Maternal prenatal stress and birth weight: evidence from 2016 Gyeongju earthquake in South Korea

By

RYU, Hyunjung

THESIS

Submitted to

KDI School of Public Policy and Management

In Partial Fulfillment of the Requirements

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Committee in charge:

Professor Tabakis, Chrysostomos, Supervisor ______________________

Professor Lee, Suil ______________________

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ABSTRACT

MATERNAL PRENATAL STRESS AND BIRTH WEIGHT: EVIDENCE FROM 2016 GYEONGJU EARTHQUAKE IN SOUTH KOREA

By

Hyunjung Ryu

A growing literature highlights that maternal prenatal stress has negative effects on birth outcomes, but the causal evidence is scarce. This study looks at the impact of the maternal prenatal stress caused by 2016 Gyeongju earthquake on birth weights. Using a difference-in-differences methodology, I find that *in utero* exposure to the earthquake significantly decreases the birth weights of children born in Gyeongju-si county. The negative effects are focused on those cohorts who were exposed during the third trimester of gestation and female infants. The findings are robust to use an alternative measure for earthquake intensity and the restricted sample, including only Gyeongsang-do region. These results provide the first evidence on the relationship between earthquake exposure and birth outcomes in Korea.

Dedicated to my parents,

Yanggie Ryu and Hyungran Kim

ACKNOWLEDGEMENTS

I would like to express my gratitude to many people for their support and assistance throughout the writing of this dissertation. First of all, I would like to express my very great appreciation to Professor Chrysostomos Tabakis and Professor Suil Lee, my research supervisors, for their warm encouragement, continuous guidance, useful critiques, and insightful comments on this research project. I would also like to offer my special thanks to Professor Booyuel Kim for his valuable and constructive recommendations on the development of this research topic during the Development Economics II class. My sincere thanks are also extended to my friends, who have given their precious time, enthusiastic energy, and good thinking to complete the research. Last but not least, I wish to thank my parents and sisters for their trust, support, and encouragement throughout my study at KDI School.

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1 Introduction

The association between maternal prenatal stress and pregnancy outcomes have been widely documented. For example, several papers have reported that maternal prenatal stress measured by pregnancy situation-specific stress, trait anxiety, current stress level, stressful life events, catastrophic events, or cortisol secretion rates has a negative impact on infant birth weight and gestational age (Bussieres et al. 2015).

This has been an important issue because infant birth status has a consequential impact on later health, education, and socioeconomic outcomes. According to the fetal origin hypothesis, *in utero* conditions (maternal malnutrition, infection, exposure to air pollution, prenatal stress, etc.) have not just substantial impact on individual's birth outcomes but persistent impacts on human capital throughout the life cycle of an individual (Almond and Currie 2011). There is also empirical evidence on the long-lasting negative effects of low birth weight on height, schooling, and earnings by using longitudinal data (Currie and Hyson 1999) and on the socioeconomic status by comparing twins (Behrman and Rosenzweig 2004).

However, whether maternal prenatal stress has a causal impact on birth outcomes is controversial. Previous studies have shown mixed results for the different timing and measures of stress. Since it is impossible to random experiment for maternal prenatal stress, there are also concerns about endogeneity and sample selection.

In this paper, I use an catastrophic event in South Korea - 2016 Gyeongju earthquake which caused geographic variation in earthquake intensity and affected cohorts *in utero* at that time - as a source of maternal prenatal stress and apply a difference in differences methodology to estimate the impact of maternal prenatal stress on birth weights.

The results show that those cohorts who were born in the closest county from the epicenter (Gyeongju-si) and were exposed during the third trimester of gestation experienced a significant reduction in birth weights, and the negative effects were larger for female births.

This research provides the first evidence on the relationship between earthquake exposure and birth outcomes in Korea.

2 Background

2.1 2016 Gyeongju earthquake

Gyeongju earthquake, which occurred on September 12, 2016 close to Yangsan fault, was the largest earthquake recorded since the Korea Meteorological Administration [KMA]'s seismological observation began in 1978. The magnitude of the main three earthquakes on September 12 and 19 ranged from 4.5 to 5.8, followed by numerous aftershocks nearby the main epicenter (KMA 2017b). 23 people were injured, and property damage was estimated at 11 billion won (Ministry of Public Safety and Security of Korea 2017).

The magnitude of the earthquake was more moderate than other contexts, but it was a shock for most Koreans who never expected such a huge earthquake in the country. There were only two previous earthquakes occurred inland of the country with more than M5, which were 1978 Sangju and 1978 Hongseong earthquakes (KMA, n.d.). As shown in [Figure 1], people in almost every county felt 2016 Gyeongju earthquake, and earthquake intensities were differed across regions by the distance from the epicenter.

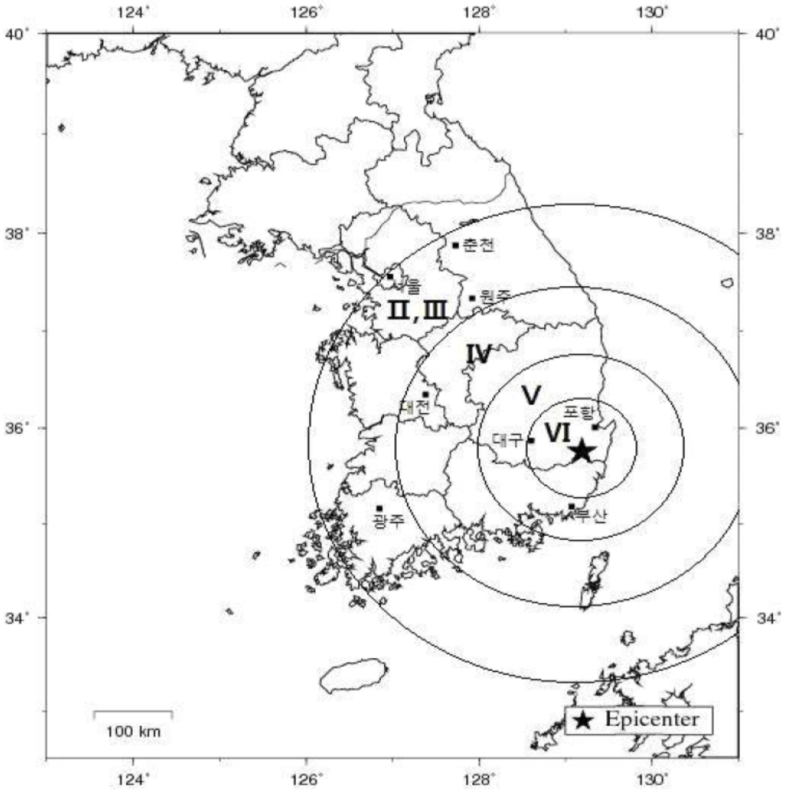

Figure 1: 2016 Gyeongju earthquake epicenter and earthquake intensity (KMA 2017a)

2.2 Literature review on catastrophic events and pregnancy outcomes

Many quasi-experimental studies have documented the association between catastrophic events and pregnancy outcomes. However, whether the relationship is causal, how much it affects, and when the timing of exposure is most vulnerable have been controversial.

When it comes to causality, sample selection and endogeneity are the main problems. For example, the estimated effects of World Trade Center collapse on birth outcomes (Lederman et al. 2004) are hard to be interpreted as a causal impact because of restricting the sample to those women who visited hospitals and voluntarily participated interview and omitting unobserved parental characteristics. To overcome the selection and endogeneity issues, Currie and Schwandt (2016) used all births born in New York and mother-fixed effects, and found large and negative effects of exposure to the dust cloud, caused by the collapse of the World Trade Center on premature delivery, focused on the first trimester.

Several papers also have used data based on the entire population with difference-in-differences, fixed-effects or instrumental variables methodology to capture a causal impact, but still, the effect sizes and the weakest timing of exposure are inconclusive.

Regarding Chile M7.9 earthquakes, Torche (2011) used a difference-in-difference methodology by using cohorts born in 2004-2006 and found the significant decline in birth weight by 50g only for cohorts born in the highest intensity region (M5.0-7.9) and exposed to the earthquake at the first trimester of gestation. Meanwhile, Suzuki et al. (2016) provide evidence that only children born to women exposed to the M7.1 Great East Japan Earthquake during the third trimester (at 28–36 weeks of gestation) in the extremely affected region (more than hundreds dead or missing) had significantly lower birth weights by 16g.

Not just in the case of earthquakes, landmine explosions by terrorist attacks in Colombia led to a significant decrease of 8.7g in birth weight for cohorts exposed during the first trimester, by using mother-fixed effects (Camacho 2008). Also, Currie and Rossin-Slater (2013) use IV with mother-fixed effects and found that mothers who were exposed to the Texas hurricane path within 30 km during the third trimester of gestation tended to deliver a newborn with abnormal conditions, but no consistent effect on birth weight.

On the other hand, other studies show no impact of catastrophic events on birth weights but the latent and persistent impact on later health and education such as the case of Chernobyl radioactive fallout variation (Almond, Edlund, and Palme 2009).

2.3 Contribution

This study provides new evidence on the causal relationship between catastrophic events and pregnancy outcomes. By including all births born in Korea a year before and after the 2016 Gyeongju earthquake and applying a difference-in-differences methodology, there is less concern about the sample selection and endogeneity issues. Also, separating cohorts by trimester exposure and gender provides additional evidence on heterogeneous effects of exposure to the earthquake.

In addition, this study is the first research on the association between earthquake and birth outcomes in Korea, where the importance of responding to an earthquake has increased after the 2016 Gyeongju earthquake. It is also the first research on the effect of an earthquake with moderate magnitude, which could be a rationale for the more extensive program for the pregnant women affected by an earthquake.

3 Data and Methodology

3.1 Data and Sample

I use Vital Statistics for birth by Statistics Korea from the MicroData Integrated Service. It includes birth weight (measured in grams), residence (Gu-Si-Gun level), birth year and month, sex of a birth, gestation length, birth order, and parental characteristics such as parental age, occupation, education, nationality, and marital status.

The study period is from 2015 to 2017, excluding November and December 2017 due to another M5.4 Pohang earthquake on November 15, 2017, and except for both September 2016 and June 2017 because the exposed and non-exposed cohorts would be mixed. Moreover, I focus on single births, because multiple births often follow a different distribution of birth weights, with non-missing information on parental characteristics.

Furthermore, I use two types of sample to analyze the impact. First, the overall sample includes all birth cohorts born in South Korea (whole 250 counties). Second, the restricted sample includes birth cohorts born in Gyeongsang-do region (74 counties except for Ulleung-gun (an island)). The sample restrictions are illustrated in [Table 1].

Table 1: Sample restrictions

	# of births	
	Overall Sample	Restricted Sample
All births born in 2015-2017	1,202,434	
Excluding those born in September 2016, June, November-December 2017	1,086,952	
Excluding multiple births	1,045,058	
Excluding missing information	993,276	
Excluding non-Gyeongsang-do region		250,803
Number of counties	250	74

Note: Overall sample includes whole births in Korea while restricted sample only refers to those born in Gyeongsangnam-do, Gyeongsangbuk-do, Ulsan, Busan, and Daegu region (except for Ulleung-gun (an island)).

3.2 Methodology

3.2.1 Geographical variation in earthquake intensity

I use the distance from the main epicenter to the center of a county (Gu-Si-Gun level) as a proxy for the earthquake intensity of the county and check the robustness with counties which had 'Did You Feel it(DYFI)' earthquake intensity data provided by United States Geological Survey (USGS)[1].

For the overall sample, I classify counties into five intensity regions according to the relationship between the distance from the epicenter and earthquake intensity, shown in [Figure 2]. The closest county, which is less than 20km away from the epicenter, is classified into the R4 region. The second closest counties, which are more than 20km but

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[1] DYFI intensity data was firstly gathered from people who lived in the affected region by questionnaires voluntarily, secondly filtered by the distance from the epicenter and magnitude of the earthquake, and finally shown in the map. As Korea Meteorological Administration does not provide consistent earthquake intensity data by counties (Gu-Si-Gun level or even Si-do level), I use DYFI intensity data in the robustness section, which provides 2016 Gyeongju earthquake intensities in 38 counties (Gu-Si-Gun).

less than 50km, are classified into R3 region. The third closest counties, which are more than 50km but less than 100km, are classified into R2 region, and the second furthest counties, which are more than 100km but less than 200km, are classified into R1 region. The furthest counties, which are more than 200km from the epicenter, are classified into R0 region.

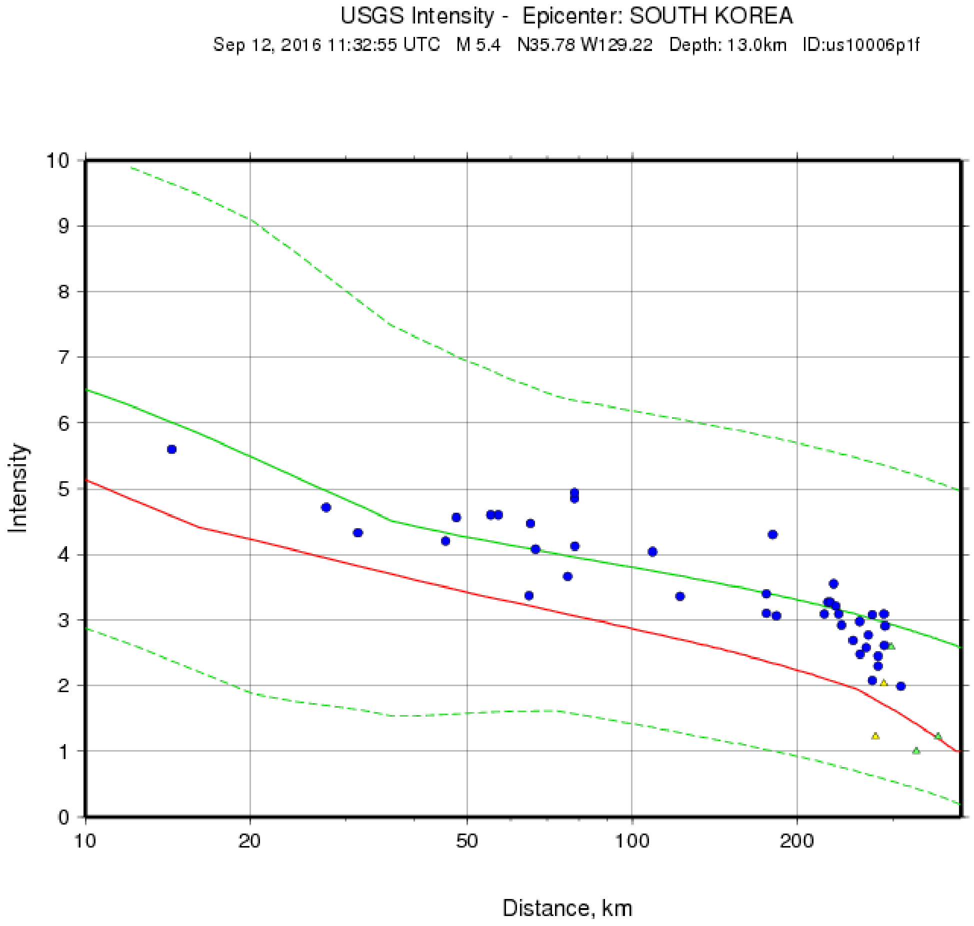
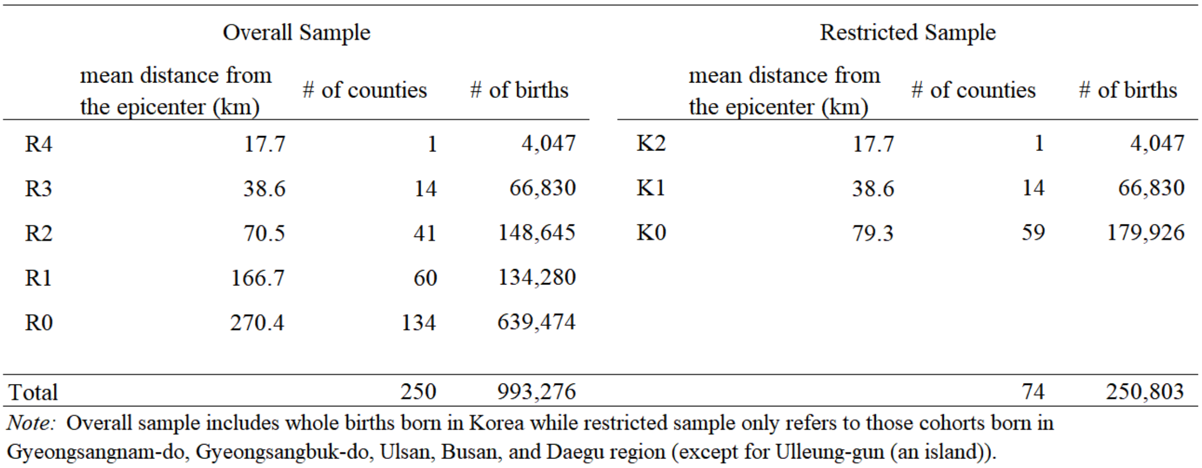


Figure 2: Macroseismic intensity versus distance from the epicenter (USGS 2016a)

For the restricted sample, I classify counties into three intensity regions. K2 region includes the closest county within 20km, K1 region includes the counties within 50km, and the rest are classified into K0 region. By the classification, K2 and K1 include the same counties in R4 and R3 respectively, while K0 differs from any regional group used in the overall sample.

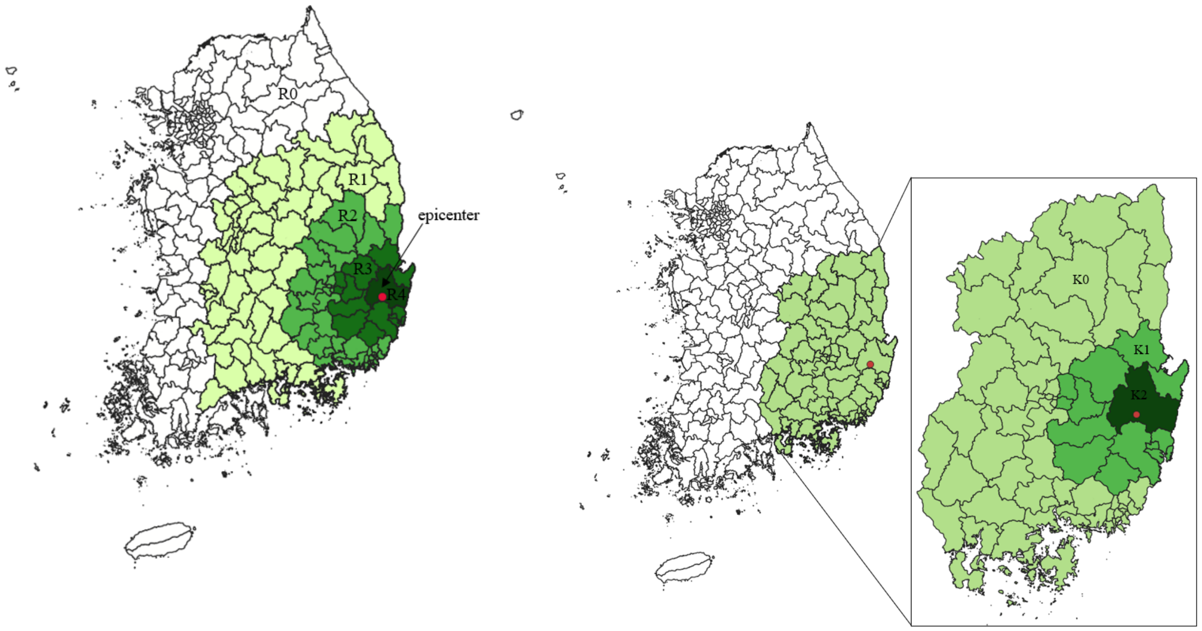
Summary for the geographical variation in earthquake intensity is presented in [Table 2] and [Figure 3].

Table 2: Geographic classification by distance from the epicenter



	Overall Sample				Restricted Sample		
	mean distance from the epicenter (km)	# of counties	# of births		mean distance from the epicenter (km)	# of counties	# of births
R4	17.7	1	4,047	K2	17.7	1	4,047
R3	38.6	14	66,830	K1	38.6	14	66,830
R2	70.5	41	148,645	K0	79.3	59	179,926
R1	166.7	60	134,280				
R0	270.4	134	639,474				
Total		250	993,276			74	250,803

Note: Overall sample includes whole births born in Korea while restricted sample only refers to those cohorts born in Gyeongsangnam-do, Gyeongsangbuk-do, Ulsan, Busan, and Daegu region (except for Ulleung-gun (an island)).



(a) Overall sample

(b) Restricted sample

Figure 3: Geographic classification by distance from the epicenter

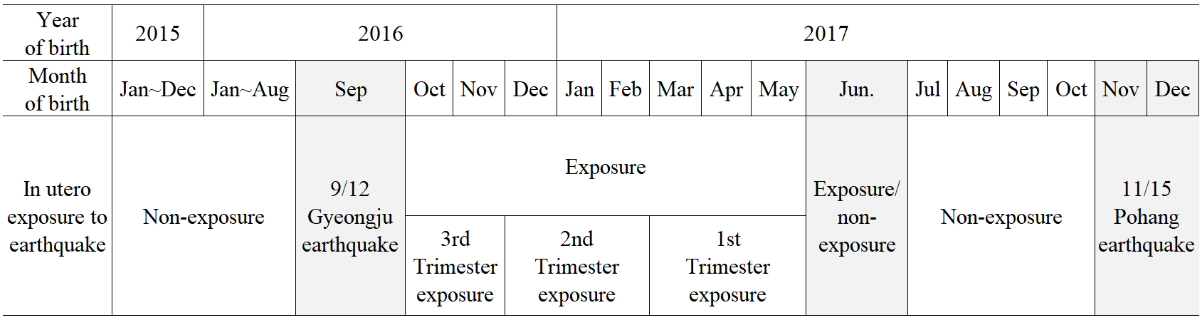
Note: the maps are created by the author, based on the administrative zone boundary maps provided by Statistical Geographic Information Service, Statistics Korea.

3.2.2 Cohort variation in *in utero* exposure to earthquake

By using the year and month of births, I firstly classify birth cohorts into two groups: exposed versus non-exposed cohorts. Those infants born during the period from October 2016 to May 2017 are classified into the exposed cohorts, while others (born before the earthquake or conception after the earthquake) are regarded as non-exposed cohorts. One concern could be the measurement errors caused by the missing information about the exact date of conception or birth so that I excluded two months (September 2016 and June 2017) in which exposed and non-exposed cohorts were mixed. In addition, because there was another M5.4 Pohang earthqake on November 15, 2017, those children born during November and December 2017 were also excluded as explained in the Data and Sample section.

Besides, I also classify those exposed cohorts into three groups in order to identify the timing of exposure. T1, T2, and T3 group refer to those who were exposed during the first, second, and third trimester of gestation, respectively. T1 includes those cohorts born from March 2017 to May 2017. T2 includes those cohorts born from December 2016 to February 2017. T3 includes those cohorts born from October to November 2016. Cohort group classification by year and month of births is summarized in [Table 3].

Table 3: Cohort classification by year and month of births



Year of birth	2015	2016					2017											
Month of birth	Jan~Dec	Jan~Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun.	Jul	Aug	Sep	Oct	Nov	Dec
In utero exposure to earthquake	Non-exposure		9/12 Gyeongju earthquake	Exposure								Exposure/ non-exposure	Non-exposure				11/15 Pohang earthquake	
				3rd Trimester exposure		2nd Trimester exposure			1st Trimester exposure									

Note : those cohorts born in September 2016, June 2017, November and December 2017 are excluded from both overall sample and restricted sample in this paper.

3.2.3 Empirical model

In this study, I apply a difference-in-differences approach. In equation (1), I compare the difference in birth weights between exposed cohorts and unexposed cohorts in the high earthquake intensity regions to the difference in birth weights between them in the low earthquake intensity region.

$$BW_i = \alpha T_i + \sum_{j=1}^{4} \beta_j (R_j * T_i) + X_i \gamma + \delta_r + \mu_{ym} + \tau_r * trend + \epsilon_i \qquad (1)$$

BW_i refers to the birth weight measured in grams. T_i indicates *in utero* exposure to the earthquake, which equals to one if a child was born during the period from October

2016 to May 2017. R_j is an indicator of earthquake intensity measured by the distance from the epicenter. If a county of birth belonged to R_j, R_j equals to one and zero otherwise. For the overall sample, there are five intensity groups, including the closest county in R_4 and the furthest counties in R_0. For the restricted sample, instead of $R_4 \sim R_0$, I use three groups from K_2 to K_0. X_i includes all individual and parental control variables such as gender, gestation length, birth order, parental age, education, occupation, nationality, and martial status. I also add δ_r, county fixed effects (Gu-Si-Gun level) and μ_{cm}, year and month fixed effects. By using the short-term period from 2015 to 2017, there is less concern about county-specific time-varying shocks except for the 2016 earthquake. However, as the slopes in [Figure 4] are different across regional groups, I additionally relieve the parallel trend assumption by including τ_r*trend, which indicates a county-specific trend[2].

In equation (2), I estimate the heterogeneous effects by the timing of exposure, using each trimester of gestation at the earthquake instead of using a dummy variable T_i.

$$BW_i = \alpha_1 T1_i + \alpha_2 T2_i + \alpha_3 T3_i + \sum_{j=1}^{4} \beta_{1j}(R_j * T1_i) + \sum_{j=1}^{4} \beta_{2j}(R_j * T2_i) + \sum_{j=1}^{4} \beta_{3j}(R_j * T3_i)$$

$$+ X_i\gamma + \delta_r + \mu_{ym} + \tau_r * trend + \epsilon_i \qquad (2)$$

$T1_i$ refers to *in utero* exposure to the earthquake during the first trimester, which equals to one if a child was born during the period from March and May 2017. $T2_i$ indicates to the second trimester exposure for those cohorts born from December 2016 to February 2017. $T3_i$ equals to one for those cohorts exposed to the earthquake during the third trimester, who were born during the period from October and November 2016.

[Table 4] shows the summary statistics. There was about 29g birth weight reduction in R4/K2 (<20km from the epicenter) region for those cohorts exposed, while in the furthest R0/K0 (>200km/>50km from the epicenter), the difference was only about 4-8g. In R4/K2, gestation length and sex ratio also much decreased, and parental socioeconomic status (education and occupation) indicated relatively low level than other regions.

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[2] It was calculated as 'county dummies' times 'year and months (numerical trends).'

Table 4: Summary Statistics

		Overall Sample									
		R0		R1		R2		R3		R4	
	Total	unexposed	(un)exposed	unexposed	exposed	unexposed	exposed	unexposed	exposed	unexposed	exposed
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Outcome variable											
birth weight(g)	3,236.382	3,239.557	3,234.620	3,241.200	3,233.847	3,227.700	3,221.445	3,232.659	3,232.326	3,247.733	3,218.854
Individual control variables											
gestation length(week)	38.624	38.657	38.613	38.627	38.585	38.568	38.536	38.556	38.532	38.749	38.516
sex of a child(=1 if boy)	0.514	0.512	0.514	0.514	0.515	0.516	0.515	0.515	0.515	0.509	0.498
birth order(=1 if the first born)	0.529	0.537	0.541	0.493	0.499	0.526	0.529	0.519	0.526	0.499	0.495
Parental control variables											
marital status	0.990	0.990	0.991	0.991	0.990	0.991	0.991	0.990	0.991	0.993	0.996
maternal age: =<14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
maternal age: 15~19	0.003	0.003	0.003	0.004	0.004	0.003	0.003	0.003	0.003	0.004	0.004
maternal age: 20~24	0.044	0.042	0.040	0.056	0.055	0.045	0.044	0.043	0.042	0.060	0.072
maternal age: 25~29	0.212	0.206	0.199	0.240	0.237	0.216	0.210	0.223	0.223	0.238	0.220
maternal age: 30~34	0.482	0.488	0.471	0.470	0.449	0.490	0.468	0.494	0.469	0.444	0.418
maternal age: 35~39	0.228	0.229	0.253	0.203	0.223	0.218	0.243	0.210	0.232	0.218	0.244
maternal age: 40~44	0.030	0.031	0.033	0.026	0.029	0.027	0.030	0.025	0.030	0.035	0.041
maternal age: 45~49	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.001
maternal age: >=50	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
paternal age: =<14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
paternal age: 15~19	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.000
paternal age: 20~24	0.015	0.014	0.013	0.017	0.018	0.014	0.013	0.014	0.015	0.016	0.020
paternal age: 25~29	0.099	0.095	0.091	0.119	0.111	0.103	0.096	0.110	0.106	0.113	0.098
paternal age: 30~34	0.416	0.417	0.393	0.424	0.402	0.431	0.404	0.437	0.412	0.397	0.353
paternal age: 35~39	0.342	0.343	0.367	0.313	0.333	0.334	0.357	0.329	0.345	0.329	0.358
paternal age: 40~44	0.103	0.105	0.108	0.099	0.104	0.095	0.103	0.089	0.099	0.113	0.141
paternal age: 45~49	0.020	0.020	0.022	0.022	0.025	0.018	0.020	0.017	0.018	0.027	0.026
paternal age: >=50	0.004	0.004	0.004	0.005	0.006	0.004	0.004	0.003	0.004	0.004	0.003
Parental control variables											
maternal education(=1 if college graduation)	0.775	0.773	0.786	0.750	0.762	0.781	0.790	0.783	0.801	0.729	0.717
paternal education(=1 if college graduation)	0.759	0.764	0.772	0.736	0.744	0.754	0.758	0.742	0.745	0.704	0.719
maternal occupation: manager	0.024	0.025	0.027	0.020	0.021	0.022	0.023	0.021	0.023	0.020	0.026
maternal occupation: professionals	0.151	0.159	0.169	0.139	0.146	0.127	0.133	0.124	0.127	0.111	0.119
maternal occupation: clerks	0.153	0.165	0.170	0.136	0.143	0.129	0.128	0.108	0.116	0.108	0.100
maternal occupation: salesperson	0.066	0.065	0.069	0.066	0.072	0.064	0.068	0.057	0.061	0.062	0.072
maternal occupation: agriculturist	0.003	0.003	0.003	0.007	0.008	0.002	0.003	0.002	0.002	0.004	0.005
maternal occupation: technician	0.006	0.005	0.005	0.006	0.005	0.008	0.007	0.005	0.005	0.006	0.006
maternal occupation: assembler	0.004	0.004	0.004	0.005	0.005	0.005	0.005	0.001	0.001	0.008	0.003
maternal occupation: simple work	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.002	0.002	0.003	0.002
maternal occupation: student or no job	0.591	0.571	0.551	0.617	0.598	0.640	0.631	0.679	0.662	0.679	0.665
paternal occupation: manager	0.121	0.115	0.119	0.111	0.115	0.139	0.145	0.139	0.145	0.142	0.150
paternal occupation: professionals	0.249	0.267	0.273	0.228	0.235	0.206	0.212	0.200	0.202	0.156	0.164
paternal occupation: clerks	0.252	0.271	0.268	0.218	0.216	0.229	0.224	0.205	0.199	0.203	0.181
paternal occupation: salesperson	0.177	0.179	0.176	0.180	0.182	0.179	0.181	0.150	0.153	0.183	0.208
paternal occupation: agriculturist	0.013	0.012	0.011	0.027	0.028	0.009	0.010	0.010	0.010	0.024	0.024
paternal occupation: technician	0.060	0.048	0.044	0.082	0.073	0.079	0.072	0.107	0.101	0.095	0.072
paternal occupation: assembler	0.074	0.060	0.061	0.090	0.088	0.098	0.098	0.118	0.119	0.126	0.131
paternal occupation: simple work	0.027	0.022	0.022	0.033	0.035	0.032	0.031	0.044	0.044	0.039	0.044
paternal occupation: student or no job	0.027	0.026	0.025	0.030	0.028	0.029	0.027	0.027	0.027	0.031	0.027
maternal nationality: Korean	0.960	0.961	0.959	0.955	0.950	0.965	0.962	0.967	0.963	0.936	0.921
maternal nationality: Naturalized as Korean	0.008	0.008	0.008	0.008	0.009	0.006	0.007	0.005	0.007	0.018	0.016
maternal nationality: Foreigner	0.032	0.031	0.033	0.037	0.041	0.028	0.031	0.028	0.030	0.046	0.062
paternal nationality: Korean	0.989	0.987	0.987	0.994	0.994	0.992	0.991	0.993	0.993	0.988	0.985
paternal nationality: Naturalized as Korean	0.002	0.003	0.003	0.001	0.001	0.001	0.001	0.001	0.000	0.001	0.001
paternal nationality: Foreigner	0.009	0.010	0.011	0.005	0.006	0.007	0.008	0.006	0.007	0.010	0.014
Observations	993,276	494,842	144,632	103,417	30,863	114,934	33,711	51,466	15,364	3,118	929

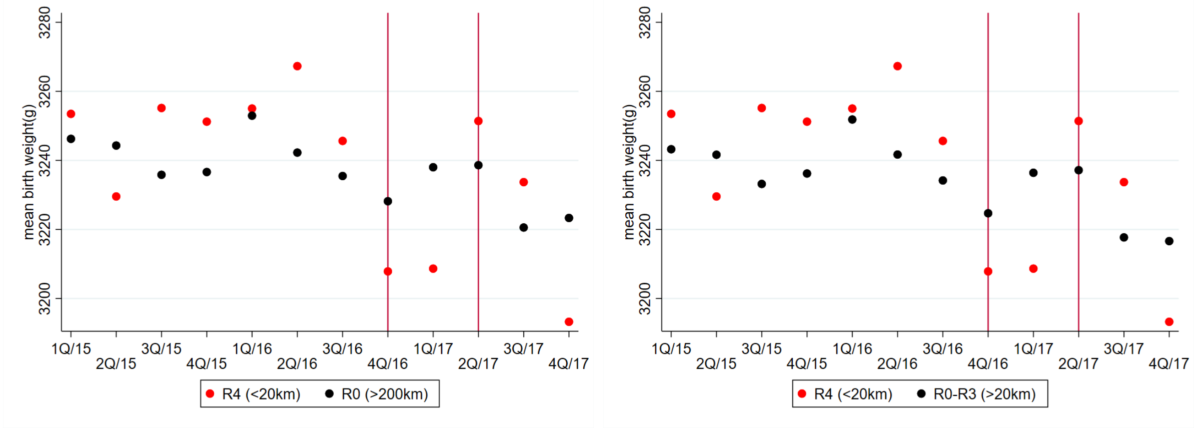
Table 4: Summary Statistics _ continued

		Restricted Sample					
		K0		K1		K2	
	Total	unexposed	(un)exposed	unexposed	exposed	unexposed	exposed
VARIABLES	(12)	(13)	(14)	(15)	(16)	(17)	(18)
Outcome variable							
birth weight(g)	3,229.043	3,229.365	3,220.970	3,232.659	3,232.326	3,247.733	3,218.854
Individual control variables							
gestation length(week)	38.557	38.566	38.526	38.556	38.532	38.749	38.516
sex of a child(=1 if boy)	0.515	0.515	0.514	0.515	0.515	0.509	0.498
birth order(=1 if the first born)	0.519	0.517	0.523	0.519	0.526	0.499	0.495
Parental control variables							
marital status	0.991	0.991	0.991	0.990	0.991	0.993	0.996
maternal age: =<14	0.000	0.000	0.000	0.000	0.000	0.000	0.000
maternal age: 15~19	0.003	0.004	0.003	0.003	0.003	0.004	0.004
maternal age: 20~24	0.046	0.047	0.046	0.043	0.042	0.060	0.072
maternal age: 25~29	0.220	0.220	0.215	0.223	0.223	0.238	0.220
maternal age: 30~34	0.483	0.488	0.465	0.494	0.469	0.444	0.418
maternal age: 35~39	0.219	0.215	0.239	0.210	0.232	0.218	0.244
maternal age: 40~44	0.027	0.026	0.030	0.025	0.030	0.035	0.041
maternal age: 45~49	0.001	0.001	0.001	0.001	0.001	0.002	0.001
maternal age: >=50	0.000	0.000	0.000	0.000	0.000	0.000	0.000
paternal age: =<14	0.000	0.000	0.000	0.000	0.000	0.000	0.000
paternal age: 15~19	0.001	0.001	0.001	0.001	0.001	0.001	0.000
paternal age: 20~24	0.014	0.014	0.014	0.014	0.015	0.016	0.020
paternal age: 25~29	0.105	0.105	0.098	0.110	0.106	0.113	0.098
paternal age: 30~34	0.426	0.431	0.405	0.437	0.412	0.397	0.353
paternal age: 35~39	0.335	0.330	0.353	0.329	0.345	0.329	0.358
paternal age: 40~44	0.096	0.095	0.103	0.089	0.099	0.113	0.141
paternal age: 45~49	0.019	0.019	0.021	0.017	0.018	0.027	0.026
paternal age: >=50	0.004	0.004	0.005	0.003	0.004	0.004	0.003
Parental control variables							
maternal education(=1 if college graduation)	0.779	0.775	0.786	0.783	0.801	0.729	0.717
paternal education(=1 if college graduation)	0.745	0.745	0.752	0.742	0.745	0.704	0.719
maternal occupation: manager	0.021	0.021	0.022	0.021	0.023	0.020	0.026
maternal occupation: professionals	0.126	0.125	0.132	0.124	0.127	0.111	0.119
maternal occupation: clerks	0.122	0.127	0.127	0.108	0.116	0.108	0.100
maternal occupation: salesperson	0.063	0.064	0.067	0.057	0.061	0.062	0.072
maternal occupation: agriculturist	0.004	0.004	0.004	0.002	0.002	0.004	0.005
maternal occupation: technician	0.007	0.007	0.006	0.005	0.005	0.006	0.006
maternal occupation: assembler	0.003	0.004	0.004	0.001	0.001	0.008	0.003
maternal occupation: simple work	0.003	0.003	0.003	0.002	0.002	0.003	0.002
maternal occupation: student or no job	0.652	0.645	0.634	0.679	0.662	0.679	0.665
paternal occupation: manager	0.137	0.134	0.140	0.139	0.145	0.142	0.150
paternal occupation: professionals	0.203	0.204	0.210	0.200	0.202	0.156	0.164
paternal occupation: clerks	0.218	0.225	0.221	0.205	0.199	0.203	0.181
paternal occupation: salesperson	0.169	0.175	0.178	0.150	0.153	0.183	0.208
paternal occupation: agriculturist	0.015	0.016	0.016	0.010	0.010	0.024	0.024
paternal occupation: technician	0.091	0.088	0.078	0.107	0.101	0.095	0.072
paternal occupation: assembler	0.103	0.098	0.096	0.118	0.119	0.126	0.131
paternal occupation: simple work	0.036	0.033	0.033	0.044	0.044	0.039	0.044
paternal occupation: student or no job	0.028	0.028	0.027	0.027	0.027	0.031	0.027
maternal nationality: Korean	0.962	0.962	0.959	0.967	0.963	0.936	0.921
maternal nationality: Naturalized as Korean	0.007	0.007	0.008	0.005	0.007	0.018	0.016
maternal nationality: Foreigner	0.031	0.031	0.033	0.028	0.030	0.046	0.062
paternal nationality: Korean	0.992	0.992	0.991	0.993	0.993	0.988	0.985
paternal nationality: Naturalized as Korean	0.001	0.001	0.001	0.001	0.000	0.001	0.001
paternal nationality: Foreigner	0.007	0.007	0.008	0.006	0.007	0.010	0.014
Observations	250,803	139,021	40,905	51,466	15,364	3,118	929

4 Results

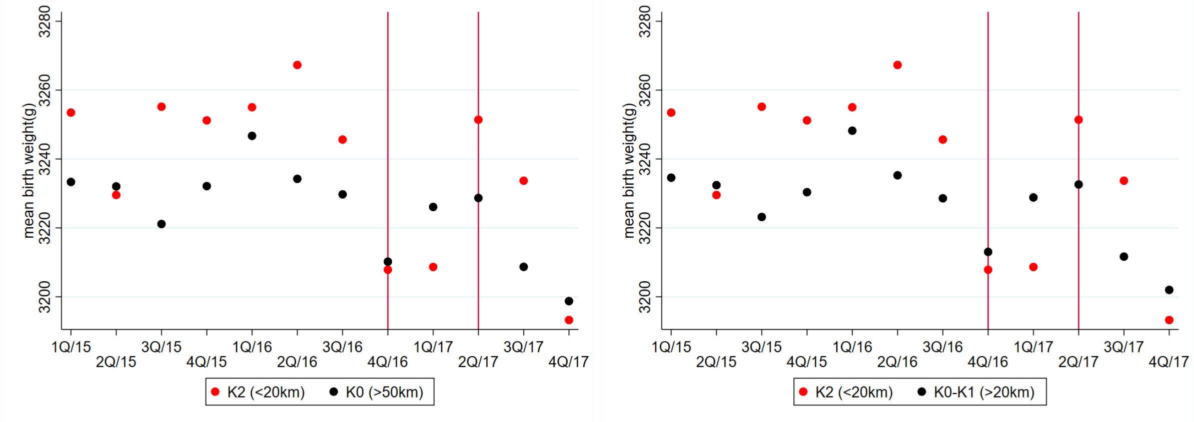
4.1 Overall trend

[Figure 4] presents the quarterly trend in birth weights across regional groups. The red bars indicate the period that those cohorts *in utero* exposed to 2016 Gyeongju earthquake were born, which is from the fourth quarter of 2016 to the second quarter of 2017.



(a) Mean birth weights in R4 and R0 (Overall sample)

(b) Mean birth weights in R4 and R0-R3 (Overall sample)



(c) Mean birth weights in K2 and K0 (Restricted sample)

(d) Mean birth weights in K2 and K0-K1 (Restricted sample)

Figure 4: Mean birth weights by regional groups and quarters of births

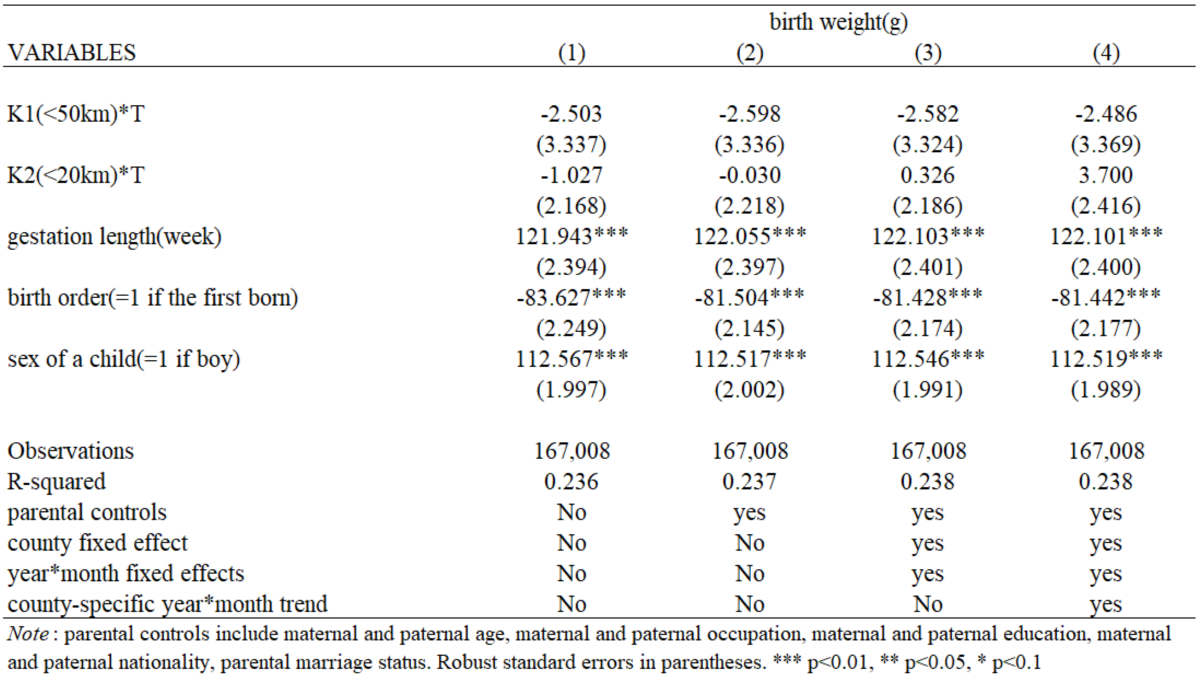
Note: the data sets described in the data and methodology section were used so that births born in the four months were excluded (September 2016, June 2017, November and December 2017).

In the overall sample (including all births born in Korea) shown in [Figure 4 (a) and (b)], there was a significant reduction in birth weights for those cohorts born in the fourth quarter of 2016 and the first quarter of 2017, who were exposed to the earthquake during the second and the third trimester, in the most affected R4 region compared to other R0 or R0-R3 regions. The same pattern was observed in the restricted sample (including births born in Gyeongsang-do region) in [Figure 4 (c) and (d)].

From those graphs, I check the parallel trend across regional groups before the earthquake and find a negative association between earthquake exposure and birth weights during the fourth quarter of 2016 and the first quarter of 2017, especially in the closest county (R4/K2).

In addition, I use the sub-sample with births born before the earthquake (from January 2015 to August 2016) in Gyeongsang-do region and analyze whether there were heterogeneous trends across regional groups when using the same monthly periods (from October to May) as a falsified exposure period. The results are shown in [Table 5].

Table 5: Parallel trend before earthquake (Jan 2015 - Aug 2016)



	birth weight(g)			
VARIABLES	(1)	(2)	(3)	(4)
K1(<50km)*T	-2.503	-2.598	-2.582	-2.486
	(3.337)	(3.336)	(3.324)	(3.369)
K2(<20km)*T	-1.027	-0.030	0.326	3.700
	(2.168)	(2.218)	(2.186)	(2.416)
gestation length(week)	121.943***	122.055***	122.103***	122.101***
	(2.394)	(2.397)	(2.401)	(2.400)
birth order(=1 if the first born)	-83.627***	-81.504***	-81.428***	-81.442***
	(2.249)	(2.145)	(2.174)	(2.177)
sex of a child(=1 if boy)	112.567***	112.517***	112.546***	112.519***
	(1.997)	(2.002)	(1.991)	(1.989)
Observations	167,008	167,008	167,008	167,008
R-squared	0.236	0.237	0.238	0.238
parental controls	No	yes	yes	yes
county fixed effect	No	No	yes	yes
year*month fixed effects	No	No	yes	yes
county-specific year*month trend	No	No	No	yes

Note : parental controls include maternal and paternal age, maternal and paternal occupation, maternal and paternal education, maternal and paternal nationality, parental marriage status. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

In column (1) - (4), I compare the birth weight differences in the closest county (K2 region) between cohorts born from October 2015 to May 2016 and other cohorts born before August 2016 with the birth weight differences in other regions (K0-K1) between the same cohorts. In column (1), after controlling for regional group dummies (K1 and K2), time dummy (T), gestation length, birth order, and sex of a child, both ‘K1*T’ and ‘K2*T’ are not statistically different from zero, which means that there were no birth weight differences between cohorts across regions. Moreover, the result was robust to use different model specifications as shown in column (2)-(4). Adding parental controls in column (2), using all county dummies (74 counties) instead of using regional group dummies (K0, K1, K2) and year and month dummies in column (3), and including county-specific time trend dummies (all county dummies times numerical monthly time trend) in column (4) have no effect on the significance of the estimates.

Therefore, [Table 5] confirms that there was no heterogeneous time trend across regional groups before the earthquake.

4.2 Overall effect

In this section, I estimate the overall effect of *in utero* exposure to the earthquake on birth weight by using the equation (1) explained in the Empirical model section. The results are shown in [Table 6].

Table 6: The overall effect of *in utero* exposure to earthquake on birth weight

	Birth weight(g)	
	Overall sample	Restricted sample
VARIABLES	(1)	(2)
R1(<200km)*T(exposed)	-0.751	
	(3.621)	
R2(<100km)*T(exposed)	-2.594	
	(2.910)	
R3 or K1(<50km)*T(exposed)	1.054	5.377
	(4.352)	(4.839)
R4 or K2(<20km)*T(exposed)	-4.814***	0.143
	(1.543)	(2.604)
gestation length(week)	120.930***	121.689***
	(1.309)	(2.377)
birth order(=1 if the first born)	-82.876***	-80.226***
	(1.160)	(1.890)
sex of a child(=1 if boy)	111.856***	113.879***
	(0.833)	(1.695)
Observations	993,276	250,803
R-squared	0.249	0.244
county fixed effect	yes	yes
year*month fixed effects	yes	yes
parental controls	yes	yes
county-specific year*month trend	yes	yes

Note: parental controls include maternal and paternal age, maternal and paternal occupation, maternal and paternal education, maternal and paternal nationality, parental marriage status. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

In column (1), I compare the birth weight differences between cohorts born from October 2016 to May 2017 (*in utero* exposure to the earthquake) and other non-exposed cohorts across the five regional groups in the overall sample. After controlling for all 250 county dummies, exposure dummy (T), year and month dummies, gestation length, birth order, sex of a child, parental controls such as parental age and education, and county-specific time trend, there was a statistically significant 4g reduction in birth weight in the closest R4 region compared to the furthest R0 region at 1 percent significance level, but no differences in other R1-R3 regions over R0 region.

In column (2), the birth weight differences between the same cohorts across the three regional groups (K0-K2) in the restricted sample are presented. In the restricted sample, there were no differences in birth weight between cohorts even in the closest K2 region, compared to the furthest K0 region.

Thus, [Table 6] implies that when comparing those cohorts exposed and non-exposed to the earthquake, overall effect on birth weight was not economically meaningful.

4.3 Heterogeneous effect

In this section, I estimate the heterogeneous effects by the timing of *in utero* exposure and gender subgroup. I use the equation (2) in the Empirical model section and apply it separately by sex of a child. The results are shown in [Table 7]. Column (1)-(3) are based on the overall sample and Column (4)-(6) on the restricted sample.

In column (1), after controlling for all 250 county dummies, trimester exposure dummies (T1, T2, T3), year and month dummies, gestation length, birth order, sex of a child, parental controls, and county-specific time trend, there were significant impacts only in the closest region (R4). However, the signs of the impacts were different according to the trimester of gestation exposed to the earthquake. While there was a significant 34g reduction in birth weights for those cohorts born *in utero* exposed during the third trimester, there was a significant 10g increase in birth weight for those cohorts exposed during the second trimester and no impact for cohorts exposed during the first trimester.

In column (2) and column (3), not just heterogeneous impacts by the timing of exposure but also them by gender were shown, and it explained that the sign difference in column (1) was due to the differential impacts by gender. Surprisingly, there was an

Table 7: The heterogeneous effect by timing of *in utero* exposure and gender

	birth weight(g)					
		Overall Sample			Restricted Sample	
VARIABLES	All (1)	Male (2)	Female (3)	All (4)	Male (5)	Female (6)
R1(<200km)*1st Trimester(exposed)	-2.563	0.184	-5.421			
	(3.863)	(5.948)	(6.080)			
R1(<200km)*2nd Trimester(exposed)	-1.718	0.678	-3.982			
	(5.226)	(7.709)	(5.437)			
R1(<200km)*3rd Trimester(exposed)	2.784	5.166	0.277			
	(5.458)	(7.604)	(6.735)			
R2(<100km)*1st Trimester(exposed)	-0.526	6.204	-8.326			
	(3.746)	(5.079)	(5.595)			
R2(<100km)*2nd Trimester(exposed)	-2.217	0.705	-5.564			
	(4.599)	(5.851)	(6.035)			
R2(<100km)*3rd Trimester(exposed)	-5.574	-4.154	-7.232			
	(3.793)	(6.306)	(5.912)			
R3 or K1(<50km) *1st Trimester(exposed)	3.488	7.105	-0.944	5.489	5.582	5.369
	(6.222)	(6.836)	(7.913)	(6.677)	(7.458)	(8.831)
R3 or K1(<50km)*2nd Trimester(exposed)	-0.820	-0.548	-0.954	4.289	3.134	5.961
	(6.551)	(9.048)	(8.633)	(7.491)	(10.029)	(9.687)
R3 or K1(<50km)*3rd Trimester(exposed)	0.579	3.906	-3.024	6.711	9.191	3.809
	(5.622)	(12.013)	(9.326)	(6.019)	(12.764)	(10.137)
R4 or K2(<20km)*1st Trimester(exposed)	2.558	36.202***	-35.714***	5.228*	34.089***	-27.566***
	(2.040)	(2.724)	(2.686)	(3.064)	(4.039)	(4.761)
R4 or K2(<20km)*2nd Trimester(exposed)	10.847***	36.901***	-13.919***	16.905***	41.960***	-6.114
	(2.184)	(2.922)	(2.802)	(4.167)	(5.336)	(4.907)
R4 or K2(<20km)*3rd Trimester(exposed)	-34.706***	-7.566***	-56.366***	-28.620***	-3.186	-50.069***
	(1.902)	(2.873)	(2.814)	(2.861)	(5.263)	(4.820)
gestation length(week)	120.931***	124.707***	116.711***	121.692***	127.113***	115.644***
	(1.309)	(1.686)	(1.752)	(2.376)	(3.232)	(3.463)
birth order(=1 if the first born)	-82.876***	-88.010***	-77.260***	-80.231***	-83.762***	-76.088***
	(1.160)	(1.432)	(1.560)	(1.890)	(2.511)	(2.931)
sex of a child(=1 if boy)	111.853***			113.875***		
	(0.833)			(1.695)		
Observations	993,276	510,108	483,168	250,803	129,109	121,694
R-squared	0.249	0.253	0.227	0.244	0.254	0.215
parental controls	yes	yes	yes	yes	yes	yes
county fixed effect	yes	yes	yes	yes	yes	yes
year*month fixed effects	yes	yes	yes	yes	yes	yes
county-specific year*month trend	yes	yes	yes	yes	yes	yes

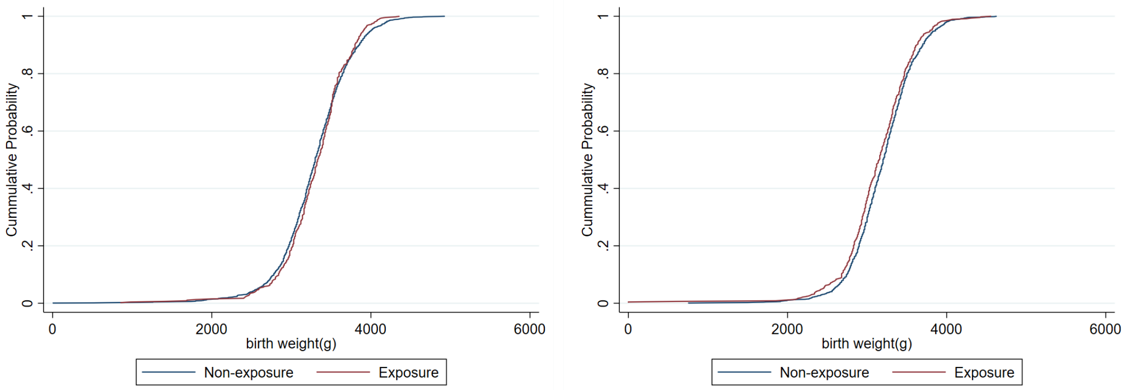
Note: parental controls include maternal and paternal age, maternal and paternal occupation, maternal and paternal education, maternal and paternal nationality, parental marriage status. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

opposite direction in the closest region (R4) between the sex groups when they exposed to the earthquake during the first or second trimester. Female births reduced their birth weight, while male births increased them. In column (2) for males, holding other things constant as column (1), there was a significant 36g increase in birth weights for those cohorts exposed to the earthquake during the first and second trimester while 7g decrease for those who exposed during the third trimester. In column (3) for females, there was a significant 35g, 13g, 56g reduction in birth weights for those cohorts born *in utero* exposed during the first, second, third trimester respectively.

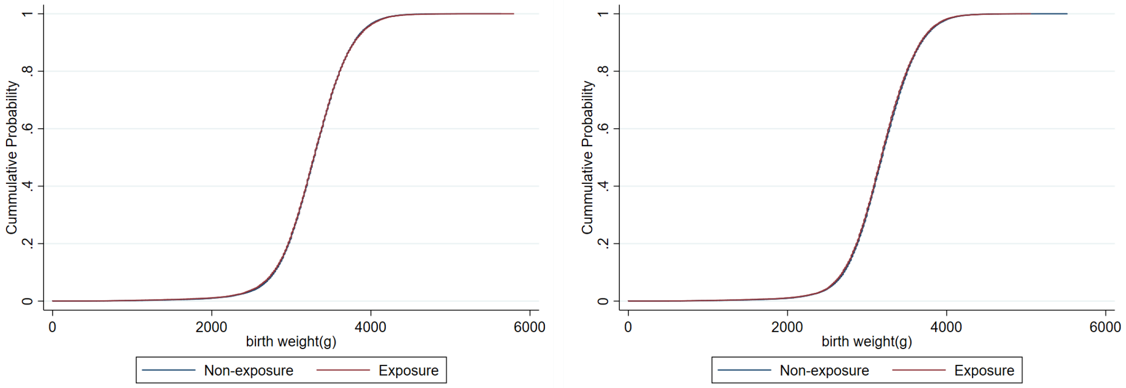
Column (4)-(6) for the restricted sample also presents the same pattern as column

(1)-(3). There was a significant 28g reduction in birth weight for those cohorts born in K2 region and exposed during the third trimester while positive impacts on birth weight for those who were exposed during the first and second trimester. Also, there were heterogeneous effects by gender and trimester exposure, which indicated larger negative impacts (-50 ∼ -27) for female cohorts and substantial positive impacts for male cohorts.

This heterogeneous impacts by gender can also be found in the cumulative distribution functions in [Figure 5]. In the closest K2 region (<20km), the cumulative distribution of birth weights for female cohorts *in utero* exposed to the earthquake moved to the left while that for male cohorts moved to the right side. On the other hand, in the furthest K0 region, there is no difference in the cumulative distribution functions for both genders.



(a) K2 (male) (b) K2 (female)



(c) K0 (male) (d) K0 (female)

Figure 5: Cumulative distribution functions of birth weights by regions and gender

Therefore, [Table 7] and [Figure 5] suggests that not considering the heterogeneous effects by the timing of exposure would lead to weak evidence on birth weights in overall effect. Also, it shows that both female and male births experienced a reduction in birth weight when they were exposed to the earthquake during the third trimester and were born in the closest county, but there were opposite directions of the effects by gender for those who were exposed during the first and second trimester in the closest county. While female births exposed to the earthquake during early gestation period had lower birth weights, there were positive effects for male births exposed during the same period.

5 Robustness

There would be a concern about the inaccuracy of the distance from the epicenter as a measure of earthquake intensity. Thus, in this robustness section, I use an alternative measure of earthquake intensity and analyze the effect of *in utero* exposure to the 2016 Gyeongju earthquake on birth weights.

I restrict the sample to 38 counties, which have DYFI (Did you feel it) earthquake intensity index[3] from the United States Geological Survey (USGS 2016b), and analyze the heterogeneous impacts of the earthquake on birth weights. The re-classified regional groups and 38 counties are illustrated in [Figure 6].

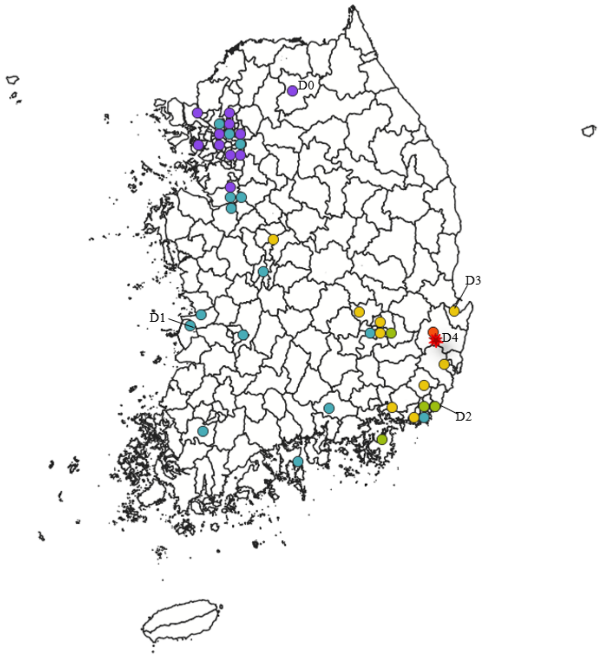


Figure 6: Geographic classification by DYFI index

Note: the map is based on the administrative zone boundary map by Statistics Korea.

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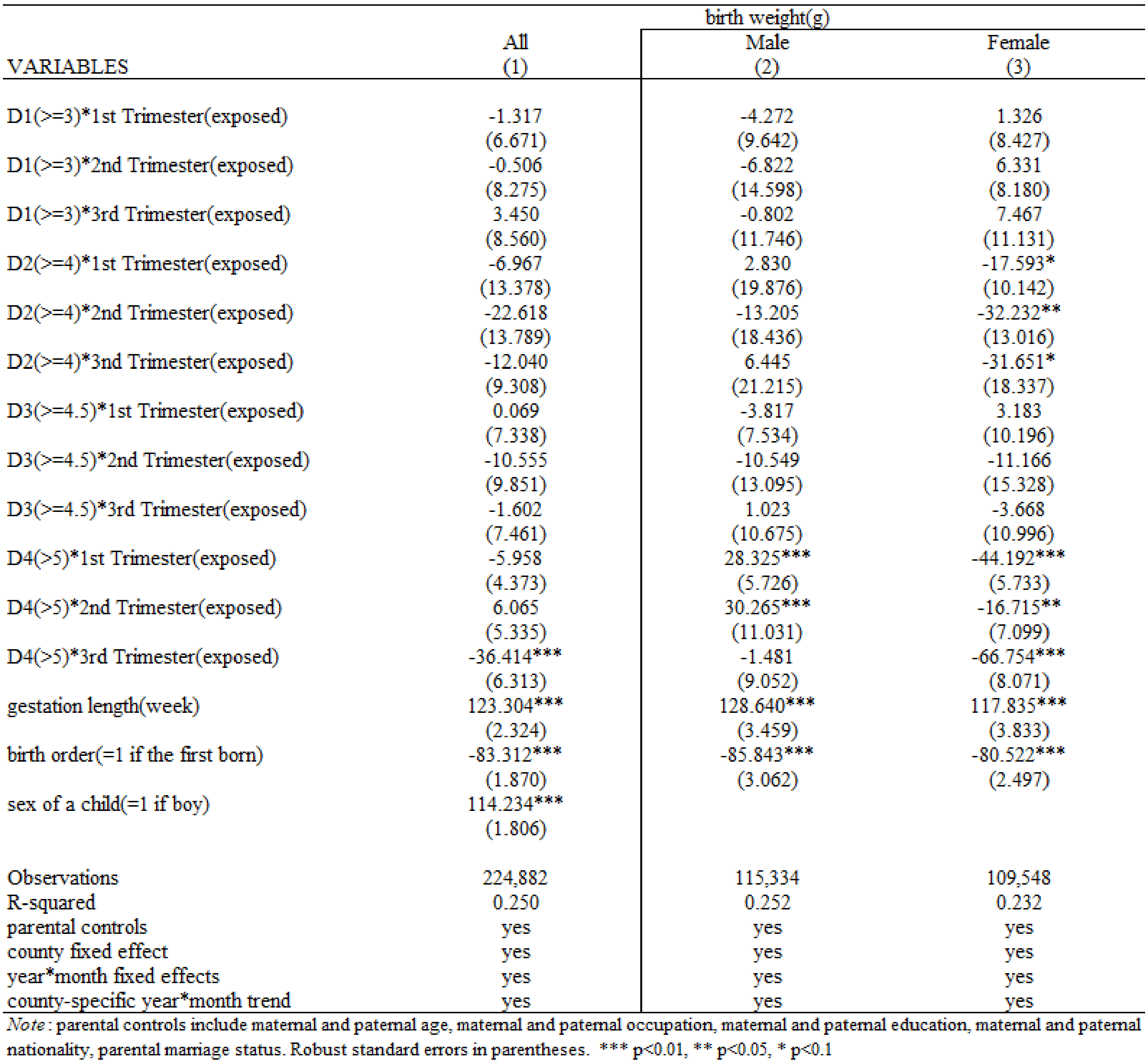
[3] DYFI index has been used in several papers such as Atkinson and Wald (2007), Wald et al. (2012)

As marked in [Figure 6], I classify 38 counties into five regional groups (D0-D4) according to the DYFI intensity data. D4 includes the county with the highest DYFI index more than 5, D3 includes the counties with the DYFI with more than 4.5 but less than 5, D2 includes the counties with the DYFI with more than 4 but less than 4.5, D1 includes the counties with the DYFI with more than 3 but less than 4, and D0 includes the other counties with DYFI less than 3. The results of using data on births born in those 38 counties are shown in [Table 8].

Table 8: The heterogeneous effect by timing of *in utero* exposure and gender (with DYFI index)



		birth weight(g)	
	All	Male	Female
VARIABLES	(1)	(2)	(3)
D1(>=3)*1st Trimester(exposed)	-1.317	-4.272	1.326
	(6.671)	(9.642)	(8.427)
D1(>=3)*2nd Trimester(exposed)	-0.506	-6.822	6.331
	(8.275)	(14.598)	(8.180)
D1(>=3)*3rd Trimester(exposed)	3.450	-0.802	7.467
	(8.560)	(11.746)	(11.131)
D2(>=4)*1st Trimester(exposed)	-6.967	2.830	-17.593*
	(13.378)	(19.876)	(10.142)
D2(>=4)*2nd Trimester(exposed)	-22.618	-13.205	-32.232**
	(13.789)	(18.436)	(13.016)
D2(>=4)*3nd Trimester(exposed)	-12.040	6.445	-31.651*
	(9.308)	(21.215)	(18.337)
D3(>=4.5)*1st Trimester(exposed)	0.069	-3.817	3.183
	(7.338)	(7.534)	(10.196)
D3(>=4.5)*2nd Trimester(exposed)	-10.555	-10.549	-11.166
	(9.851)	(13.095)	(15.328)
D3(>=4.5)*3rd Trimester(exposed)	-1.602	1.023	-3.668
	(7.461)	(10.675)	(10.996)
D4(>5)*1st Trimester(exposed)	-5.958	28.325***	-44.192***
	(4.373)	(5.726)	(5.733)
D4(>5)*2nd Trimester(exposed)	6.065	30.265***	-16.715**
	(5.335)	(11.031)	(7.099)
D4(>5)*3rd Trimester(exposed)	-36.414***	-1.481	-66.754***
	(6.313)	(9.052)	(8.071)
gestation length(week)	123.304***	128.640***	117.835***
	(2.324)	(3.459)	(3.833)
birth order(=1 if the first born)	-83.312***	-85.843***	-80.522***
	(1.870)	(3.062)	(2.497)
sex of a child(=1 if boy)	114.234***		
	(1.806)		
Observations	224,882	115,334	109,548
R-squared	0.250	0.252	0.232
parental controls	yes	yes	yes
county fixed effect	yes	yes	yes
year*month fixed effects	yes	yes	yes
county-specific year*month trend	yes	yes	yes

Note: parental controls include maternal and paternal age, maternal and paternal occupation, maternal and paternal education, maternal and paternal nationality, parental marriage status. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

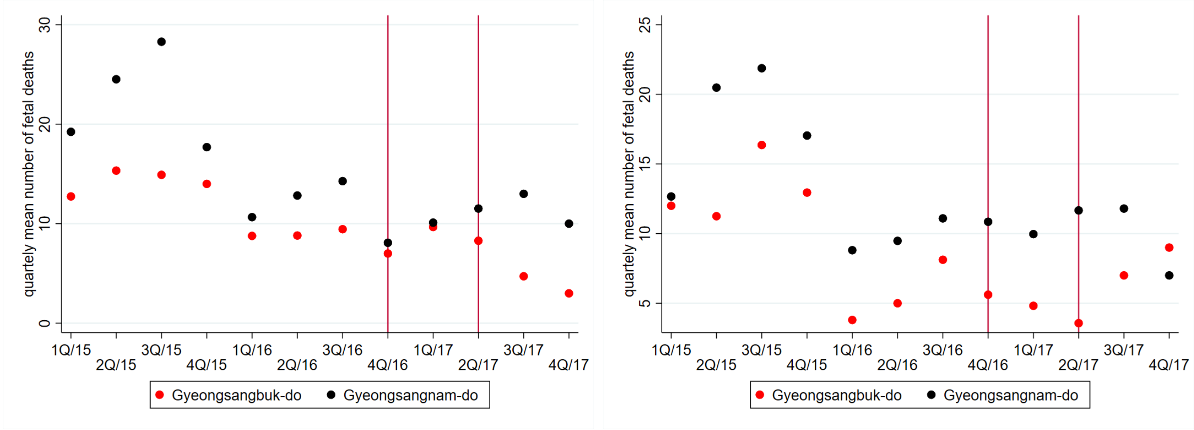
The findings were robust. In column (1), only in the highest DYFI intensity region (D4), there was a 36g reduction of birth weight for those who exposed to the earthquake during the third trimester. Moreover, Column (2) and (3) show that the negative effects were focused on female births, whereas positive effects were observed for male births. Those outcomes are similar to the results presented in [Table 7], based on the distance from the epicenter.

6 Discussion

6.1 Selective mortality

To interpret the effect size of main outcomes in this paper, it is important to know whether there was selective mortality or not. If maternal prenatal stress caused by an unexpected earthquake leads to more stillbirths or miscarriages, I might underestimate the effect of earthquake exposure on birth outcomes with Vital Statistics for those births alive. Also, if this selective mortality occurs more for male births than female births, this may be the reason for the heterogeneous effects on birth weights.

By using complementary investigation into the cause of fetal deaths by Statistics Korea, which includes regional data in Si-Do level, I check whether there was selective mortality during our research period or not.



(a) Fetal (male)

(b) Fetal (female)

Figure 7: The quarterly mean number of fetal deaths by regions and qender

[Figure 7] shows the quarterly trend on the mean number of fetal deaths by two regions (Gyeongsangbuk-do, including R4/K2 region, and Gyeongsangnam-do) and gender.

[Figure 7 (b)] indicates parallel trends throughout the research period for female births, but there were sudden increases in fetal deaths for male births during the fourth quarter of 2016 and the first quarter of 2017, as shown in [Figure 7 (a)].

The results of a difference-in-differences approach, comparing fetuses in Gyeongsangbuk-do (including R4/K2 region) to them in Gyeongsangnam-do between exposure and non-exposure periods, are shown in [Table 9].

Table 9: The heterogeneous effect on the monthly mean number of fetal deaths by gender

	Monthly mean number of fetal deaths	
	Male	Female
VARIABLES	(1)	(2)
Gyeongsangbuk-do	-6.208***	-4.708***
	(1.550)	(1.524)
1st Trimester(exposed)	-1.247	-0.212
	(2.028)	(2.374)
2nd Trimester(exposed)	-2.675	-0.601
	(1.956)	(1.477)
3rd Trimester(exposed)	-4.753***	-2.203
	(1.307)	(3.892)
Gyeongsangbuk-do*1st Trimester(exposed)	4.875*	-0.625
	(2.912)	(2.617)
Gyeongsangbuk-do*2nd Trimester(exposed)	4.542*	-1.625
	(2.314)	(2.110)
Gyeongsangbuk-do*3rd Trimester(exposed)	2.208	-0.792
	(2.027)	(4.412)
year*month fixed effects	yes	yes
Observations	64	64
R-squared	0.523	0.408

Note: the complementary investigation into the cause of fetal deaths by Statistics Korea was used for this analysis. I restricted the dataset to the study period (2015-2017) and the most affected regions (Gyeongsangbuk-do (including Gyeongju-si) and Gyeongsangnam-do). The results of difference-in-differences analysis comparing the monthly mean number of fetal deaths between Gyeonganbuk-do and Gyeongsangnam-do across exposure status are shown in the table above. Observations were 64 as I collapsed the dataset into 32 months (excluding 4 mixed months) by 2 regions (Gyeongsangbuk-do or Gyeongsangnam-do). During the study period, the number of male fetal deaths in Gyeongsangbuk-do was 301 while that in Gyeongsangnam-do was 467. For female fetal deaths, there were 235 fetal deaths in Gyeongsangbuk-do and 394 deaths in Gyeongsangnam-do. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Column (1) provides some evidence that Gyeongsangbuk-do regions (including R4/K2 region) increased the number of male fetal deaths for those exposed during the first and second trimester. There were 4.8 more male fetal deaths occurred in Gyeongsangbuk-do region (including R4/K2 region) than Gyeongsangnam-do region for those cohorts exposed to the earthquake during the first trimester compared with those cohorts unexposed. Exposure during the second trimester led to 4.5 more male fetal deaths in Gyeongsangbuk-do region compared to Gyeongsangnam-do region and unexposed cohorts. Both estimates were statistically significant at 10 percent significance level. On the other hand, there was no statistically significant impact of the third trimester exposure on male fetal deaths. Also, Column (2) shows that no heterogeneous effects on the number of female fetal deaths by the timing of exposure.

Therefore, the result shown in [Table 9], the selective mortality for male fetuses in Gyeongsangbuk-do region, implies that our estimated effects on male births' weights could be underestimated and that the positive effects on male cohorts who were exposed to earthquake during the first and second trimester were caused by positive selection (more fetal deaths for weaker male fetuses). However, because of lack of information on Gu-Si-Gun (counties) level, I could not figure out whether these sex-specific fetal deaths occurred in R4/K2 (the closest county) among counties in Gyeongsangbuk-do region.

As an alternative approach, I try to use vital Statistics for deaths, which includes data with Gu-Si-Gun level, but there were only two infant deaths for those aged less than one year old in R4/K2 (<20km) region among total 12 deaths during the 2015-2017 period. Because of too low infant death rates[4], it is hard to confirm the heterogeneous effects on infant deaths across the same regional groups I used in [Table 7] or [Table 8].

6.2 Biological response

Then, what are the mechanisms that lead to different responses by sex of fetuses? In this section, I review the previous literature about the sex-specific effect of maternal prenatal stress on birth outcomes.

It is known that female and male fetuses respond deferentially to maternal stress. One of the mechanisms is a sex-specific adaptation of the placenta. Female fetuses reduce growth under maternal prenatal stress by adapting to placental genes and protein expressions several times, while male fetuses continue to grow as their placental adjustments are minimal. Thus, adverse birth outcomes are often observed in females, while the probabilities of macrosomia and fetal deaths are greater in males (Clifton 2010).

When it comes to low birth weight, there are also differential channels by sex. Female fetuses' cardiac sympathetic activity and blood pressure are larger in response to maternal

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[4] infant deaths rate per 1,000 births was only 2.7-2.8 in South Korea during the study period (Statistics Korea 2018)

stress than male fetuses, and they are associated with low birth weights for females. On the other hand, higher peripheral vascular resistance is associated with low birth weight for males (Glover and Hill 2012).

There is also empirical evidence. For example, the negative effects of rocket attack alarms on low birth weight, and small head circumference were significant only for female fetuses (Wainstock et al. 2015). Also, in the context of the 2005 Chile earthquake, the effect of *in utero* exposure to the earthquake on preterm delivery was larger for female than male births (Torche and Kleinhaus 2011).

Therefore, our finding, larger impacts of earthquake exposure on birth weights for females, is in the line with the previous literature.

However, our results on male births, which show a significant and positive impact on birth weights, are uncommon. There is only one previous literature that reported a positive effect of maternal prenatal stress on male birth weights. The paper analyzed the effect of *in utero* exposure to 2003 Canberra wildfires on birth weights and found significant gains in birth weights for male births in the fire-affected region but no effect for female births. It explained that there might be another channel from maternal stress to male birth weights through maternal blood glucose levels elevation (O'Donnell and Behie 2015).

Although mechanisms from maternal prenatal stress to birth outcomes are not fully understood, our research firstly shows both significant negative effects on female birth weights and positive effects on male birth weights. Also, unusual positive effects of maternal prenatal stress on birth weights for males in this study require further research.

6.3 Cultural response

Another possible channel might be a cultural response. There is some belief that low weight of a son is regarded as a much bigger problem than that of a daughter[5], and it is much stronger in the southeast part of Korea (Gyeongsang-do region), where people have a strong history of preference for boys (Maeil Business News Korea 1999; SBS News 2007;

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[5] There is also a research, showing that children born prematurely or underweight may exhibit more severe metabolic diseases when a boy becomes an adult than a girl (Kim et al. 2015).

Lee and Lee 2015). Although it is hard to be tested without tracking the growth status of a child throughout the gestation period, the reverse pattern of male cohorts (increase in birth weight rather than decrease) might be explained by women's behavioral response to recover the lower growth of their son during the rest of the gestation period if they were exposed to the earthquake at the early stage of pregnancy.

7 Conclusion

This study estimates the effects of maternal prenatal stress induced by exposure to the earthquake on birth weight, using difference-in-differences methodology with the geographical variation in earthquake intensity and the cohort variation in *in utero* exposure to the 2016 Gyeongju earthquake.

There was a significant reduction in birth weight by 30g for those who lived in the closest county from the epicenter and were exposed to the earthquake during the third trimester. Also, most of these negative effects were driven by female births.

This heterogeneous effects by gender could be the results of differential strategies in response to maternal prenatal stress, and further differential fetal deaths between males and females. Our results are consistent with the previous studies that have shown larger impacts of maternal prenatal stress on female birth outcomes than male.

Our findings could be a rationale for disaster psychiatric assistance program, focusing on pregnant women. The negative impact on birth weights and the probability of differential response imply that at least informing the effects of exposure to the earthquake on birth weights and helping pregnant women to relieve the stress would reduce the risk of low birth weights of children, which affects a child in a lifetime.

Also, future work is needed to figure out whether this negative effects of *in utero* exposure to the earthquake on birth weights are persistent throughout the life cycle. If there is a clear causal link between maternal prenatal stress caused by catastrophic events and human capital development, more active response to the events such as an earthquake would be required.

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