lower panel) on grades in compulsory schooling (columns (1) and (2)) and level of completed education (column (3)) and a gender dummy.[28] We find that a 1% move within the grade distribution is associated with a

---

[27] We thank an anonymous referee for suggesting this monetization exercise.

[28] Unfortunately, we do not have parental characteristics matched to this sample.

TABLE VIII
RETURNS TO EDUCATION, 1972 BIRTH COHORT

	(1)	(2)	(3)
	log(2003 earnings)		
Grade percentile:[a]			
Math	0.0058*** [0.0001]		
Sum		0.0063*** [0.0001]	
Completed education:[b]			
High school			0.187*** [0.014]
College			0.353*** [0.144]
R^2	.103	.106	.090
	Earnings distribution (percentiles)		
Grade percentile:[a]			
Math	0.235*** [0.003]		
Sum		0.259*** [0.003]	
Completed education:[b]			
High school			5.58*** [0.35]
College			14.59*** [0.36]
R^2	.21	.219	.186
N	85,706	85,706	85,706

Notes. The (mutually exclusive, collectively exhaustive) education categories are high school dropout or less, high school graduate, some college or more. All regressions include a dummy for female and a constant.

[a] Compulsory school.

[b] As of 2003.

*Significant at 10%; **significant at 5%; ***significant at 1%.

0.6% change in earnings, or a 0.25% change in the percentile distribution.[29] For the `inutero` cohort in the worst affected area, we estimated that Chernobyl fallout reduced mathematics grades, on average, by 0.67 (Table III), or a 2.2% reduction.[30] Plugging in these numbers, we obtain a Chernobyl damage of about 1.3% of earnings, or a 0.55 drop in the percentile earnings distribution,

---

[29] Estimating men and women separately, we find a slightly larger effect for women.

[30] This calculation assumes that the observed grades are the midpoints in uniform distributions (within observed bins).

for the worst affected cohort. For those in the least affected area (outside Norrbotten), R1, the corresponding numbers are a 1.3% reduction in the mathematics grade, implying a 0.8% reduction in earnings, or a 0.3% drop in the earnings distribution.

If, instead, we used the grade average, the estimated damage was a reduction of about 6%, which predicts an earnings reduction of 3.3% or a drop of 1.5%, in the earnings distribution.

As for high school graduation (column (3)), we find that high school graduates earned on average 19% more than those without high school degrees, or in terms of position in the earnings distribution, a 5.6% difference. Taking our estimated reduction in probability of obtaining a high school degree of 2.9% this alone would predict a 0.5% reduction in this cohort's earnings. This estimate is lower than that predicted by differences in mathematics grades, which may derive from the fact that it ignores the possibility that there is also an effect on continuation to college (an outcome that it is too early for us to observe).

Europe. Most of Europe—or more precisely, the area between 5° and 50° east, and 45° and 65° north, plus most of Europe east of Italy (UNSCEAR, 2000, Figure X)—received fallout at or above the level of R1. This area is home to about 410 million people.[31] If we assume the 1986 birth cohort to be 1/100 of the total population, and the August–December births to account for 5/12 of those births, we arrive at 1.7 million children affected. Assuming a 1% loss in productivity and annual income at US$30,000, this translates into half a billion U.S. dollars (30,000 × 1.7M/100) in lost productivity annually when these cohorts reach prime working age.

V. COMPENSATORY RESPONSES?

A complete accounting of Chernobyl damage in Sweden would include the cost of avoidance behavior and responsive investments. The fact that we find stronger effects when we compare exclusively among siblings (Tables V and VII) underscores the potential importance of behavioral responses to a negative health or endowment shock. In our context, these behaviors would occur primarily in the postnatal period, as it was not known at

---

[31] For this calculation, we subtract from Europe's population of 728 million 22 percent of Russia's population (of 142 million) and the populations of the United Kingdom, the Netherlands, Belgium, France, Spain, Portugal, Italy, and Turkey. Turkey (70 million people) is excluded for lack of fallout data.

the time of the accident that the level of radiation exposure would generate damage, let alone disproportionate damage to fetuses between 8 and 25 weeks gestation.[32] In the case of the observed cognitive damage, investments could respond to damage regardless of whether damage was attributed to Chernobyl. Such investments might include changes in parental time and schooling inputs.[33] Failing to account for remedial investments in early childhood, should they exist, would lead to an underestimate of costs; see Harrington and Portney (1987) and Deschênes and Greenstone (2007).[34]

We start by investigating whether there was a compensatory response in terms of public school expenditures on primary education (which accounts for almost the entirety of primary school expenditures in Sweden). To evaluate such responses, we have studied two schooling inputs: (i) average municipality school expenditures per pupil during the nine years when the children are in comprehensive school, and (ii) average teacher–pupil ratio. The results from this analysis, presented in Online Appendix C, show no evidence that municipalities in the more heavily exposed areas spent extra resources on the cohorts affected by the Chernobyl accident *in utero*.

Next we consider the possibility of compensatory behavior on the parts of parents. To that end, we divide the sample according to father's education. The top panel of Table IX presents the results for those whose fathers had two years or fewer of high school education, and the bottom panel the remainder of the sample.[35] First, we note that restricting the comparison to be within sibling pairs doubles the estimated effect size (see Table V). Second, the effects are concentrated among those with low-education fathers. For this group, the effect size ordering is preserved for mathematics and Swedish. For the high–paternal education group, the

---

[32] Nor do we find any evidence of avoidance behavior in our data with respect to place of birth. For example, there was no change in the tendency for high-education mothers to give birth in high-radiation areas of Sweden in the months after the Chernobyl accident.

[33] We also explored whether the likelihood and timing of subsequent children varied with prenatal exposure to Chernobyl fallout changed—that is, we ran the "quantity–quality" experiment in reverse. In contrast to Rosenzweig and Wolpin (1988), we did not detect a systematic gradient between the birth endowment and subsequent fertility behavior.

[34] An alternative approach to estimating costs of nuclear accidents/safety might consider housing prices near nuclear reactors (e.g., in the United States) before and after the Chernobyl accident relative to farther removed areas, as suggested by Chay and Greenstone (2005) and Davis (2008).

[35] The cutoff was chosen to create groups roughly equal in size.

TABLE IX
COMPULSORY SCHOOLING, COHORTS 1983–1988—SIBLING FIXED EFFECTS BY FATHER'S EDUCATION

	Grade average (1)	Qualify HS (2)	Math (3)	Swedish (4)
	Sample: father 2-yr HS or less			
`inutero` × area:				
R3	−1.287**	−0.113*	−2.243***	−0.691
	[0.516]	[0.058]	[0.678]	[0.792]
R2	−0.975**	−0.056	−1.656***	−0.793
	[0.387]	[0.049]	[0.544]	[0.539]
R1	−0.852**	−0.031	−1.510***	−0.61
	[0.405]	[0.053]	[0.581]	[0.574]
N	6,290	6,290	6,290	6,290
R^2	.78	.66	.7	.75
	Sample: father 3-yr HS or more			
`inutero` × area:				
R3	−0.253	0.027	−0.334	−0.426
	[0.707]	[0.060]	[0.772]	[0.774]
R2	−0.394	0.017	−0.915	−0.733
	[0.582]	[0.048]	[0.738]	[0.732]
R1	−0.129	0.030	−0.654	−0.60
	[0.592]	[0.050]	[0.745]	[0.747]
N	4,804	4,804	4,804	4,804
R^2	.79	.68	.72	.75

Notes. Standard errors clustered at the municipality level in brackets. `inutero`—indicator variable, 1 if date of birth between August and December 1986. In addition to the vector of family indicator variables, all regressions include indicator variables for year of birth, month of birth, municipality of birth, the employment and unemployment rates in the county of birth three quarters prior to the quarter of birth, and an `inutero` main effect.

*Significant at 10%; **significant at 5%; ***significant at 1%.

estimates are smaller and are not statistically significant. In the difference-in-differences analysis, damage is also concentrated among low-education families (results available on request).[36]

This finding echoes a parallel literature in health economics (Currie and Hyson 1999; Currie and Moretti 2007; Lin, Liu, and Chou 2007) that has considered whether the negative impact of poor childhood health on subsequent human capital accumulation is greater in low-education or low-income families. In general, these papers find larger effects of poor health among low-SES families, consistent with our findings for cognitive damage. However,

---

[36] For average grades, qualification, and Swedish, tests of equality of effects across education groups are easily rejected.

there is evidence that the "arrival rate" of subsequent health conditions is also higher among low-SES families (Case, Lubotsky, and Paxson 2002; Currie and Stabile 2003; Condliffe and Link 2008).

As there is no reason to think that low-education families with a child born in fall 1986 were disproportionately exposed to subsequent radiation shocks, how do we interpret the concentration of Chernobyl damage in low-education families? One possibility is that the better educated were less affected by the fallout in 1986. Generally speaking, the better educated tend to be more cautious. For instance, better educated groups tend to consume more preventive health care; for a recent contribution see McCrary and Royer (2006). Moreover, they are more likely to hold white-collar jobs, and therefore they may have spent less time outdoors in the week(s) following the Chernobyl accident. Whether the better educated were more conscious of the risks at the time is difficult to assess. The Otake–Schull study had only been published two years earlier (in 1984) and the mean dose in that study had been ten times higher than the highest dose estimated for Sweden. Thus, the established view then (and now) was that the radiation doses in question were too small to have an effect. Whether knowledge of, and/or trust in, this finding created more or less stress (Camacho 2008) is difficult to evaluate. On the one hand, this knowledge would have indicated no danger. On the other hand, skepticism and general knowledge of radiation-related damage may have been greater among the better educated, which may have led to more avoidance behavior (which would go in the direction of our results).[37]

Another possibility is the role of stress (e.g., Camacho [2008]). If the less educated experienced greater stress, and more so in high-fallout areas, this could account for our results. It is interesting to note that whereas two areas were heavily affected (around Gävle and Sundsvall), only Gävle was mentioned in mass media at the time. The fact that we find strong effects for Sundsvall as well leads us to infer that stress from general knowledge of the accident does not underlie our found effects, unless stress interacted with radiation to create a greater impact on the developing brain in high-fallout areas.

---

[37] However, substituting parental education for child outcomes in equation (1) (and omitting the parental education variables from the X vector), we find no evidence of higher fallout being associated with different parental education.

If, instead, the *in utero* exposure did not vary systematically with parental characteristics, what can account for the observed pattern of damage being concentrated among those whose parents were less educated? We consider three possibilities:

1. Although the negative health shock might have been similar, initial endowment levels may have been different. For instance, the better educated likely had a higher initial cognitive endowment. If so, all we need for a smaller Chernobyl effect on the measured outcome is decreasing marginal productivity, be it in the production of "innate ability," or in the transformation of this ability into, say, a mathematics grade. This first possibility assumes a purely mechanical effect, with no investment response (and does not explain the stronger results within families).
2. It is possible that parents responded to the observed cognitive endowment. These responses could either be compensating (offsetting endowment differences generated by Chernobyl) or reinforcing (varying positively with endowment differences) (Becker and Tomes 1976). Furthermore, better educated parents may have reacted differently to the endowment shock than less educated ones. The observed concentration of damage among children with low-education parents is consistent with a larger compensatory response by high-education parents compared to low-education parents (or alternatively, a smaller reinforcing response by high-education parents).

   Absent additional data on parental investments, it is difficult to discern which of these scenarios is more likely. The fact that sibling fixed effects estimates of Chernobyl damage are larger than the difference-in-differences estimates suggests that reinforcing investments may play a role.

   The production technology may also have shaped the parental response to Chernobyl damage. Economic models implicitly assume that "production of skills at different stages of childhood are perfect substitutes" (Cunha and Heckman 2007). Here, we consider the substitutability between prenatal damage and postnatal investments in producing cognitive ability. If postnatal investments in cognitive ability are perfect substitutes for prenatal ones, then the timing of investments across stages of childhood is not very important (discounting aside). If instead postnatal investments are a poor substitute for prenatal ones, then altering the cognitive trajectory set *in utero* is more costly (e.g., in terms of foregone consumption required for investing). In the extreme case of perfect production complements, compensatory investments would be completely ineffective. In fact, the optimal response would be to reinforce prenatal cognitive damage. In this Leontief case, "early disadvantages should be perpetuated" on efficiency grounds (Cunha and Heckman 2007). A reinforcing response is thus consistent with a low elasticity of substitution in production among different stages of childhood.[38]

3. A third possibility is that parents have a target level for school performance, for instance that the child achieves at the parental level. Furthermore, assume that absent Chernobyl, the target is binding for children with high-education parents, but not for children of low-education parents. Following an equivalent-sized Chernobyl shock, children of high-education parents would be further away from their target than children of low-education parents. High-education parents would have much more remediation to do following the Chernobyl shock than low-education parents. Here as well, greater damage would be observed among children of less educated parents. However, unless these targets varied within family across siblings, we would not expect larger damage estimates from the siblings comparison.

VI. SUMMARY AND DISCUSSION

In summary, we found that Chernobyl fallout caused damage well beyond the accident vicinity at radiation doses currently deemed safe.[39] Swedish children of gestational age 8–25 weeks at the time of the accident had substantially lower grades in compulsory school. These effects were identified by stark geographic differences in Chernobyl fallout across Sweden. Further, the estimated effects were robust to (and strengthened by) within-family comparisons, suggesting that reinforcing postnatal investments may be empirically important. In contrast, we

---

[38] Heterogeneity in the magnitude of a reinforcing response across families is possible for high complementarity that is short of a Leontief production function.

[39] See UNDP/UNICEF (2002, Table 3.4). Our findings also contrast with those of the International Atomic Energy Agency, which concluded that "the mental health impact of Chernobyl is the largest public health problem unleashed by the accident to date" (IAEA 2006, 36).

detected no corresponding differences in health outcomes. We conclude that despite remaining subclinical, prenatal exposure to Chernobyl fallout caused long-term cognitive damage.

The external validity of our findings does not rest on the likelihood of “another Chernobyl.” Among the various sources of ionizing radiation, the applicability of our results can be roughly ordered. We start with the most closely related:

1. *Power Plant Accidents.* Major nuclear accidents are expected in the next 50 years. Despite technological advances in reactor design since Chernobyl, the risk of future accidents remains (Deutch and Moniz 2003, p. 9). Moreover, there is renewed interest in nuclear power generation in light of global warming concerns and high energy prices. The 2005 Energy Policy Act in the United States provided incentives and loan guarantees for nuclear power (*Wall Street Journal*, Nuclear Energy’s Second Act? September 5, 2007). As of August 2009, 52 new nuclear power plants were under construction, with 32 of these in China, India, or Russia.[40]
2. *Nuclear Attacks.* Whether propelled by a nuclear explosion or by a terrorist’s radiological dispersion device (i.e., a dirty bomb), an attack would “probably be targeted at a public area, possibly in an urban environment” (Valentin 2006) and thus would be more damaging, other things equal, then a nuclear accident. In addition, because “Nuclear explosions produce air movements, which disperse the radioactive substances” (Vogel 2007), these may create substantial health damage both to the targeted area and afar. This cognitive damage can be expected to occur at doses an order of magnitude lower than those evaluated for Nagasaki and Hiroshima.
3. *Radon.* In addition to comprising the bulk of natural radiation exposure, the population distribution of radon exposure has high variance (Price and Gelman 2005). Thus, radon doses can be high relative to those from Chernobyl fallout. In 1986, Hùlka and Malátová (2006) took *in vivo* radiation measurements in Czechoslovakia (direct “whole body” measurements). Radiation doses from “indoor natural exposure were often higher than outdoor exposure to Chernobyl impact,” even over the summer of 1986. Our

---

[40] Source: http://www.iaea.org/programmes/a2/index.html.

findings suggest that radon testing and remediation efforts (e.g., ventilation of basements) might be increased.

4. *Medical Radiation.* Current medical doses can be substantial, particulary for computer tomography (CT) scans: mean whole-body doses are between 10 and 40 mGy (or roughly an order of magnitude greater than the estimated Swedish dose from Chernobyl). Because the exposure window is shorter for medical X-rays and CT scans relative to Chernobyl-related irradiation, a given medical dose should be expected to cause more damage (Brenner et al. 2003, p. 13,762). The highest radiation doses to the fetus come from pelvic and abdomen CT scans of the mother (10–25 mGy), procedures of nuclear medicine, and barium enemas (70 mGy) (DeSantis et al. 2005). An advantage of studying medical radiation is the availability of exposure measures at the individual level. Future research should seek to combine this advantage with compelling identification strategies.

COLUMBIA UNIVERSITY AND NATIONAL BUREAU OF ECONOMIC RESEARCH
COLUMBIA UNIVERSITY
STOCKHOLM UNIVERSITY

REFERENCES

Almond, Douglas, Lena Edlund, and Mårten Palme, "Chernobyl's Subclinical Legacy: Prenatal Exposure to Radioactive Fallout and School Outcomes in Sweden," NBER Working Paper No. 13347, 2007.

Angrist, Joshua D., and Jörn-Steffen Pischke, *Mostly Harmless Econometrics: An Empiricist's Companion* (Princeton, NJ: Princeton University Press, 2009).

Auvinen, Anssi, Mikko Vahteristo, Hannu Arvela, Matti Suomela, Tua Rahola, Matti Hakama, and Tapio Rytmaal, "Chernobyl Fallout and Outcome of Pregnancy in Finland," *Environmental Health Perspectives*, 109 (2001), 179–185.

Banzhaf, Spencer, and Randall P. Walsh, "Do People Vote with Their Feet? An Empirical Test of Tiebout," *American Economic Review*, 98 (2008), 843–863.

Becker, Gary S., and Nigel Tomes, "Child Endowments and the Quantity and Quality of Children," *Journal of Political Economy*, 84 (1976), S143–S162.

BEIR. *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII, Phase 2* (Washington, DC: National Academies Press, Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation, National Research Council, 2006).

Brenner, David J., Richard Doll, Dudley T. Goodhead, Eric J. Hall, Charles E. Land, John B. Little, Jay H. Lubin, Dale L. Preston, R. Julian Preston, Jerome S. Puskin, Elaine Ron, Rainer K. Sachs, Jonathan M. Samet, Richard B. Setlow, and Marco Zaider, "Cancer Risks Attributable to Low Doses of Ionizing Radiation: Assessing What We Really Know," *Proceedings of the National Academy of Sciences*, 100 (2003), 13,761–13,766.

Camacho, Adriana, "Stress and Birth Weight: Evidence from Terrorist Attacks," *American Economic Review*, 98 (2008), 511–515.

Case, Anne, Darren Lubotsky, and Christina Paxson, "Economic Status and Health in Childhood: The Origins of the Gradient," *American Economic Review*, 92 (2002), 1308–1334.

Chay, Kenneth Y., and Michael Greenstone, "Does Air Quality Matter? Evidence from the Housing Market," *Journal of Political Economy*, 113 (2005), 376–424.

Condliffe, Simon, and Charles R. Link, "The Relationship between Economic Status and Child Health: Evidence from the United States," *American Economic Review*, 98 (2008), 1605–1618.

Cunha, Flavio, and James J. Heckman, "The Technolgy of Skill Formation," *American Economic Review*, 97 (2007), 31–47.

Currie, Janet, and Rosemary Hyson, "Is the Impact of Shocks Cushioned by Socioeconomic Status? The Case of Low Birth Weight," *American Economic Review*, 89 (1999), 245–250.

Currie, Janet, and Enrico Moretti, "Biology as Destiny? Short- and Long-Run Determinants of Intergenerational Transmission of Birth Weight," *Journal of Labor Economics*, 25 (2007), 231–263.

Currie, Janet, and Mark Stabile, "Socioeconomic Status and Child Health: Why Is the Relationship Stronger for Older Children?" *American Economic Review*, 93 (2003), 1813–1823.

Datar, Ashlesha, Rebecca Kilburn, and David Loughran, "Endowments and Parental Investments in Infancy and Early Childhood," *Demography*, forthcoming.

Davis, Lucas W., "The Effect of Power Plants on Local Housing Values and Rents: Evidence from Restricted Census Microdata," manuscript, University of Michigan, 2008.

Dehejia, Rajeev, and Adriana Lleras-Muney, "Booms, Busts, and Babies' Health," *Quarterly Journal of Economics*, 119 (2004), 1091–1130.

DeSantis, M., E. DiGianantonio, G. Straface, A.F. Cavaliere, A. Caruso, F. Schiavon, R. Berletti, and M. Clementi, "Ionizing Radiations in Pregnancy and Teratogenesis: A Review of Literature," *Reproductive Toxicology*, 20 (2005), 323–329.

Deschênes, Olivier, and Michael Greenstone, "Climate Change, Mortality, and Adaptation: Evidence from Annual Fluctuations in Weather in the US," NBER Working Paper No. 13178, June 2007.

Deutch, John, and Ernest Moniz, *The Future of Nuclear Power: An Interdisciplinary MIT Study* (Cambridge, MA: MIT Press, 2003).

Devell, Lennart, "Composition and Properties of Plume and Fallout Materials from the Chernobyl Accident," in *The Chernobyl Fallout in Sweden, Results from a Research Programme on Environmental Radiology*, Leif Moberg, ed. (Stockholm: The Swedish Radiation Protection Institute, 1991).

Donald, Stephen G., and Kevin Lang, "Inference with Difference-in-Differences and Other Panel Data," *Review of Economics and Statistics*, 89 (2007), 221–233.

Edvarson, Kay, "External Doses in Sweden from the Chernobyl Fallout," in *The Chernobyl Fallout in Sweden, Results from a Research Programme on Environmental Radiology*, Leif Moberg, ed. (Stockholm: The Swedish Radiation Protection Institute, 1991a).

——, "Fallout over Sweden from the Chernobyl Accident," in *The Chernobyl Fallout in Sweden, Results from a Research Programme on Environmental Radiology*, Leif Moberg, ed. (Stockholm: The Swedish Radiation Protection Institute, 1991b).

Ericson, Anders, and Bengt Källén, "Pregnancy Outcome in Sweden after the Chernobyl Accident," *Environmental Research*, 67 (1994), 149–159.

Gluckman, Peter, and Mark Hanson, *The Fetal Matrix: Evolution, Development and Disease* (Cambridge, UK: Cambridge University Press, 2005).

Hall, Eric J., and Amato J. Giaccia, *Radiobiology for the Radiologist*, 6th ed. (Philadelphia: Lippincott Williams & Wilkins, 2005).

Harrington, Winston, and Paul R. Portney, "Valuing the Benefits of Health and Safety Regulation," *Journal of Urban Economics*, 22 (1987), 101–112.

Hohenemser, Christoph, "The Accident at Chernobyl: Health and Environmental Consequences and the Implications for Risk Management," *Annual Review of Energy*, 13 (1988), 383–428.

Holmberg, M., K. Edvarson, and R. Finck, "Radiation Doses in Sweden Resulting from the Chernobyl Fallout: A Review," *International Journal of Radiation Biology*, 54 (1988), 151–166.

Hùlka, J., and I. Malátová, "A Comparison of Exposure due to Chernobyl Accident and Radon Exposure in the Czech Republic," manuscript, National Radiation Protection Institute, 2006.

IAEA, "Chernobyl's Legacy: Health, Environmental and Socio-economic Impacts and Recommendations to the Governments of Belarus, the Russian Federation and Ukraine," Technical Report, International Atomic Energy Agency, 2006. [Available at http://www.iaea.org/Publications/Booklets/Chernobyl/chernobyl.pdf].

Isaksson, Mats, Bengt Erlandsson, and Maj-Lena Linderson, "Calculations of the Deposition of 137Cs from Nuclear Bomb Tests and from the Chernobyl Accident over the Province of Skåne in the Southern Part of Sweden Based on Precipitation," *Journal of Environmental Radiology*, 49 (2000), 97–112.

Kjelle, Per Einar, "Gamma Monitoring Stations Annual Reports 1985–1986," Technical Report SSI rapport 87-08, National Insitute of Radiation Protection, Statens Strålskyddsinstitut, Stockholm, March 1987.

Kolominsky, Y., S. Igumnov, and V. Drozdovitch, "The Psychological Development of Children from Belarus Exposed in the Prenatal Period to Radiation from the Chernobyl Atomic Power Plant," *Journal of Child Psychology and Psychiatry*, 40 (1999), 299–305.

Laziuk, G.I., I.O. Zatsepin, P. Verger, V. Gagniere, E. Robert, Zh.P. Kravchuk, and R.D. Khmel, "Down Syndrome and Ionizing Radiation: Causal Effect or Coincidence," *Radiatsionnaia Biologiia, Radioecologiia*, 42 (2002), 678–683.

Lin, Ming-Jen, Jin-Tan Liu, and Shin-Yi Chou, "As Low Birth Weight Babies Grow, Can Well-Educated Parents Buffer this Adverse Factor? A Research Note," *Demography*, 44 (2007), 335–343.

Loganovskaja, Tatiana N., and Konstantin N. Loganovsky, "EEG, Cognitive and Psychopathological Abnormalities in Children Irradiated In Utero," *International Journal of Psychophysiology*, 34 (1999), 213–224.

Lüning, Günther, Jens Scheer, Michael Schmidt, and Heiko Ziggel, "Early Infant Mortality in West Germany before and after Chernobyl," *Lancet*, November 8671 (1989), 1081–1083.

Mattsson, Soren, and Raine Vesanen, "Patterns of Chernobyl Rainfall in Relation to Local Weather Conditions," *Environment International*, 14 (1988), 177–180.

McCrary, Justin, and Heather Royer, "The Effect of Female Education on Fertility and Infant Health: Evidence from School Entry Policies Using Exact Date of Birth," NBER Working Paper No. 12329, June 2006.

Moberg, Leif, ed. *The Chernobyl Fallout in Sweden*, *Results from a Research Programme on Environmental Radiology* (Stockholm: The Swedish Radiation Protection Institute, 1991).

Nowakowski, Richard S., and Nancy L. Hayes, "Radiation, Retardation and the Developing Brain: Time Is the Crucial Variable," *Acta Paediatrica*, 97 (2008), 527–531.

Nyahu, Angelina I., Konstantin N. Loganovsky, and Tatiana K. Loganovskaja, "Psychophysiologic Aftereffects of Prenatal Irradiation," *International Journal of Psychophysiology*, 30 (1998), 303–311.

Otake, M., and W.J. Schull, "In Utero Exposure to A-Bomb Radiation and Mental Retardation. A Reassessment," *British Journal of Radiology*, 57 (1984), 409–414.

——, "Review: Radiation-Related Brain Damage and Growth Retardation among the Prenatally Exposed Atomic Bomb Survivors," *International Journal of Radiation Biology*, 74 (1998), 159–171.

Peplow, Mark, "Special Report: Counting the Dead," *Nature*, 440 (2006), 982–983.

Price, Philip N., and Andrew Gelman, "Should You Measure Your Home's Radon Concentration?" in *Statistics—A Guide to the Unknown*, 4th ed. Roxy Peck, George Casella, George Cobb, Roger Hoerl, Deborah Nolan, Robert Starbuck, and Hal Stern, eds. (Pacific Grove, CA: Duxbury Press, 2005).

Rosenzweig, Mark R., and Paul T. Schultz, "Market Opportunities, Genetic Endowments, and Intrafamily Resource Distribution: Child Survival in Rural India," *American Economic Review*, 72 (1982), 803–815.

Rosenzweig, Mark R., and Kenneth I. Wolpin, "Heterogeneity, Intrafamily Distribution and Child Health," *Journal of Human Resources*, 23 (1988), 437–461.

Rosenzweig, Mark R., and Junsen Zhang, "Do Population Control Policies Induce More Human Capital Investment? Twins, Birthweight, and China's 'One Child' Policy," *Review of Economic Studies*, 76 (2009), 1149–1174.

Scherb, Hagen, Eveline Weigelt, and Irene Brüske-Hohlfeld, "European Still-Birth Proportions before and after the Chernobyl Accident," *International Journal of Epidemiology*, 28 (1999), 932–940.

Sperling, K., J. Pelz, R.-D. Wegner, A. Dorries, A. Gruters, and M. Mikkelsen, "Significant Increase in Trisomy 21 in Berlin Nine Months after the Chernobyl Reactor Accident: Temporal Correlation or Causal Relation?" *British Medical Journal*, 309 (1994), 158–162.

St. Clair, David, Mingqing Xu, Peng Wang, Yaqin Yu, Yoorong Fang, Feng Zhang, Xiaoying Zheng, Niufan Gu, Guoyin Feng, Pak Sham, and Lin He, "Rates of Adult Schizophrenia Following Prenatal Exposure to the Chinese Famines of 1959–1961," *Journal of the American Medical Association*, 294 (2005), 557–562.

UNDP/UNICEF, "The Human Consequences of the Chernobyl Nuclear Accident: A Strategy for Recovery," Report 240102, 2002. [Available at http://www.undp.org/dpa/publications/chernobyl.pdf].

UNSCEAR, *Report to the General Assembly: Sources and Effects of Ionizing Radiation*, Vol. II, Annex J (New York: United Nations, 2000). [Available at http://www.unscear.org/docs/reports/annexj.pdf].

Valentin, Jack, *Protecting People against Radiation Exposure in the Event of a Radiological Attack*, International Commission on Radiological Protection Series, Vol. 96 (Amsterdam: Elsevier, 2006).

Vogel, H., "Rays as Weapons," *European Journal of Radiology*, 63 (2007), 167–177.