Low Doses of Radiation, Dose-Response Model and Cognitive Endowment

Bachelor’s Thesis
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Abstract

Dose-response models are used widely to assign risks with corresponding levels of irradiation. The effects of higher doses of radiation are well documented, however, the effects of much lower doses have not been established. This literature review focuses on the proposed relationship between low doses of radiation and cognitive endowment. Contrasting previous research, some more recent studies have been able to present evidence proposing that levels of irradiation generally considered of being safe, could hinder cognitive endowment. The evidence from the studies suggests that regarding cognition, a person is most sensitive to the adverse effects of irradiation during the gestational weeks 8-25. This observation and the plausibility of the empirical strategy is supported by evidence from the fields of embryology and brain development.

Keywords Prenatal, Ionising radiation, cognitive endowment, dose-response model
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1 Introduction and Motivation

My thesis draws heavy inspiration from a study conducted by Douglas Almond, Lena Edlund and Mårten Palme titled “Chernobyl’s subclinical legacy: Prenatal exposure to radioactive fallout and school outcomes in Sweden”. In their research, Almond et al. exploit the in utero exposure to ionising radiation caused by the Chernobyl accident in order to study, as the title suggests, “Prenatal exposure to radioactive fallout and school outcomes in Sweden”.

A big portion of my thesis will revolve around the possible descriptive evidence considering the relationship of interest. Within the scope of my thesis this exercise serves two separate agendas. First it helps to motivate the reader, as the regressor, in this case, is universally considered of having no effect on the regressand. Second, with the help of this interdisciplinary review, I hope to be able to provide tools for the evaluation of the causal mechanics of the proposed relationship and thereby guide the future research on the given subject. I also feel that in the absence of more evidence an outside-in perspective provides a more coherent ‘picture’ considering the goals of this thesis.

Theoretically this thesis falls under the category of human capital research as the main output variable of interest is cognitive endowment. While human capital is by no means a brand new economic concept, the complexity of the term alone is perfectly capable of spinning endless hours of discussion (see Savvides and Stengos, 2008). The OECD defines human capital as follows: “the knowledge, skills, competencies and other attributes embodied in individuals or groups of individuals acquired during their life and used to produce goods, services or ideas in market circumstances,” (OECD, 2017). This is also the interpretation I will be using throughout this thesis. The relationship between human capital, individual’s cognitive abilities and productivity is based upon a somewhat intuitive idea: the more you know of a given subject, the better the expected outcome of a task given a matching field of interest.
Several empirical studies focusing on human capital have been trying to isolate a certain underlying variable through the differences in other inputs. According to Almond et al (2008), this approach suffers from a major weakness – lack of exogenous variation. They argue that the observed latent variables are often interrelated: For example, a child’s cognitive abilities are commonly believed to be interrelated to the family background ever since the Coleman report: “Equality of Educational Opportunity” published in 1966. The report demonstrated a substantial relationship between the students’ achievements and the family background (Coleman, 1966).

The pursuit for external variation to exploit, has led researchers to look for sources provided by the environment. The problem often present with this type of an approach is described by Banzhaf and Walsh (2008) by using the Tiebout model in order to explain the choices people make, when facing different bundles of taxes and public goods. The findings of Banzhaf et al. would suggest that people in fact do vote with their feet, thereby making the selection less representative of the population. It’s easy to imagine that the Tiebout model does not only apply to taxes and public goods, but to basically any situation where choices can be based on a cost-benefit analysis. This issue of the selection bias limits the number of possible quasi experiments to a point, where the chosen source for the external variation to be exploited can sometimes feel somewhat counter intuitive: through this thesis, I shall be focusing on one of these cases – low amounts of ionising radiation. And especially its relationship with endowed cognitive skill set.

The relationship between ionising radiation and lower cognitive abilities has been the subject of an increasing number of studies. Tragedies such as Hiroshima, Nagasaki (see, Otake and Schull, 1984), Chernobyl (see: Nyagu et al., 1998; Almond, Edlund and Palme 2009; Heiervang, 2010) and Nuclear weapons tests carried on by the former Soviet Union (see: Black et al., 2013) all have their own unique characteristics and provide foundation for and infinite array of research on numerous fields of study. The majority of the research so far has focused on the effects of higher levels of radiation, presenting consistent evidence of the adverse effects of ionising
radiation. The ones studying the effects of lower dosages have not, until recently, been able to provide any coherent evidence of the effects of lower amounts of radiation. It’s also worth noting that a relatively large portion of the research seems to be focusing on the mutagenic effect of radiation and its ultimate manifestation such as brain tumors and cancer, while its effect directly on cognition remains to be less studied.

One fundamental concept surrounding biological research is the dose-response model. The function of a dose-response model is to associate an appropriate risk with the corresponding dose of a given treatment. It has been argued that despite their central roles, the models themselves have not been thoroughly researched, and especially the effects corresponding the low doses remain to be controversial (Calabrese, 2016). The current predominant models, such as the linear no threshold model, map the direct genetic damage to the energy obtained by the cellular DNA. One observation challenging this approach is the bystander effect. The radiation-induced bystander effect describes a process where the cells neighboring a cell exposed to radiation also respond to the shock by triggering the DNA repair mechanism without any direct stimulus. (Prise et al., 2003). An experimental study finds that the cells adaptive protection mechanism and the radiation induced damage correlate with the radiation dose. The results from the study suggest that for doses smaller than 200 mGy, the DNA repair mechanism would over-perform the induced damage. For the doses larger than 200 mGy the repair mechanism can no longer keep up with the damage (Feinendegen, 2003).

In 2015 US Nuclear Regulatory Commission sought comments whether the linear no threshold model should be substituted with the hormesis dose response model, where instead having adverse effects, small doses would be considered of having a slight positive impact (Calabrese, 2015).
1.1 Why is it of interest?

A better understanding of the effects of low doses of ionising radiation would be highly useful. To begin with, it would provide foundation for better estimation of the direct monetary costs of the negative effects. It would also contribute to the volatile debate surrounding the dose-response models. Better understood and more accurate models would presumably steer the policy makers towards more efficient policies by allowing more accurate predictions of the economic consequences of the regulatory changes.

1.1.1 Estimating the monetary costs

Studies conducted by De Sants et al (2005) have linked radium irradiation of the maternal pelvis with microcephaly and mental retardation given the doses above 100 mGy. As obvious as it might be, it’s worth pointing out that the social cost of mental retardation is substantial.

Another perspective is provided by the research studying the relationship between schooling and income. Almond et al. (2009) find a strong correlation between schooling outcomes and prenatal exposure to subclinical amounts of radiation. Using the data from Sweden, they estimate the negative impact of the fallout from Chernobyl accident to a subject’s cognitive abilities. They argue that given gestational age of 8-25 weeks at the time of the accident, the negative effect for the subjects born within the most contaminated areas in Sweden is equivalent of missing one year of schooling. Angrist and Kreuger (1991) study the relation between the years of schooling and the birth date due to the compulsory schooling laws. Using the variation in education, resulting from the combination of the birth month of the subject and the schooling laws, as an identifier, they draw the positive correlation between the time spent in school and higher earnings. They estimate the monetary return on one year of additional schooling as being around 7.5%. Almond et al. also estimate the relationship between subclinical amounts of radiation and recorded earnings. Using the grade averages alone, they estimate the decrease in income as being around 3.3% for the in utero cohort, born in the areas of high...
contamination. Their findings are consistent at the order of magnitude with the results of a similar study later conducted by Black et al. (2014). Black et al. observe where they also find evidence suggesting that it would not only be the affected cohort, but also their children who demonstrate lower performance levels. However, to what extent the observed effect can be explained with the parental level of education was not addressed.

These findings seem to suggest that there is indeed a negative relationship between the ionising radiation and the schooling outcomes that could turn into lower levels of income and productivity. Correspondingly, they also challenge some of the positions taken by authoritative institutions towards the concept of the linear no-threshold model.

1.1.2 A guideline for policies

As noted before, a potential benefit from the better understanding of the costs of sub-clinical amounts of ionising radiation would be its ability to help steer the policymakers towards more optimal decisions. A meaningful cost benefit analysis of this magnitude demands highly accurate estimates of the true costs of ionising radiation. Just to exemplify, we could think of the case of obtaining ionising radiation via natural sources, such as radon, a natural gas created as a byproduct from the decay of uranium and thorium. The U.S. Environmental Protection Agency estimate that radon alone accounts as many as 21,000 lung cancer deaths annually. The proposed effect on cognition would further increase the total costs stemming from the radiation.

An effective way to reduce the probability of acquiring a radon related health defect is to install proper ventilation system into the basement of the house you are living in and thereby decrease the intake of radon induced radiation. The problem is that the renovations of this nature are often expensive, and are thereby seen as less desirable by individuals under uncertainty. From the individual point of view, it’s difficult to tell for sure if the future buyer of the house will appreciate the expensive
renovation to its full cost. In the presence of strong myopia, a more efficient solution can be reached with better regulation.

The already well known radiation induced deterministic effects combined with the better understanding of the effects now classified as stochastic would thereby allow better evaluation of the effectiveness of the current policies in relation to the actual risks of radiation.

2 Literature Review

When used properly, the proper statistical models, can reveal relations between changes of different variables. However, what they fail to do is to differentiate correlation from causation. Given the current sentiment of the effects of low doses of ionising radiation, a coherent approach should begin with a question: Is there any evidence of the effects of low doses of radiation? The purpose of this section is to answer this intriguing question and to provide definitions of the conceptual frameworks relevant to the subject on a very coarse level.

2.1 Conceptual Framework

2.1.1 Classification of Radiation

Radiation can be classified in two different categories: non-ionising and ionising radiation. Non-ionising radiation carries enough energy to move atoms or to vibrate atoms, where ionising radiation has enough energy to punch electrons out of atoms, hence the name ionising radiation. On the electromagnetic spectrum ionising radiation is located on the high frequency end of the spectrum while the lower frequencies are considered non-ionising. Typical sources for non-ionising radiation would be visible light, radio waves and microwaves. Sources for ionising radiation include ultraviolet light, x-rays and radioactive elements to name a few (EPA, 2017).
2.1.2 Classification of the Effects of radiation

The effects from the exposure to radiation can be classified as stochastic or deterministic. The effects caused by ionising are considered of being stochastic if the effects take place sometime after the exposure and where the probability of the effect is a function of the dose without a threshold. The deterministic effects, also known as the clinical damage, occur mainly on doses above the threshold line, where the increase in the dose increases the severity as well as the incidence of the effect. In other words, if direct organ or tissue damage can be observed, the effect is considered of being deterministic. (Ionizing Radiation, Part 1: X- and Gamma -Radiation, and Neutrons.) The deterministic effects take effect mainly through the cell killing properties of radiation (Leenhouts & Chadwick 1989).

2.2 How ionizing radiation affects living matter

The adverse effects of exposing a developing brain to radiotherapy are relatively well known. However, the understanding how irradiation affects the cognition, especially when the actual dose is relatively low. From the field of epidemiological studies, we can read about the physiochemical process triggered by the ionising radiation passing through the living matter. This process results in changes at the molecular and cellular, and even tissue and organism levels. On higher doses these changes have been linked with severe mental retardation and cancer (Miller, 1999).

Actively dividing stem cells have been found to be more vulnerable to ionising radiation in comparison with cells that have already completed mitosis and reached terminal differentiation. According to a number of studies, the sensitivity of the human cells to ionising radiation is largely dictated by the cell cycle. Hence given the subject of cognition, the main area of interest can be limited to neural cells. The fate of the development of the brain and the prolonged mitosis has been linked by Pilaz et al (2016). The amount of proliferation in the adult brain is very limited. Hence any neural damage is considered as being permanent (Nowakowski and Hayes, 2008). Delayed DNA damage combined with mitotic catastrophe due to X-irradiation was
observed by Ianzini and Mackey (1998).

2.3 Radio sensitivity

The age of the subject exposed to ionising radiation plays an important role in predicting the damage caused by the exposure radiation. This assumption is a combination of two different factors: how the irradiation affects the mitosis and the increased mitotic activity in developing organs.

The mitotic activity within the brain is not uniform over the embryonic phase. Different parts of the brain develop during different phases of the pregnancy. The nervous system develops through a rapid division of stem cells (Martin, 2012). On average, a newborn baby is equipped with more than 100 billion neurons. In order to reach this number, the average growth rate of the brain is around 250 000 neurons every minute throughout the entire pregnancy (Ackerman, 1993). It is also known that terminally differentiated neurons no longer divide. While it does not mean that all the neurons of an adult brain would have developed during the embryonic period, the mitotic activity inside the brain after the development phase, is substantially lower. (Purves et al., 2012). The development of the nervous system starts early on during the pregnancy, however it is only after the closing of the neural tubes, during the week 4, when cerebellum begins to develop and the cerebral hemispheres start to grow more rapidly. During the week 14, the cerebellum starts to resemble its adult form (Martin, 2012).

To further exemplify the development of the different areas of the brain, let us focus on hippocampus for a moment. The hippocampus is a major component within the limbic system of the brain. Its main functions outside are related to consolidating short-term information into long-term and spatial memory. It also provides a good starting point as several studies also link together hippocampal dysfunction and cranial irradiation. These dysfunctions include learning and memory defects, spatial and verbal memory issues and lower problem solving abilities. (Son et al. 2015). The actual development of the hippocampus begins around the gestational weeks 12 and
The resemblance of its adult form is reached around the weeks 18-20. (Hill, 2017)

On a side note, this is consistent with the finding by Almond et al. (2009). In their study, they observe the strongest effect within the in utero cohort of 8-25 weeks. This observation aligns with the research investigating the relation between brain development and ionising radiation. The expansion of the neocortex over the weeks from 8 to 25 is discussed by Nowakowski and Hayes (2008). Similarly, De Santis et al. (2005) narrow down the increased sensitivity to radiation with the development of the central nervous system and the increased mitotic activity of the neuronal cells from 2 to 25 weeks, where the weeks from 8 to 15 are proposed of being the most critical.

3 Case Chernobyl: Background

This section will take a closer look into the accident of Chernobyl Nuclear Power Plant in 1986 and how it was exploited by Almond et al. (2009) in the research on the effects of low amounts of ionising radiation to cognition. For evaluating the credibility of the observations, it is important to have an understanding of the accident itself and especially of the mechanism responsible for administering the radionuclides from the collapsed reactor to the people across the Europe. I will also spend some time describing the data and the identification strategies used by Almond et al.

While a properly designed, controlled and rigorously executed experiment could yield accurate estimates of the causal effects in question, performing such experiments can often be next to impossible. With the relation of interest in mind, experiments of this nature would be not only difficult to perform, but also notably expensive and also in this case, ethically questionable if not illegal. In the absence of the possibility for a real randomised experiment, a natural experiment could prove to be just as useful. This, however, is only possible if there is sufficient data available. Another requirement is the mechanism substituting for the need for random
sampling. For researching the impacts of sub-clinical amounts of radiation, the Chernobyl accident provides a nearly perfect natural experiment: the amount of data is extensive and the amount of people affected, in other words, the sample size is enormous, and the variation mimicking experimental design is provided by the rainfall patterns.

I will also be comparing the observations made by Almond et al (2009). with the observations from a very similar study done by Black et al.(2014). The research conducted by Black et al. focuses on the effects of the fallout from the former Soviet Union’s nuclear weapons test to Norway on Norwegian population. The mechanism of the experiment and their identification strategies follow closely the ones used by Almond et al.(2009).

3.1 The Accident of the Chernobyl Nuclear Power Plant (CNPP)

April 26th, 1986 a nuclear accident took place in the Chernobyl Nuclear Power Plant in the former Soviet Union. The accident materialised when one of the RBMK-1000–type reactors exploded while releasing a substantial amount of radioactive substances into the environment. The meltdown took place early in the morning, yet the incident was not publicly reported until two days later when the radiation levels in Forsmark, Sweden triggered the alarms at the local power plant over 1000 km away from CNPP (UNSCEAR, 2000). The release of the radionuclides continued for 10 days after the accident, totaling up to 14 exabecquerels of radioactive substances released into the atmosphere. (EPRS, 2016).

3.2 Composition of the Fallout

The spectrum of radionuclides released into the atmosphere due to the meltdown of the Chernobyl Nuclear Power Plant was significant. Some of the radioactive particles that were observed immediately after the meltdown included iodine-131, iodine-132, zirconium-95, plutonium-239, caesium-131, caesium-134, cerium-141, cerium-144 and tellurium-132 to name a few (De Cort et al., 1998).
Even though the variety of the released radionuclides was wide, only a few contributed significantly to the Europe-wide fallout. Because of their different properties, different radionuclides carry different levels of importance when estimating their impact as a source of ionising radiation in a specific place at given time. In the immediate aftermath of the accident, the short-lived radionuclides, mainly iodine-131 (half-life of 8 days), were the most significant sources for a majority of the radiation dosage. Caesium’s contribution to the overall total dose during the first year of the accident is believed to be around 10% (De Cort et al., 1998). Over longer periods of time the importance of caesium-137 (half-life of 28 years) and caesium-134 (half-life 2 years) as sources of radiation increased because of their longer half-lives. Similarly, to iodine-131, caesium’s small particle size allows it to disperse in air and water rather quickly making it more likely to contribute to the global fallout. (De Cort et al., 1998).

3.3 Transportation of the Fallout

The initial release of radioactive substances into the atmosphere from the Chernobyl accident was due to two thermal explosions taking place at the power plant. The explosions created a cloud several kilometers high, where some of the particles were dispersed well above the planetary boundary layer. About one fourth of the total amount of radioactive substances got released during the early phases of the disaster. The combustion of the graphite moderator drove the subsequent, rather large, release of radionuclides into the atmosphere during the following ten days. (De Cort, 1998)

The aerial and the ground measurements of radiation across Europe reveal a substantial amount of geological variation in the dispersion of radioactive substances. The strong winds of the free atmosphere combined with the altering directions during the ten-day period were responsible for the relatively quick transportation of the radionuclides across the bigger part of Europe, including Sweden and Finland, within days form the initial explosions (De Cort, 1998). Part of the initial plume
arrived to Finland from the Baltic where it was divided into two on the 27th of April. The other main part of the plume reached Sweden on the 28th (Valkama et al., 1997; Persson et al., 1987).

The strength of the winds above the planetary boundary layer (PBL) are mostly explained with the absence of the turbulence caused by the surface drag. In comparison with the winds within the PBL, the wind speed above the PBL are much stronger and more homogenous thereby allowing the smaller particles travel greater distances in a short amount of time. (Mason, 1995). It is beyond the scope of this thesis to provide a more detailed description of the dispersion mechanism. While it would be highly useful for more careful analysis of the possible uncertainties within the estimates, it would require expert level understanding of the meteorological conditions surrounding the accident.

3.4 Deposition and Contamination

While the winds explain the movement of the radionuclides across the Europe, a strong positive correlation can be found between the increased measurements and the rainfall. In other words, most of the radioactive substances in Sweden and Finland were deposited due to rainfall. This process is known as the wet deposition (STUK, 2017; Holberg et al., 1988; De Cort, 1998, UNSCEAR, 2008). Due to the rain patterns the fallout in Sweden and Finland was not evenly distributed thereby creating areas with high levels of concentration in comparison with areas that stayed virtually clean (Paatero et al. 2010).

People can be exposed to irradiation either directly through the gamma rays emitted by the radionuclides currently present in the air or on the ground. Also, inhaling the particles or absorbing them through skin exposes a person to irradiation. Yet another way of exposure is the consumption of contaminated food in the case where the radionuclides are deposited directly on plants or animals, or when the plants have absorbed the fallout through their roots or when the animal have eaten the contaminated plants (Black et al., 2013).
The amounts of caesium deposition varied across the Europe. It is estimated that the amount of caesium deposition due to the Chernobyl accident in Sweden was 2.9 pBq. In Finland, the corresponding number was 3.1 pBq. The estimate for the caesium deposition from the Chernobyl accident across the Europe totals to 63 pBq. (De Cort et al., 1998).

Also, the acquisition of the dose was not evenly distributed throughout the year of the accident, as can be observed from the data collected from observation station in Njurunda, Sweden. On the 29th of April, the measured dose spiked to 1094 Nano Sieverts per hour, where the same measurement was 92 Nano Sieverts per hour just two days before. 10 days later, on the 9th of May, the corresponding number was 567 and after 30 days from the initial spike it was down to 285. By the end of the December 1986 the daily measured dose in Njurunda dose was down to 125. The daily average in 1985 was 108.3 Nano Sieverts per hour. (See: Figure I; Kjelle, 1987).

4 Case Chernobyl: Chernobyl’s subclinical legacy

The purpose of this section is to describe the research and discuss the mechanism exploited by Almond et al (2009).

4.1 The Data

The data set used by Almond et al. is fairly comprehensive. Schooling outcomes are evaluated at individual levels for 584,014 individuals by measuring performance during the final year of compulsory education. The education data also includes the times and the places of birth, and has been augmented with the corresponding fallout data for each one of the entries.

4.1.1 Radiation

For radiation exposure, Almond et al use both aerial and on-site ground measurements. The aerial measurements in Sweden were conducted by the Swedish
Geological Company. The aerial measurements were performed starting from May, sampling over 2500 locations that allowed the aggregating samples up to a county level. Instead of caesium-137, caesium-134 was measured instead. The relationship between the two isotopes was known and allowed the estimation of caesium-137. This allowed separating the fallout from the past nuclear weapons tests from the Chernobyl fallout. For the on-site ground measurements, the coverage was limited. The on-site ground measurements were collected from 61 monitoring sites. The aerial measurements differed from the on-site ground measurements. The measurements of caesium-134 were used for estimating the deposition of iodine-131. In the absence of actual dosage data Almond et al. use the measured levels of radiation as a proxy for the dosage.

4.1.2 The Outcome Variables

The outcome variables used by Almond et al are qualifying to high school and the grade points. The total grade points are calculated by summarising 16 of the individual grades, all ranging from 0 to 20, thereby giving the total grade points variable a range from 0 to 320. An average grade from the same 16 subjects is used for applying to secondary education. In order to qualify to high school in Sweden a student must pass 9th grade Mathematics, English and Swedish.

The student data used by Almond et al. focuses on people born from 1983 to 1988 with almost complete coverage of the cohort. It is extended with the data from the National Birth Register and from the National In-patient Register. The data is arranged in three cohorts: In utero, in utero 5 to 25 weeks post conception at the time of the fallout and also in utero 0 to 7 weeks post conception. Their data set consists of 551 630 observations. A more detailed descriptive statistic of this data will be found in the appendix.

For evaluating high school graduation, average grades, and grades in Mathematics and Swedish, Almond et al. use the High school records from 2006. The average year for a Swedish student to graduate is the year they turn 19.
In their research Almond et al., classify the fallout into four different categories on a county level. Gävle and Sundsvall being in the highest category and Norrbotten in the lowest. The population weighted averages for the given categories ranged from 44.2 to 0.03 KBq/m² of caesium-137.

4.1.3 Control Variables

Parental education is controlled through dummy variables corresponding the highest level of education attained for both of the parents individually. The data comes from the National Education Register and was received from the LISA database. The impact of the family background is considered of being strongest amongst the subjects coming from families with more modest financial prowess (Currie and Moretti, 2007).

As Dehejia et al. (2004) have proposed, due to the effect of business cycles on the characteristics of an average parent, local labor market conditions are controlled with a nine month lag, given the estimated length of the pregnancy. Almond et al use the quarterly data available from the Statistics Sweden. The data is available for people between 16 and 64 years of age on a county level.

5 Case Chernobyl: The Results

Because of the observed seasonality in education related performance, comparison is made between the treatment cohorts and corresponding adjacent cohorts: matching the months across adjacent years.

By comparing the areas suffering from the highest levels of fallout with the rest of the country, they find decreased cognitive performance within the in utero cohort. The observed effect increases with the estimated dose of ionising radiation.
5.1 Identification Strategy

In their research, Almond et al focus on three main identification strategies. The strategies rely on an assumption that the regional differences or the control variables are not connected with the disturbances. For the regression, they also make the assumption that the place of birth equals the location at the time of the exposure.

5.1.1 The first strategy

\[ y_i = \alpha_0 \times I(\text{in utero})_i + \sum_{j=1}^{3} \alpha_j \times R_j \times I(\text{in utero})_i + \beta X_i + \tau_{\text{mob}} + \gamma_{\text{region}} + \lambda_{\text{muni}} + \epsilon_i, \]

\( Y \) being the vector for the variables of interest and I a dummy variable with the value of 1 for the cohort in utero during the fallout. R1-R3 indicate the areas with the corresponding level of fallout. In theory, this should be able to capture the suspected linear relationship between the dose and the weakened performance. Controls are used for gender, labor market conditions and for parental education. Controlling the labor market conditions is believed to tackle the possible bias concerning the fertility decisions. The model allows fixed effects for the year and the month of birth, and for the municipality of birth.

The sample for the model are the individuals in the *in utero* cohort. The comparison is made between the contaminated areas and the reference areas, under the assumption that the error terms are homoscedastic. In the absence of the data used by Almond et al. The distribution of the error terms remains unknown.

5.1.2 The second strategy

The second strategy can be described as following:

\[ y_i = \alpha_0 \times I(\text{in utero})_i + \alpha_1 \times \log(FALLOUT_{\text{r}}) \times I(\text{in utero})_i + \beta X_i + \tau_{\text{mob}} + \gamma_{\text{region}} + \lambda_{\text{muni}} + \epsilon_i, \]
Where most of the variables remain the same as in the model for the first strategy, except for the areal indicators R that were replaced with LOG Fallout. The FALLOUT variable represents the average Cs-137 kBq/m2 fallout levels for the county or municipality in question.

5.1.3 The third strategy

\[ y_i = \alpha_0 \times I_{inuero} + \sum_{j=1}^{3} \alpha_j \times R_j \times I_{inuero} + \tau_{family} + \tau_{gdb} + \gamma_{mb} + \lambda_{muni} + e_i, \]

The third strategy follows the first strategy except for the controls for the labor market conditions, gender and the parental education. The controls for the family background, labor market conditions and for the gender from the first identification strategy have been replaced with the siblings fixed effects for the families with two children of the same sex. The sample is also limited to married parents, where one of the children belongs to the exposed in utero cohort and the other does not, but still belongs to the cohort born between 1983 and 1988.

The rationale behind this specification is holding all the family level variables constant and by doing the comparison within the families, hence rendering all the inference within-siblings. Given the requirements of the approach, the number of observed families is now 5547.

5.2 Health

The analysis of health-related outcomes revealed no significant results. All the found estimates were not only small, but also statistically insignificant. While they did not test for all the imaginable health related outcomes, the array of output variables used matches the usual suspects proposed by the literature. No congenital malformations, mental issues, hospitalisations or any other statistically significant
deviations were observed. Similarly, there was no evidence of increased rates of still births or distortion of gender ratio due to the fallout.

5.3 Schooling

From the data illustrating the fraction qualifying to high school per cohort a 3% drop can be observed when comparing the R3 cohort to the rest of the sample. Because of the seasonality, the \textit{in utero} cohort is compared to the same cohort in adjacent years. When the control group is replaced with the R0 cohort (representing the lowest areas of fallout) the gap grows to 5%. However according to Almond, the above normal performance of the control group partially contributes to this visual observation. The observed effect grows weaker as the subject \textit{in utero} at the time of the exposure grows older and ceases to exist after 25 weeks post conception. Similar effects could also be observed for grades presented according to the month of birth. The R3 cohort born during the fall of 1986 demonstrates a notable decrease in average and in Mathematics grades. This too is consistent with the research describing the effects of ionising radiation.

5.3.1 Regression analysis

The comparison of the \textit{in utero} cohort with the rest of the year does reveal a negative effect on all the schooling related outcomes, but the observed effect fails to carry any statistical significance. Including the different levels regional fallout into the difference in the differences model increases the significance of the estimates. The observed negative effect grows stronger as the degree of fallout increases. For the average grades in the R3 \textit{in utero} cohort Almond et al. estimate a drop of 0.54 points or correspondingly 2,5% percentiles. The same cohort was also found to enter high school with a 3% lower probability in comparison with the group in the lowest radiation group. The Mathematics scores for the same cohort were found to be 6% lower. The researchers argue that a drop of this magnitude is equivalent to starting school a year later.
The second strategy relies partly on a smaller sample due to the lower number of the ground monitoring sites. Instead of classified levels of radiation this model uses continuous measurements for caesium and iodine from both on-site and aerial measurements. The observed negative effect on Mathematics is significant for both of the measuring methods: aerial and ground level. The effect on qualification to high school on county level, is significant for the aerial measurements.

The third strategy, the within siblings analysis, supports the findings from the cross section analysis. The observed negative effect on Mathematics grades is over 10%. According to Almond et al., this indicates evidence of parental reinforcement. Meaning that the parental response to the fallout could have strengthened the effect. This observation is consistent with earlier observations by Rosenzweig and Zhang (2009). For the grades from high school graduation, a significant, albeit smaller effect was observed. It is suggested that the voluntary nature of high school and the positive selection could explain the difference.

6 Discussion

6.1 Internal Validity

Almond et al. deliver strong evidence that would suggest that there is a relationship between low amounts of ionising radiation and cognitive abilities. Because of the massive coverage of the plume, the unpredictability of the rains within the given time window, and the role the rain plays for administering the radiation, a random sampling can be assumed.

The lack of any statistically significant effect on health outcomes would also suggest that there is no reason to suspect any differential loss of participants across the groups. The same-sex within siblings comparison should help reduce the possibility of an omitted variable bias, however, as noted by Almond et al. there is always the possibility for the existence of time-variant characteristics.
How big of a portion of the estimated effect can be credited to the actual radiation dose received, instead of the negative shock caused by the increased stress levels, remains to be unclear. According to The IAEA (2006) the largest health related impact of the Chernobyl accident would be the mental health issues. However, Black et al. (2014) report similar results from a similar experiment supporting the findings of Almond et al. They also argue that due to the fact that during the time of Soviet nuclear weapons tests there was no research available of the given subject, rendering the stress caused by the fear of the effects from the fallout non-existent.

Probably the biggest challenge arises from the errors within the measurements and the estimates. Potential measurement error could arise from the assumptions for the different estimates. Even though caesium-137 and iodine-131 were the highest contributors to the radiation spike, the aerial measurements for the ground deposition, conducted by the Swedish Radiation Protection Authority, measured caesium-134 instead. Separating the caesium-137 from the nuclear weapons tests performed by the Soviet Union, from the caesium-137 originating from the Chernobyl accident would have been problematic. According to Almond et al. the Caesium-137/Caesium-134 ratio during the Chernobyl fallout would have been known to be 1:7. However, Kawada et al. (2012) estimated the same ratio between 1.4 and 1.66. They also note that this ratio varies depending on the efficiency of the degree of burn-up and the age of the fuel rods. Considering the timeframe of the accident, the age of the fuel rods could be considered constant but the degree of the burn-up factor would most likely have changed over the 10-day long release period.

In order to eliminate the bias created by a significant amount of measurement error, a possible solution could be using an instrument variable. The function of the instrument variable is to reveal the part of the estimator that is not correlated with the error term. Because of its central role in administering the radiation, rainfall would be the most obvious candidate. The rainfall is not only responsible for administering the rain, it also washes out substantial amounts of the radionuclides at the ground level especially in the urban areas where the surface layers often consist
of concrete and asphalt. The heavier the rain, the stronger the wash-out effect. (Devell, 1991).

6.2 External Validity

The external validity of the experiment appears to be strong. There seems to be no reason to assume any selection bias. Similarly, the possibility of observing any reactive effects such as the Hawthorne effect should be next to none as the test subjects had no knowledge of their participation in the test to start with. The majority of the possible multiple-treatment interferences should be ruled out by the difference in differences model as the overall levels of background radiation combined with the existing radiation from the past fallouts is considered being constant over shorter periods of time due to the half-life of the radionuclides. Likewise, it is also difficult to imagine for the treatment to differ due to the differences in the institutional settings. If the rainfall patterns responsible for administering the fallout from the Chernobyl accident did follow the typical rainfall patterns in Sweden, a possible selection bias could emerge, but as reported by Almond et al., the correlation between the rainfall patterns during the fallout and in general was small and negative. However, it is possible to imagine a possible relationship between the parents socioeconomic standing and the received dose of irradiation: According to Finck (1991) a large portion of the radiation could have been avoided by staying indoors, thereby making the people working outdoors more likely to receive higher amounts of radiation. This would result in estimates being biassed towards zero.

It remains to be unclear whether avoidance behaviour had any role during the fallout in Sweden. While the sibling fixed effects is extremely powerful at eliminating time constant variation stemming from the family background, it is also able to provide biassed inference presence of Missing at Random data; Or in this case Missing Not at Random. This type of sampling error could propose a threat to the external validity of the specification via possible coverage error. In their similar research using corresponding data from Norway Black et al. tested whether the exposure to fallout plays a role to the future child bearing decisions. No significant effect was to be
found. However, because of the differences in the public availability of research studying the harmful effects of ionising radiation there is a possibility that people aware of the research could have postponed or avoided child bearing. At the time of the Chernobyl accident, first studies of the effect of ionising radiation to cognition were already published (see: Otake and Schull, 1984), similarly the public awareness of the fallout was much greater in Sweden at the time of the Chernobyl accident than what it was during the Soviet nuclear tests in Norway (Black et al., 2014). If avoidance behavior was a factor, it would bias the estimates towards zero.

6.3 In Comparison with Similar Research

As noted earlier, Almond et al were not the first with the idea of comparing cognitive outcomes with nuclear fallout. Several researchers before them already tried to reveal the relationship between subclinical amounts of ionising radiation and an individual’s cognitive abilities. However, the bulk of them had not been able to observe any substantial effect or in the few cases where evidence had been found the validity of the experiment has not been very strong (See: Kolominsky et al., 1999; Loganovskaja and Loganovsky, 1999).

In their research using the same natural experiment, the Chernobyl accident, Litcher et al. (2000) included children who were already over one year old at the time of the accident. Similarly, the sample used by Joseph et al. (2004) included children up to 4 years old. The literature suggests that the children, older than 25 weeks in utero, are already much more resilient to ionising radiation, hence the average effect on cognition would be smaller and the variation higher. This would bias the estimate towards zero with a decreased level of statistical significance. And as mentioned before another issue arises from the unsuccessful random sampling. The stress related health issues of the parents living in the contaminated zones can have a negative impact on the child’s performance (Kolominsky et al., 1999) and also affect the behavior of the parents undermining the external and the internal credibility of the study.

In the case of Chernobyl, the logistics of the randomisation are somewhat
complex but the underlying rationale remains. Random assignment helps to eliminate the selection bias and ceteris paribus comparison more plausible. Next to random assignment comes the question of sample size. One possible explanations for many of the studies failing to find any coherent evidence on radiation’s effect on cognition could be the small sample size. As we increase the number of trials, in this case the sample size, the occurrence of a random event becomes equal to its probability. With the assumption that the model itself is BLUE, there are two explanations for a low T-static. The observed difference is small or the standard error is large (Angrist et al., 2013). Often the sample sizes have been relatively small, given the scale of the effect in question. This of course affects the magnitude of the measured standard as it is a decreasing function of the sample size. Increasing the sample size helps to even out the effect of individual random attributes. Another possible issue next to the standard error arises from the random assignment. The process of sampling is not satisfactory due to its non-random nature.

6.4 Future research

It should be fair to argue that the now dominant general opinion considering the effects of low doses of ionising radiation leans towards the safe end of the spectrum. However, the evidence based on the Swedish (Almond et al., 2009) and the Norwegian (Black et al., 2014) data, appears to suggest that even low doses of radiation can prove to be harmful. These findings contradict the previous research and rise questions over the universality of the dose-response models: is it reasonable to assume that a single model would be able to explain an array of outcomes ranging from cancer to cognitive endowment? Another question of importance is if there was something fundamentally different with the research conducted by Almond et al.? On a quick glance there seems to be three potential explanations for their observation: the sample size and the special emphasis on the fact that the effect in question is not only a function of dose, but a function of dose and time. Thirdly, they also seem to take the approach where the sensitivity to ionising radiation varies over the subjects lifecycle. By narrowing down the test subjects to the most vulnerable age, from the cognitional point of view, and by measuring cognitional outcomes, they were able to
measure effects carrying statistical significance and substantial economic weight.

The dose-response models generally approaches time on a very broad level. Also the general opinion seems to be that the threshold line, assuming there is one, would be constant over the lifespan of an individual. While the cancer research, given its massive economic impact factor, seems to be on the highest priority when estimating suitability of a dose-response model in regard to policy making, it could be argued that it should not be the only one. The implied assumption that the threshold line would be universal is challenged by the findings of Almond et al. (2009). Their findings suggest that the evidence from one field of study might not always transfer directly over to other areas of interest, take cognition for example. Similarly their findings seem to suggest that at least in regard to cognitive endowment, the effect of ionising radiation is not only a function of dose and time it took to obtain the dose, but also the age of the subject seems to be a crucial factor explaining the outcome.

The findings of Almond et al. (2009) and Black et al. (2014) seem to encourage further research. Similarly a quick comparison of the availability of the data and measured levels of radiation from the Chernobyl accident would suggest that a similar effect should be observable by using the data from Finland: for the most parts the Chernobyl fallout in Finland follow the exact same mechanics as the fallout in Sweden (see Figures 2 & 3, figure 4 is created by overlaying figures 2 & 3 in order to illustrate the correlation between the rainfall pattern and the measured radioactivity). Also the levels of radioactive deposition are comparatively similar with the levels measured in Sweden. According to Koivukoski (1986) the highest levels of contamination in Finland would have spiked roughly around 1 micro sievert per hour. More recent research (STUK, ###) suggests that the highest doses measured during the Chernobyl fallout would have peaked around five micro sievert per hour, roughly 20-30 times the higher than normal speed of the background radiation. The total amount of caesium-137 deposited to Finland is estimated to be 3.1 PBq in comparison with 2.9PBq caesium-137 deposited to Sweden (De Cort et Al, 1998).

Considering the nature of the evidence provided by Almond et al. (2009) and
Black et al. (2014), a convenient starting point for the future research could be the comparison of the observed effects between Sweden, Norway and Finland. This of course would require replicating the study with the data from Finland. Given the identification strategies used by Almond et al., it would be possible to construct a satisfactory dataset from the Finnish data. On the other hand, now that more time has passed since the accident, it is possible to pit the schooling outcomes against direct monetary outcomes: reported incomes. For the most parts, the in utero cohort at the time of the accident would be roughly around 31 years of age, rendering them part of the workforce and thereby subjects to taxation. Another possibility would be matching the data with the book-entry system data. This would allow observing if the suggested effect could also be observed from the subjects’ investing behaviour. Furthermore, other than using the schooling outcomes as a proxy for cognitive endowment, using the Finnish P1-test data. The P1 is a mandatory test for all the Finnish men attending the Finnish military service. The test measures the subjects cognitive skills including linguistic, visual and numeral reasoning (Alho et al., 2012).

7 Conclusion

The evidence of the effects of the low doses of ionising radiation are controversial. While a big portion of the research has not been able to produce any evidence of the adverse effects of low doses of radiation, some more recent studies have been able to do so. Some studies have observed decreased performance during the final year of compulsory schooling for the cohort exposed to ionising radiation at the gestational age from 8 to 25 weeks. While making any claims about causality at this point is quite ambitious, the suggestive evidence alone calls for further research. Multiple testing could also address the potential issue of being significant by chance. However, the proposed causal mechanism is supported by the evidence from the fields of embryology and brain development to a degree. These findings also contribute to the discussion regarding the suitable dose-response models responsible for assigning risks for the corresponding levels of ionising radiation. With further research the accuracy of the models could be improved, where the improved models would enable more efficient policy decisions.
8 References

References


Figures

**Figure I:**

Daily ground level nanosievert/hour rates at Njurunda

Data source: Gamma monitoring stations Annual reports 1985 - 1986

**Figure 2:**
Figure 3:

Source: Paatero et al., 2009.

Figure 4
The figure 4 is an overlay of the precipitation map (source: Paatero et al., 2009) and the total caesium-137 deposition from the Chernobyl accident (Source: European Environment Agency, 2009). The illustration demonstrates the correlation between the rainfall patterns and the deposition of the radionuclides.