I Z A Institute
of Labor Economics
Initiated by Deutsche Post Foundation

DISCUSSION PAPER SERIES

IZA DP No. 15345

Does the Employment Effect of National Minimum Wage Vary by Non-employment Rate? A Regression Discontinuity Approach

Lei Xu
Yu Zhu

JUNE 2022

I Z A Institute
of Labor Economics

Initiated by Deutsche Post Foundation

DISCUSSION PAPER SERIES

IZA DP No. 15345

Does the Employment Effect of National Minimum Wage Vary by Non-employment Rate? A Regression Discontinuity Approach

Lei Xu
Bournemouth University

Yu Zhu
University of Dundee School of Business and IZA

JUNE 2022

ISSN: 2365-9793

IZA – Institute of Labor Economics

Schaumburg-Lippe-Straße 5–9
53113 Bonn, Germany

Phone: +49-228-3894-0
Email: publications@iza.org

www.iza.org

ABSTRACT

Does the Employment Effect of National Minimum Wage Vary by Non-employment Rate? A Regression Discontinuity Approach* **

We examine the impact of increasing minimum wage on employment by exploiting variation in the age-dependent National Minimum Wage (NMW) in the UK. We extend the Regression Discontinuity model to evaluate the procyclicality of employment effect and show that previous estimates may be biased due to failure to account for the local non-employment rate. Contrary to the existing literature, we report a positive employment elasticity after accounting for the effect of local labour market conditions. The results suggest that the positive employment effect of increasing minimum wage is strongly procyclical, i.e. is more pronounced in areas with low non-employment rates. Under an assumption that employers have no direct impact around the cut-off point, the results suggest that a higher minimum wage increases labour supply of young workers.

JEL Classification: J22

Keywords: minimum wage, macroeconomic fluctuation, regression discontinuity, age dependent, procyclicality

Corresponding author:
Lei Xu
Bournemouth University
Business School
Fern Barrow Poole, BH12 5BB
United Kingdom
E-mail: lxu1@bournemouth.ac.uk

* Data Availability: Office for National Statistics, Social Survey Division, Northern Ireland Statistics and Research Agency, Central Survey Unit. Quarterly Labour Force Survey, 1992-2018: Secure Access. UK Data Service. SN. 6727, http://dx.doi.org/10.5255/UKDA-SN-6727-15. Additional results and copies of the computer programs used to generate the results presented in the article are available from the corresponding author [lxu1@bournemouth.ac.uk]
** We thank participants at the annual meetings of the Scottish Graduate Programme in Economics and the European Association of Labour Economists for helpful comments.

1. Introduction

Previous evidence for the UK points to a non-negative employment elasticity with regard to a minimum wage increase (Dickens et al 2014). This is not entirely surprising given the fact that the minimum wage in the UK is relatively low compared to other European countries, like Denmark. However, there is less consideration of heterogeneity in local labour markets in the current literature when examining the employment effect of minimum wage.

To the extent that regional variation in wages and labour market tightness is unaccounted for, the estimated employment effect of national minimum wage upratings represents the average effect across regions and does not reflect whether the minimum wage is binding in the region, which is the one of the main interests of research (Thompson 2009). Moreover, the average employment effect in a region represents the compound effect between labour supply and labour demand after increasing minimum wage. In the areas with higher economic growth generally there will be more opportunities for those looking for jobs, suggesting a higher matching rate, but fewer workers in those areas will look for a minimum wage job at same time. Neglecting the regional heterogeneity may result in the ambiguous employment effect by overlooking the impact of different proportions of workers who will respond to the increasing minimum wage. The minimum wage in the UK has been administered on a national basis since its introduction despite considerable regional variations in local prosperity, cost of living, labour demand and supply (Dolton et al., 2015). Using Regression Discontinuity (RD) framework, previous work by Dickens et al. (2014) presents robust and consistently positive employment effects of increasing minimum wage in the UK, although it has not accounted for the regional heterogeneity,

In this paper, we mainly contribute to the literature by examining the effect of local non-employment on the impact of increasing minimum wage using British data and showing that the heterogeneous effect of increasing minimum wage is driven by both the direct impact of macroeconomic environment and the proportion of young workers affected by the tightness of local labour market. Instead of estimating the average treatment effect as in Dickens et al. (2014), we extend the RD framework to explore the heterogenous effect on the ground that the employment effect could vary by distinctive macroeconomic environment locally. Specifically, we use the term 'responsiveness' to refer to the situation where young workers react on the eligibility for higher minimum wage band. By extending the standard RD to allow covariates affecting the discontinuity, our strategy provides a credible way to identify a procyclical effect of an increase in the minimum wage on employment. In a scenario where the effect of increasing minimum wage on employment is procyclical with the local non-employment rate, the estimate of the employment effect is more pronounced after accounting for the local non-employment rate, suggesting that the conventional RD strategy will result in underestimates.

In line with previous results, our results consistently point to a conclusion that the age-dependent minimum wage at 21 years-old in the UK is not binding, in the sense that the prevailing minimum wage is below the market clearing wage for people who are looking for a minimum

wage job.[1] Previous evidence has suggested that labour market frictions resulting from the modern version of monopsony allow firms to affect the wage (Machin and Manning 1994; Metcalf 2008). Our extended RD model suggests that the employment effect of minimum wage for young workers in the UK is underestimated in the previous results, by 0.1-0.2% for each 1 percentage point increase in the local non-employment rate. After accounting for the business environment and regional heterogeneity, the discontinuity increases significantly and the employment effect could reach the maximum 8.7% for an average annual increase in the national minimum wage of £0.4 per hour.[2] In the absence of labour demand cut induced by the increasing minimum wage, the rise in employment could be attributed to an effect of labour supply increase induced by the age-dependent national minimum wage uprating.

2. Literature on minimum wage and employment effects

The research on employment effects of minimum wage has recently advanced both from improved data sources and methodology. Broadly speaking, there are two main strands of the literature. The first strand focuses on examining the effect of increasing minimum wage on employment rate (Card and Krueger, 1994; Machin et al., 2003; Stewart, 2004; Arulampalam et al., 2004). A consensus is that a modest increase in minimum wage will not lead to a large reduction in employment as a whole, whereas, it tends to compress wage distribution (Machin et al., 2003) and reduce income inequality. Few negative effects have been found in subgroups (Dickens et al., 2015). Firms manage to reorganize production processes to offset the increasing minimum wage (Draca et al., 2011, Riley and Bondibene, 2017). The second strand studies the impact of increasing minimum wage on the labour flow, rather than the stock of labour, e.g. by studying whether higher minimum wage is associated with lower hiring rate and lower job separation rate (Brochu and Green, 2013; Dube et al., 2016; Kreiner et al., 2019). This strand of literature has been recently advanced by taking advantage of large administrative datasets in the U.S. and Europe, focusing on disentangling the equilibrium effect by examining labour exit and entry separately.

Despite the heated debate on this topic lasting decades, the employment effect is still elusive to some extent.[3] There is a growing literature recently attempting to disentangle the effect by examining impacts on firms (Gioliano, 2013; Bell and Machin, 2017; Harasztosi and Lindner, 2018). Another strand focuses on the association between business environment and the effect of

[1] It has been argued that the minimum wage in the UK is too low and there is a room for the minimum wage to increase without having an adverse impact on employment (Dube 2019).

[2] The local non-employment rate is calculated using all individuals between 25 and 65 years old, and constructed as one minus employment rate as per the ONS/ILO definition, where employment includes self-employment.

[3] There are difficulties to pin down the employment effect. First, the effect could be small in nature and it may be offset by employers' effect, including reducing workers' benefit or increasing product prices. Second, labour markets may be imperfect. Third, increases in minimum wage could be dynamic. The employment effect would last for years after increasing minimum wage (Meer and West, 2016). And production could be altered due to the increase in labour cost (Riley and Bondibene, 2017). Fourth, the effect is ambiguous to pin down from an econometric point of view, especially with state-level data (Manning, 2010).

increasing minimum wage. Addison et al. (2013) include an interaction of minimum wage rate with unemployment rate to capture the impact of unemployment rate on the employment effect of minimum wage. They find a negative elasticity of minimum wage in states with higher unemployment rates in U.S. Dolton et al. (2015) exploit geographic variation of exposure to minimum wage with employment in the UK and argue that there is no impact on employment when uprating the minimum wage and recession has only a marginal negative effect on employment. By implementing a regional-specific effect, Addison et al. (2015) do not find strong negative employment effect in sectors with more workers below the minimum wage. Clemens and Wither (2019) show that increasing minimum wage during the Great Recession had a significantly negative impact on employment for lower skilled workers, although they do not specifically account for the effect of the macroeconomic environment.

In the standard Search and Matching theory, the matching function would be correlated with tightness of labour market. Although there is no direct evidence regarding correlation between macroeconomic environment and minimum wage, many papers have examined the impact of macroeconomic environment on economic outcomes, such as employment and earnings (Carneiro et al., 2012). In particular, many studies have examined the differential impacts of increasing minimum wage during recession (Thompson, 2009; Allegretto et al., 2011; Addison, et al., 2013; Dickens et al. 2015; Clemens and Wither, 2019). In addition, the existing studies are mostly making use of regional variations in the tightness of the labour market which are affected by increasing the national minimum wage to a greater or lesser extent (Addison et al., 2013; Brochu and Green, 2013; Dube et al., 2016). This method, known as 'differential impact', is based on identification assumptions which have been challenged. Specifically, using regional variation to evaluate the effect of increasing minimum wage is problematic if the wage distribution is altered after increasing minimum wage, due to general equilibrium effect. Dickens et al. (2014) argue that Regression Discontinuity (RD) provides a clear quasi-experiment to generate more robust results.

3. Identification Strategy

In our paper, we extend the model of Hahn et al. (2001) to allow differential impacts of external factors on the discontinuity by affecting response of treatment. We propose a model to explain the discontinuity when external factors can affect the discontinuity and estimate the heterogeneous effect of increasing minimum wage. The RD design is a quasi-experimental design in which the probability of receiving a treatment changes discontinuously across the threshold as a function of control variables (Hahn et al. 2001). It is an increasingly popular method in applied econometrics (Imbens and Lemieux 2008).

We take advantage of the age-dependent minimum wage structure when young workers become eligible for the adult wage rate based on an assumption that young workers are the same preceding and following the age threshold of becoming eligible for adult wage rate. The National Minimum Wage (NMW) in the UK was first introduced in 1999 with different rates for the age bands 18-21 and 22-years and above (*adult wage rate*). The age-dependent minimum wage structure took its

current form in 2004, when a lower rate of minimum wage (*development wage rate*) was introduced for 16-17 year-olds (Young Workers).[4] In 2018, the minimum wage for the age band 22-years and above is £7.38, rising from £5.9 for the age band 18-21.

Our model is similar to Becker et al. (2013) which extend the concept of local average treatment effect (LATE) in RD to heterogeneous local average treatment effects (HLATE), in which they assume conditional independence between the treatment indicator, $T_i(z_i)$, and an exogenous factor of interest, such that the interaction terms meet the exclusion restriction and are uncorrelated with the error term in the outcome equation, conditional on observables.

The independent variables are assumed to not affect the treatment assignment and treatment response, implying that there are no other variables affecting the taking up of the treatment. It is easy to test this hypothesis, in this scenario, by checking whether the discontinuity will be changed after adding other variables into the equation.

The key difference in our model is that we relax the Conditional Independence Assumption (CIA) on the variable of interest and allow the treatment response to vary with the independent variables in a heterogeneous RD model. In this paper, we show that external factors can lead to heterogeneous results when the factors affect the response of the treatment.

To implement our model, we apply interaction between the discontinuity dummy and the distance in the forcing variable to the cut-off point to allow for the slope changing after crossing the age threshold, using quadratic and cubic models. The forcing variable used is the month of birth and calculate the distance between the surveyed time and the month when become eligible for the higher minimum wage.

$$Y_i = \alpha + \beta D_i(z_i) + \delta(z_i) + \rho X_i + \varepsilon_i \tag{1}$$

of which

$$\delta(z_i) = \theta_1 z_i + \theta_2 {z_i}^2 + \theta_3 z_i * D_i(z_i) + \theta_4 \big(z_i * D_i(z_i)\big)^2 \tag{2}$$

where Y_i is the outcome variable and X_i are the control variables for individual i. D_i denotes the treatment assignment and is completely determined by the forcing variable. β is the effect of discontinuity induced by the increasing minimum wage. z_i is the forcing variable which determines status of treatment. $\delta(z_i)$ represents the continuous age function which captures the effect of age. The samples before and after birthday are assumed to be randomly distributed, which guarantees that the treatment variable is the only source of discontinuity.

Based on the conventional sharp RD setting, we extend our baseline model into a model where the treatment status can vary with the observables.

$$Y_i = \alpha + \beta T_i(U_i, z_i) + \delta(z_i) + \rho X_i + U_i + \varepsilon_i \tag{3}$$

[4] Before Oct 2010, an increase in minimum wage is due on one's 22nd birthday, but the age threshold is changed into the 21st birthday after 2010.

$T_i(z_i)$ is the actual treatment indicator and is the function of the forcing variable and exogenous factors. It equals one if an individual has received higher age-dependent minimum wage because of the eligibility for the higher wage band. In this paper, we distinguish between the eligibility and responsiveness, the latter term measures the extent to which young workers react on the eligibility for age-dependent higher minimum wage band.. In the presence of potential non-responsiveness, where being eligible for higher minimum wage rate may not affect employment decisions, we assume that there is a linear relationship between being affected by (i.e. eligibility) and responding to the increasing minimum wage (i.e. responsiveness). Given a linearity assumption, the treatment status T_i could be extended to a linear form with responsiveness indicator D_i combining with the impact of local non-employment rate and here the treatment status is associated with the forcing variable and the local non-employment rate. Therefore Equation 3 could be modified to take the form below:[5]

$$Y_i = \alpha + \beta D_i(z_i) + \theta f(U_i) * D_i(z_i) + \delta(z_i) + \rho X_i + U_i + \varepsilon_i \quad (4)$$

where the treatment effect is β_i and the interacted term is to capture the effect associated with the determination of treatment. $f(U_i)$ denotes the non-employment rates of local authorities to represent the tightness of local labour markets. $f(U_i)$ affects the discontinuity through the sample selection function and it will not affect the discontinuity independently since $f(U_i)$ is continuous at z_0 .[6] $f(U_i)$ affects the employment probability directly and independently, leading to heterogenous employment effects. Adding the local non-employment rate as a control variable is important because it captures the benchmark effect of non-employment rate before increasing minimum wage, otherwise the interacted term is a compound effect. We have also added a regional fixed effect term to additionally control for any time-invariant regional effects.

We argue that the heterogeneity of the discontinuity is caused by the differences in responsiveness with the increasing minimum wage across areas. On the one hand, the non-employment of local labour market directly affects the employment effect, but the effect of non-employment rate will be cancelled out given the nature of RD design. On the other hand, the environment of the local labour market affects the proportion of young workers affected by the increasing minimum wage and changes the responsiveness rate in a scenario where minimum wage conventionally affects a small proportion of total labour market.

The model may imply that the effect of the non-employment rate on employment effect can be decomposed into two channels. The first channel is how many people will respond to the increasing minimum wage. The treatment indicator will not only depend on the age function but also exogeneous factors affecting the possibility of being affected by the higher wage band. After accounting for the regional fixed effect, in areas with lower non-employment rate, which may

[5] Appendix B describes the detailed derivation for the equation.
[6] We provide evidence that the non-employment rate is continuous around the threshold and show that the employment effect is smaller in an area with higher non-employment rate in the Appendix A.

imply higher average income, few people will respond to the adult rate increase.[7] Hence, a smaller discontinuity will be observed. The second channel is the impact of the business environment on the probability of employment. In areas with lower non-employment rate, the probability of finding a job is higher, which reinforces the employment effect of increasing minimum wage. The two channels work in opposite directions. Therefore, a larger employment effect of increasing minimum wage implies that the second channel dominates.

4. Data and Sample selection.

The data in this paper is based on Quarterly Labour Force Survey (QLFS) from 2000 to 2018. The QLFS is a quarterly survey with a rotating panel design conducted since 1992 in which each individual participates for five consecutive waves. Our sample consists of the first and fifth waves in which hourly payment is reported. It contains the exact date of birth which is used to calculate distance between day of survey and day of birth. The sample is restricted to individuals who are 21 and 22 years-old before 2010, or 20 and 21 years-old after 2010. Observations are sorted on the basis of their distances between the day of survey to the day of birth as a continuous measure in weeks to avoid measurement error. It is worth emphasizing that the sample only includes individuals within one year of the adult wage rate age cut-off point.

There might be a non-negligible effect on employment probability of individuals with different levels of education. A significant share of young A-level graduates may have minimum wage level jobs. Therefore, instead of focusing on the 18 year-old threshold, the effect of the increase in minimum wage on employment probability of individuals who are turning into 21 year-olds could to a large extent avoid the problem of school leavers entering the labour market at the same time. We have also dropped the 25% or so of people in this age group who are in continuous full-time education, most of whom in Higher Education.[8] It is expected that those university graduates are not looking for jobs with minimum wage. Including them will inevitably bring bias into the results as they will gradually enter labour market when they approach 21 years of age, the threshold of adult minimum wage.

In the following, we distinguish between the "full sample" which is used for descriptive analysis showing the changing labour market statuses arising from the age-dependent NMW rate, and the "analytical sample" used in the RD analysis. The full sample consists of individuals who are within 12 months either side of the cut-off point. The analytical sample consists of individuals

[7] There is also a concern that some young workers are paid less than the adult wage rate but did not get the pay rise after the birthday, known as employer non-compliance. This is illegal but we can not observe them due to data limitation.

[8] Apprentices who are subject to a different minimum wage framework are also excluded because apprentices have a different minimum wage in the UK.

whose highest qualification is below A-level, referring to individuals reporting GCSEs, other qualifications, and no qualifications in the survey.[9]

The definition of low earners workers who are mostly affected by NMW should be straightforward conceptually, but in practice this is controversial. A sample which consists of most directly affected workers is of great importance in understanding the effect of minimum wage (Neumark 2019). Including more irrelevant workers may reduce the discontinuity around the cut-off point. Since workers who earn around minimum wage account for only about 10% of all employees in the UK, the discontinuity might not be strong enough if more irrelevant workers are included. Dickens et al. (2014) argue that defining the low earners by their earnings can be biased by measurement error and spillover effect. Instead, they concentrate on low skilled individuals who are in the bottom third of the skill distribution. However, the effect might not be strong when using educational level as indicator of being affected by the NMW since it still involves measurement errors and those individuals with lower levels of education can earn more than NMW. This is especially an issue in the UK since few young workers earn around minimum wage compared to other countries, such as Denmark. There is no unified framework to identify the minimum related workers. The empirical papers on minimum wage largely restrict the low skilled sample up to 10% above the minimum wage (Stewart, 2004; Brochu and Green, 2013; Dickens et al, 2015). Defining low earners by earnings may introduce compositional bias into the results. In order to avoid the compositional bias, we decide to limit our analytical sample to individuals whose highest qualification is below A-level. In this case, the analytical sample includes individuals with the same demographic features preceding the discontinuity.

5. Descriptive Results.

Table 1 presents the summary statistics. Panel A highlights the changing characteristics as we impose restrictions on the sample. The first part contains all observations in the sample. The employment rate of young workers is around 66%. The average local non-employment rate of around 27% is calculated from the same QLFS data using all individuals between 25 and 65 years-old, in order to avoid the endogeneity problem. The local non-employment rates are used to capture the tightness of local labour markets, in order to proxy for the extent to which young workers will be affected by the increasing minimum wage.[10] The employment rate follows the definition of the Office for National Statistics and accounts for both employment as employees and self-employment. The non-employment rate is one minus the employment rate. The second part describes the analytical sample which restricts the sample to the low-earners, i.e. those with below A-level and equivalent as the highest qualification.

[9] Other qualifications refer to qualifications below A-level, including NVQ, BTEC, etc.
[10] In this paper, we choose non-employment rate over unemployment rate to capture economic inactivity (including "discouraged workers" and "adder workers").

Panel B describes the differences between the treatment and the control groups, in which the treatment group consists of individuals who are eligible for higher minimum wage and the control group is the other way around. The sample includes 6 months at each side of the cut-off point for being eligible to a higher rate of minimum wage.

<Table 1 Here>

To show how an increase in minimum wage affects employment dynamics, we provide figures to motivate the RD design. Figure 1 presents the percentages of individuals by employment status, based on analytical sample. The figure directly shows a positive discontinuity on employment and a negative discontinuity on ILO unemployment rate, and a marginal negative discontinuity on self-employment. The discontinuity varies with the qualifications, shown in Figure A.1. The positive discontinuities are found in individuals with other qualifications and no qualification. To examine whether substantial amount of workers are made redundant, we describe the average tenure of workers around the cut-off point, shown in Figure A.2. No evidence is shown that there is significant employer behavioural response to increasing the minimum wage.

<Figure 1 Here>

To motivate the impact of business environment, Figure 2 directly shows a crude relationship between changes in employment rate and local non-employment rate, at the local authority level. In this paper, we examine the heterogeneous employment effect, making use of the variations across local authorities in the UK.[11] The figure removes the local fixed effect on employment by comparing the change in employment in each local authority and presents the relationship between changes in employment and non-employment of local authorities. The local non-employment rate is calculated given full sample and the change in employment is estimated using analytical sample. The negative slope in Figure 2 suggests that the increase in employment rate is higher after increasing minimum wage in areas with lower local non-employment rates.

<Figure 2 Here>

6. Regression Results

Table 2 follows the literature and examines the discontinuity in employment after increasing minimum wage as a benchmark. In addition, we provide the effects in different periods to differ from the previous findings and motivate the main findings of this paper. We include individuals whose age lies between 12 and 6 months on either side of the relevant birthday. For the first Panel,

[11] There are five types of local authority in England, including county councils, district councils, unitary authorities, metropolitan districts and London boroughs. There are 333 local authorities in England, including 24 county councils, 181 district councils, and 128 single-tier authorities (33 London boroughs and 36 metropolitan boroughs) (Sandford 2021). The local government is responsible for housing, leisure, recreation, environmental health, waste collection, planning applications and local taxation collections (https://www.politics.co.uk/reference/local-government-structure/).

we examine the effect based on both quadratic and cubic age functions. In the second Panel, the results are examined in quadratic forms. There is an issue when estimating the interaction term in Probit model (Ai and Norton 2003). To have consistent results, we apply OLS to all regressions.

Panel A presents the discontinuities after increasing minimum wage on employment, under different specifications. The results are based on the analytical sample which includes individuals whose highest qualification is below A-level. The results are consistent with the literature and suggest that employment increases by 2-4 percentage points after becoming eligible for the adult rate. The standard method of applying RD is narrowing down the window length to further remove the bias from idiosyncratic factors. The discontinuities are larger based on smaller window length. On the other hand, with a smaller sample size, the standard error may increase.

<Table 2 Here>

To explore the heterogeneous effect of increasing minimum wage in different macroeconomic environment, we start by examining the discontinuity before and after the great recession. Dickens et al. (2014) examine the employment effect before 2009, which largely predates the Great Recession. Panel B shows the discontinuity in employment based on different calendar years. The recession period is defined as the period between 2009 and 2014 inclusive.[12] The average non-employment rate is displayed in Figure A.3. No significant employment effect has been found during the recession period when it is less likely to find a job, implying that the adverse macroeconomic environment may offset the employment effect of the minimum wage increases. On the other hand, the effect of increased NMW is more pronounced, at 3-5 percentage points, during normal times.

Table 3 presents the main results on the heterogeneous effect of increasing minimum wage after considering the impact of macroeconomic environment. As in Table 2, we estimate a linear probability model where the dependent variable is a dummy for being employed. To show the consistency of the results, we specify various window lengths, age functions, and control variables. Compared to the previous results, we allow the discontinuity to change with local non-employment rates to capture the heterogeneous effects of increasing minimum wage on employment. The procyclicality measure, defined as the interaction between the discontinuity and the local non-employment rate, captures to what extent the effect on employment varies with the local non-employment rate. The discontinuities remain constant across the various specifications and compared with the results in Table 2, the employment effects increase to 6-8 percentage points after accounting for the effect of local business. In addition, it shows a strong negative effect of local non-employment rate on probability of employment, although the procyclicality measures

[12] Note that this is our own definition of the recession period based on unemployment rates, which differs from the official recession period between Q2 2008 and Q3 2009. According to ONS, the Great Recession in the UK started from second quarter 2008 and ended in second quarter 2009. In this paper, we define the recession period as between 2009 and 2014 given the nonemployment rates we calculated in the data in Figure A.3 in the appendix. To differ the impact of macroeconomic environment, we split the time periods based on the employment rate. The employment rates between 2009 and 2014 are significantly lower than the other years.

are not statistically significant based on smaller window lengths due to larger standard errors.[13] The results suggest that the employment effect of becoming eligible for the adult rate will reduce by 0.15-0.2% whenever the local non-employment rate decreases by 1%. To rule out the possibility that employment rate has a discontinuity around the cut-off point (and hence endogenous to the NMW), Figure A.4 shows the continuity of local non-employment rates based on the time between birthday and date of survey. We do not find any discontinuity across the threshold, ruling out any specific factors from the local authorities.

<Table 3 Here>

Figure 3 displays the marginal effects of the discontinuity given local non-employment rates, which are grouped into six equal-spaced groups. The marginal effects of the discontinuities decrease from 6% to 2%, as the local non-employment rates increase from 20% to 40%. The slope of the fitted line between local non-employment rate and employment probability is about -0.2.

<Figure 3 Here>

6.1. Sensitivity checks and other channels

In order to examine whether the employment rates behave erratically around the cut-off point and to avoid the direct impact of discontinuity on labour redundancy and anticipation effect, we check robustness of the results by replicating Table 3, but excluding the month immediately before and after the cut-off point in Table A.1. The discontinuities remain largely the same. The interaction increases and become more significant. In addition, the discontinuity in RD strategy may also vary with different window length and sample selection. To examine the robustness of the employment effect around the cut-off, we provide more sensitivity tests based on various window lengths and sample selections. Since qualification is not perfectly correlated with low pay, the discontinuity may be attenuated by including irrelevant workers. To remove the observations of non-response of NMW, we exclude workers who have wage 20% above adult rate in Table A.2. The estimates are increased after restricting to the sample which are more likely to be affected by NMW. We also provide sensitive tests based on various window lengths in Table A.3. The results remain consistent based on various window lengths.

To prove that the discontinuity is not driven by channels other than the age-dependent NMW rates, we provide placebo tests based on false age thresholds which do not affect NMW. Panel A and Panel B of Table A.4 provide the robustness check for the effect of increasing minimum wage on employment. While in reality the age threshold of minimum wage was decreased from 22 to 21 years-old in 2010, we deliberately assign the false age cut-off as 21 years-old before 2010 and 22 years-old after 2010. The results provide strong support to our results, as no significant employment effects have been found, and the magnitude of the estimate is very small compared to the genuine results. Panel C and Panel D of Table A.4 examine the discontinuities based on one year before and after the eligible age for adult rate. Still we do not

[13] It comes highly significant after excluding workers with 20% salary above adult rate.

find any significant discontinuities and the magnitude of the coefficients remain very small. In addition, we explore a wider range of subgroups and channels affected by the increasing minimum wage, including wage effect, full-time job, permanent job, firm size effect, and industrial differences, shown in Table A.5 and Table A.6.

6.2. Heterogeneous responses across regions

There is considerable geographical variation in non-employment rates in the UK, see Table A.7. Few papers take advantage of the geographic variation to evaluate the impacts of increasing minimum wage on local area performance (Stewart, 2002; Dolton et al., 2015). The more affluent areas in the Southeast may have a smaller response to the increasing minimum wage because few workers will have to comply with the increase compared to other areas. In this context, these local areas will have smaller wage growth on average and smaller discontinuity in employment when upgrading to adult rate.

To have a clear understanding of the responses of increasing minimum wage, we describe the breakdown of hourly wages during development wage rate and adult rate in Table 4. The areas with lower average earning at development rate are expected to have larger and more consistent wage increase at adult rate compared to the areas with higher average earning within development rate. The correlation is displayed in Figure 4.

<Figure 4 Here>

On the other hand, the employment rates across regions present more elusive implications in Table 4, due to the fact that it may include more measurement errors. The first two columns describe the average wages for people who are eligible for development rate and adult rate respectively. The areas with higher average earning may have fewer observations earning below adult rate and hence there could be smaller positive effect on employment. The effect is very likely to compound with state dependence of local employment rate in the area.

Figure 5 which describes the correlation between average wage and percentage of workers below adult rate shows that regions with higher wages indeed have larger decrease in the proportion of workers below adult rate. It is counter-intuitive since regions with lower earnings should have more workers being eligible with the adult rate. The confusing results may stem from regional state dependence. The workers in regions with more opportunities have higher probability to get out of low-paid jobs. The figure suggests that the results are spurious if the state dependence is not accounted for carefully.

<Figure 5 Here>

<Table 4 Here>

6.3. Elasticity

The consensus of employment elasticity lies approximately between -0.1 and -0.3 for the whole labour force, mostly based on U.S. evidence, and there is a wide range of elasticity for teenagers between -0.4 and 0.4. The non-negative evidence is mostly found in the UK. Allegretto et al. (2011) argue that the results would be substantially downward biased if not considering particular trends in regions and find employment elasticity of youth is around zero in the U.S after accounting for heterogeneous employment patterns across states. Newmark (2014) uses synthetic control analysis and finds an elasticity from -0.05 and -0.1 for teenagers. Dube et al. (2016) find an employment elasticity of -0.17 and separation elasticity of -0.23 for teen workers in the U.S. using a border-discontinuity design. But recently the close-control design has raised concerns about its validity on the ground that the results could be biased by unobserved factors and commuting across areas (Neumark, 2019). Totty (2017) uses a factor model and finds an elasticity between -0.01 and -0.04 and -0.06 for teenage employment.

The evidence in the UK is mixed and focuses on estimating the elasticity when introducing the NMW. Machin et al. (2003) find an employment elasticity between -0.08 and -0.38 in the home care sector in the UK when the NMW was first introduced in 1999. Stewart (2004) does not find significant dis-employment effect and the elasticity varies from 0 to 0.1. Dolton et al. (2015) suggest that the elasticity of updating NMW is around -0.1 for all workers in the UK.

Similar evidence which exploits the age-dependent minimum wage based on regression discontinuity has been found in recent years. Dickens et al. (2014) find a relatively large elasticity of around 0.4 for teenagers in the UK. Keriner et al. (2019) report the employment elasticity of young workers in Denmark ranges between -0.6 and -1.1, using a regression-discontinuity design.

We report the employment elasticity of young workers in the UK on the basis of the RD results presented in Table 4. Firstly, taking advantage of the different responses to adult rate across regions, we draw a simple figure to describe the correlation between wage growth and employment growth. The linear fit of scatter plots in Figure 6 suggests that regions with higher wage growth have higher employment growth. The slope is 0.38 given the regression of employment growth on wage growth, suggesting that the elasticity of minimum wage is about 0.38.

<Figure 6 Here>

The regression-adjusted employment rate increases by around 3-4% after qualifying for the adult rate. After accounting for the effect of macroeconomic environment, the employment effect increases to 8.2%. [14] Therefore, to compute an elasticity, we use the regression-adjusted employment effect and actual percentage increase in minimum wage rate, which is 25.9%, [15] suggesting that the elasticity of increasing minimum wage for young workers is around 0.44. [16]

[14] The preferred specification from column 3 in Table 3.

[15] The development rate and adult rate in 2018 is £5.60 and £7.05, respectively.

[16] The elasticity is calculated as $\varepsilon = \frac{\partial e/e}{(\partial w/w)*\rho}$, where ρ denotes the percentage of workers who are paid below adult rate, ∂w denotes the increase in hourly wage, and w represents the average hourly wage at development wage rate.

Together with the simple correlation result above, we argue that the elasticity is between 0.38 and 0.45. However, it is worth noting that the local average treatment effect (LATE) of the NMW we estimate only applies to the particular age threshold under study and might not generalize to other minimum wage rates (nor for other age groups). In addition, the elasticities between introduction of minimum wage and updating minimum wage may also be different given the different response from employers and workers.

7. Conclusions and discussions

We examine the heterogeneous effects of increasing the age-dependent national minimum wage on employment in the UK. We contribute to the literature by directly examining the causal effect of increasing minimum wage on employment, considering business fluctuations. We extend the RD framework and contend that the employment effect might vary across regions due to the macroeconomic environment and the rate of responsiveness. Neglecting the regional heterogeneity may result in bias by overlooking the impact of varying rates of responsiveness in an imperfect responsiveness scenario.

With a larger dataset than Dickens et al. (2014), we extend the standard RD framework to accommodate heterogeneous employment effect caused by macroeconomic environment after increasing minimum wage. We uncover the mechanisms of increasing employment around the cut-off point and argue that the discontinuity caused by the increased minimum wage can be affected by the differences in responsiveness across areas and the direct impact of local labour market conditions. Consistent with the previous research, we find that the employment effect induced by the age change is positive. A more novel finding is that the positive employment effect is decreasing in the ILO unemployment rate and self-employment rate. More importantly we show the discontinuity is more pronounced during the non-recession periods but statistically insignificant during the recession period, suggesting that the local business environment could have sizable impacts on the employment effect of minimum wage. After accounting for the local non-employment effect, the regression results suggest that the employment probability increases by 3-4 percentage points after one becomes eligible for adult rate.

The estimated employment effect will reduce by 0.1-0.2% when the local non-employment rate increases by 1 percentage point. After accounting for the heterogeneous macroeconomic environment across local labour markets, the employment effect reaches the maximum 8.7%. Both the model and the empirical evidence suggests that the estimated employment effect might be downward biased without considering business environment. Under an assumption that employers have no direct impact around the cut-off point, the increasing minimum wage increases labour supply of young workers.

Contributing to the ongoing debate on the employment impact of minimum wages, our results suggest that employment elasticity of minimum wage for young workers in the UK is around 0.4, which is distinct from other countries. The reason behind distinctive employment

elasticities across demographic groups leads to a central question of minimum wage, that is whether minimum wage is binding, globally or locally. Our paper provides further evidence on evaluating to what extent the minimum wage is binding at the adult rate in the UK. Previous work by Dickens et al. (2014) presents robust and consistently positive employment effect of increasing minimum wage. In line with their results, our results consistently point to a conclusion that the age-dependent minimum wage at 21 years-old in the UK is not binding. Therefore, in the absence of employers' response to the increase in minimum wage, the increase in minimum wage will increase labour supply instead and not cause a significant dis-employment effect. Our research has found a sizeable positive increase in employment after addressing the heterogeneity across local areas and suggests that further adjustments to the minimum wage should take the macroeconomic environment into consideration. We speculate that modest increases in the relative low minimum wage in the UK may not bring further damage to the labour market which has already been massively damaged by the COVID.

We are aware of the caveats of our analysis. It is worth noting that the local average treatment effect (LATE) of the NMW we estimate only applies to the particular age threshold under study and might not generalize to other minimum wage rates (nor to other age groups). In addition, the elasticities estimated from the introduction of minimum wage may also be different from those derived from minimum wage upratings, given the different response from employers and workers. Ultimately, the effect of the increasing minimum wage depends on the interaction between employers and employees. There is a growing literature that explore the role of firms in determining the elusive employment effect after increasing minimum wage. Building on this paper, the heterogeneous effects could be further explored with rich employer-employee datasets.

References:

Addison, J T., Blackburn, M.L., Cotti, C.D., 2013. Minimum wage increases in a recessionary environment. *Labour Economics*, 23, 30-39.

Addison, J T., Blackburn, M.L., Cotti, C.D., 2015. On the robustness of minimum wage effects: geographically-disparate trends and job growth equations. IZA Journal of Labor Economics, Vol. 4, 1-16.

Ai C., and Norton, E.C., 2003. Interaction terms in logit and probit models. *Economics Letters*, 80(1), 123-129.

Allegretto, S.A., Dube, A., Reich, M., 2011. Does minimum wages really reduce teen employment? Accounting for heterogeneity and selectivity in state panel data. *Industrial Relations*, 50(2), 205-240.

Angrist, J. D., Rokkanen, M., 2015. Wanna get away? Regression discontinuity estimation of exam school effects away from the cutoff. *Journal of the American Statistical Association*, 110(512), 1331-1344.

Arulampalam, W., Booth, A.L., Bryan, M.L., 2004. Training and the new minimum wage. *The Economic Journal*, 114(494), 87-94.

Autor, D., Manning, A., and Smith, C.L., 2016. The contribution of the minimum wage on US wage inequality over three decades: A reassessment. *American Economic Journal: Applied Economics*, 8(1), 58-99.

Becker, S.O., Egger, P.H., Ehrlich, M.V., 2013. Absorptive capacity and the growth and investment effects of regional transfers: A regression discontinuity design with heterogeneous treatment effects. *American Economic Journal: Economic Policy*, 5(4), 29-77.

Bell, B., Machin S., 2017. Minimum wages and firm value. *Journal of Labor Economics*, 36(1): 159-195.

Blondal, S. and Pearson, M., 1995. Unemployment and other non-employment benefits. *Oxford Review of Economic Policy* 11(1), 136-169.

Booth, A.L., Francesconi, M., Frank, J., 2002. Temporary jobs: Stepping stones or dead ends? *The Economic Journal*, 112(480), 189-213.

Brochu, P., Green, D.A., 2013. The impact of minimum wages on labour market transitions. *The Economic Journal*, 123(573), 1203-1235.

Card, D., Krueger, A.B., 1994. Minimum wages and employment: A case study of the fast-food industry in New Jersey and Pennsylvania. *The American Economic Review*, 84(4), 772-793.

Carneiro, A., Guimaraes, P., Portugal P., 2012. Real wages and the business cycle: Accounting for worker, firm, and job title heterogeneity. *American Economic Journal: Macroeconomics*, 4(2), 133-152.

Clemens, J., Wither, M., 2019. The minimum wage and the Great Recession: Evidence of effects on the employment and income trajectories of low-skilled workers. *Journal of Public Economics*, forthcoming.

Dickens, R., Manning, A., 2004. Has the national minimum wage reduced UK wage inequality? *Journal of Royal Statistical Society Series A*, 167(4), 613-626.

Dickens, R., Riley, R., Wilkinson, D., 2014. The UK minimum wage at 22 years of age: A regression discontinuity approach. *Journal of Royal Statistical Society Series A*, 177(1), 95-114.

Dickens, R., Riley, R., Wilkinson, D., 2015. A re-examination of the impact of the UK national minimum wage on employment. *Economica*, 82(328), 841-864.

Dolton, P., Bondibene, C.R., and Stops, M., 2015. Identifying the employment effect of invoking and changing the minimum wage: A spatial analysis in the UK. *Labour Economics*, 37, 54-76.

Dong, Y.Y., 2016. Jump or Kink? Regression probability jump and kink design for treatment effect evaluation. Department of Economics Working Paper, University of California Irvine.

Draca, M., Machin, S., Reenen, J.V., 2011. Minimum wages and firm profitability. *American Economic Journal*, 3(1), 129-151.

Dube, A. 2019. Impacts of minimum wages: review of the international evidence. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/844350/impacts_of_minimum_wages_review_of_the_international_evidence_Arindrajit_Dube_web.pdf.

Dube, A., Lester, T.W., Reich, M., 2016. Minimum wage shocks, employment flows, and labor markets frictions. *Journal of Labor Economics*, 34(3), 663-704.

Glynn, A.N., Quinn, K.M., 2010. Introduction to the augmented inverse propensity weighted estimator. *Political Analysis*, 18, 36-56.

Hahn, J. Y., Todd, P., and Klaauw, W.V., 2001. Identification and estimation of treatment effects with a regression-discontinuity design. *Econometrica*, 69(1), 201-209.

Harasztosi, P., Lindner, A., 2018. Who pays for the minimum wage? *American Economic Review*, forthcoming.

Heckman, J.J., Urzua, S., and Vytlacil, E., 2006. Understanding instrumental variables in models with essential heterogeneity. Review of Economics and Statistics, 88(3), 389-432.

Sandford, M. 2021. Local government in England structures. House of Commons, No. 07104.

Imbens, G.W., Lemieux, T., 2008. Regression discontinuity designs: A guide to practice. *Journal of Econometrics*, 142(2), 675-697.

Kabatek, J., 2015. Happy birthday, you're fired! The effects of age-dependent minimum wage on youth employment flows in the Netherlands. *IZA, Discussion paper*, No. 9528.

Kreiner, C.T., Reck, D., Skov, P.E., 2019. Do lower minimum wages for young workers raise their employment? Evidence from a Danish discontinuity. *Review of Economics and Statistics, forthcoming.*

Lee, D.S., David, C., 2008. Regression discontinuity inference with specification error. *Journal of Econometrics*, 142(2), 655-674.

Machin, S., and Manning, A., 1994. The effects of minimum wages on wage dispersion and employment: Evidence from the U.K. wages councils. *ILR Review*, Vol. 47(2), 319-329.

Machin, S., Rahman, L., Manning, A., 2003. Where the minimum wage bites hard: Introduction of minimum wages to a low wage sector. *Journal of the European Economic Association*, 1(1), 154-180.

Manning, A., 2010. Imperfect competition in the labour market. CEP Discussion Paper, No. 981.

Meer, J., West, J., 2016. Effects of the minimum wage on employment dynamics. *Journal of Human Resources*, Vol. 51(2), 500-522.

Metcalf, D. 2008. Why has the British National Minimum Wage had Little or No Impact on Employment? *Journal of Industrial Relations*. Vol. 50(3), 489-512.

Neumark, D., Salas, J.M. I., and Wascher, W., 2014. More on recent evidence on the effects of minimum wages in the United Stated. *IZA Journal of Labor Policy*, 3-24 (On-line).

Neumark, D., 2019. The econometrics and economics of the employment effects of minimum wages: Getting from known unknowns to known knowns. *German Economic Review* 20(3), 293-329.

Riley, R., Bondibene, C.R., 2017. Raising the Standard: Minimum wages and firm productivity. *Labour Economics*, 44, 27-50.

Skinner, C., Stuttard, N., Beissel-Durrant, G., and Jenkins, J. 2002. The measurement of low pay in the UK Labour Force Survey. *Oxford Bulletin of Economics and Statistics*, Vol. 64, Supplement, 0305-9049.

Stewart, M.B., 2002. Estimating the impact of the minimum wage using geographical wage distribution. *Oxford Bulletin of Economics and Statistics*, Vol. 64(Supplement), 0305-9049.

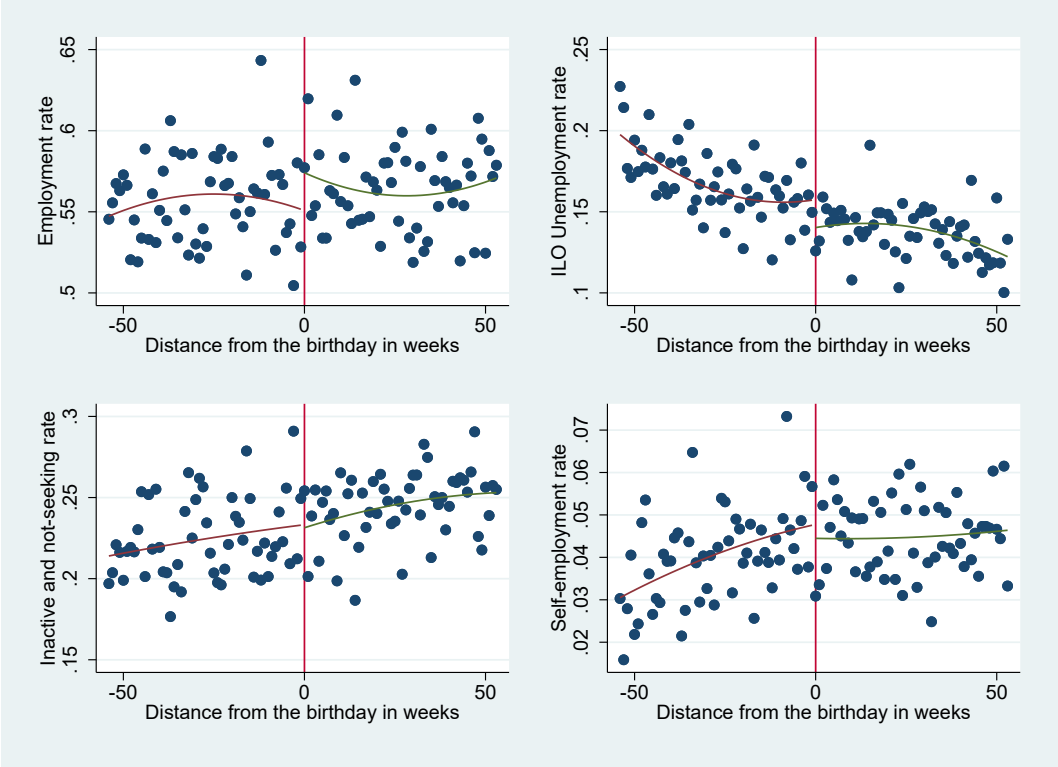
Stewart, M.B., 2004. The impact of the introduction of the UK minimum wage on the employment probabilities of low-wage workers. *Journal of the European Economic Association*, 2(1), 67-97.

Thompson, J. P. 2009. Using local labor market data to re-examine the employment effects of the minimum wage. *ILR Review*, Vol. 62, No. 3, 343-366.

Totty, E., 2017. The effect of minimum wages on employment: A factor model approach. *Economic Inquiry*, Vol. 55(4), 1712-1737.

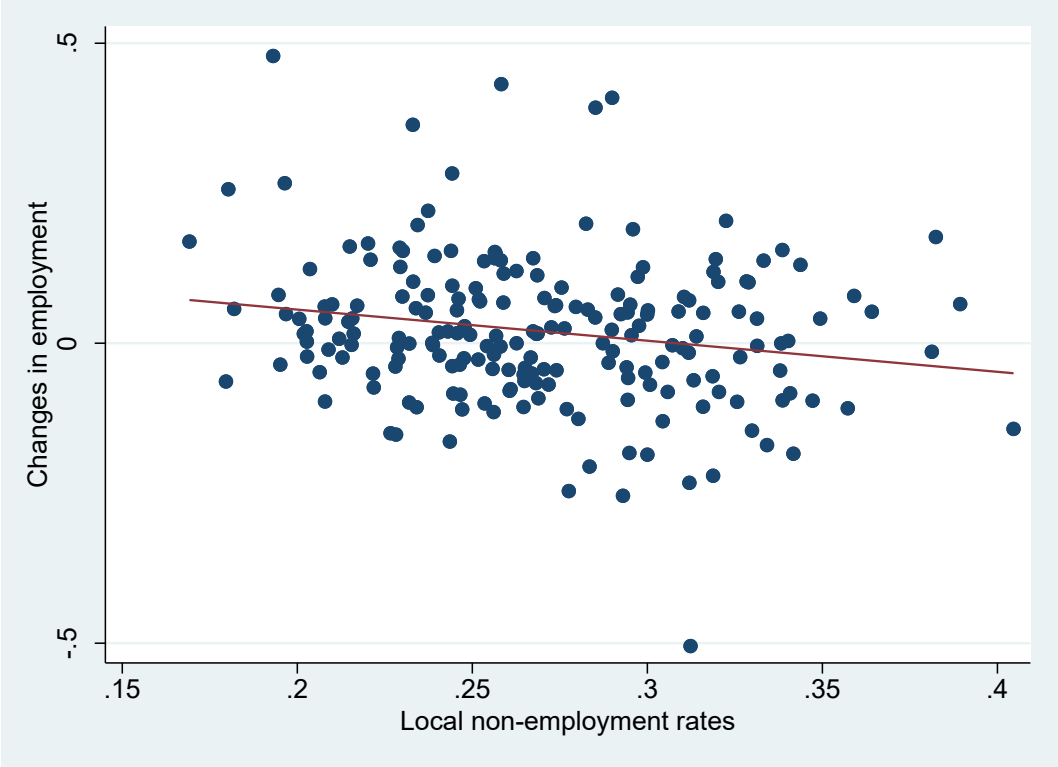
Figures:

Figure 1. Transition around birthday.



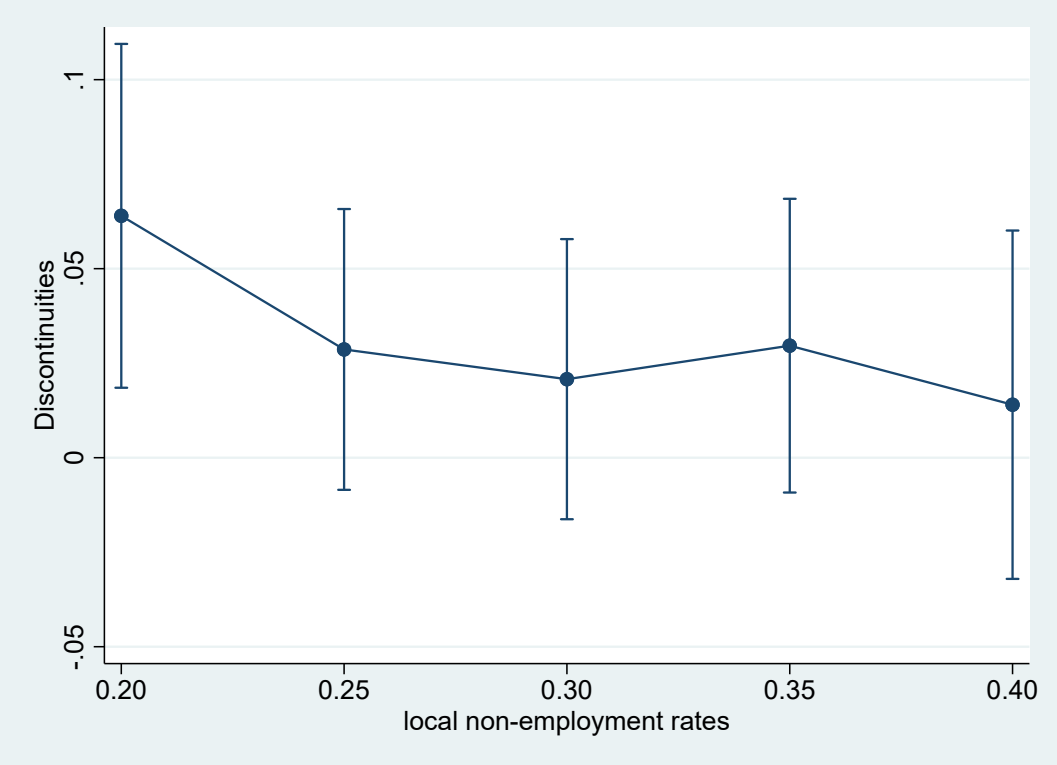
Notes: Analytical sample. Quadratic fit.

Figure 2. Relation between local Non-employment rates and changes in employment among low earners.



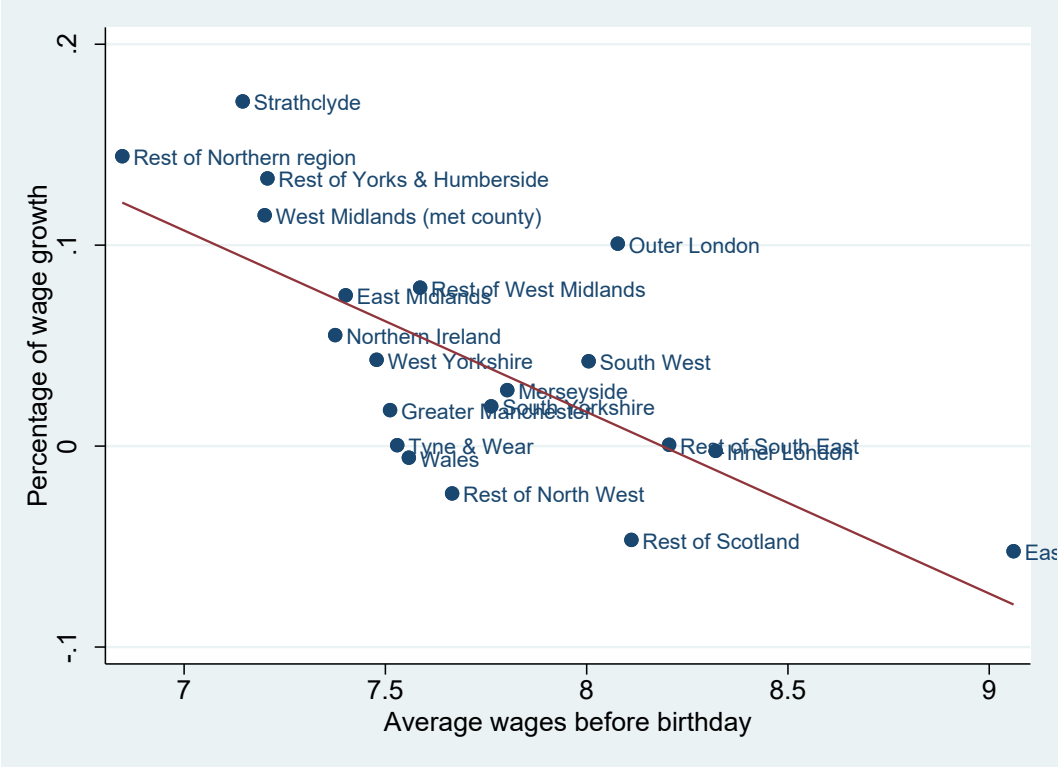
Notes: Analytical sample, restricting to 6 months before and after the cut-off point. X-axis shows of local non-employment rate across local authorities. Y-axis shows the changes in employment rate around the cut-off for each quantile.

Figure 3. Discontinuities in employment effect.



Notes: Analytical sample. X-axis shows the local non-employment rates in 6 equally-spaced groups. The figure reports the regression coefficients of discontinuity at given local non-employment rates. The local non-employment rates for 25-65 year olds are constructed as one minus employment rate as per the ONS/ILO definition, where employment includes self-employment. The marginal effect is estimated based on the specification of column 3 in Table 3.

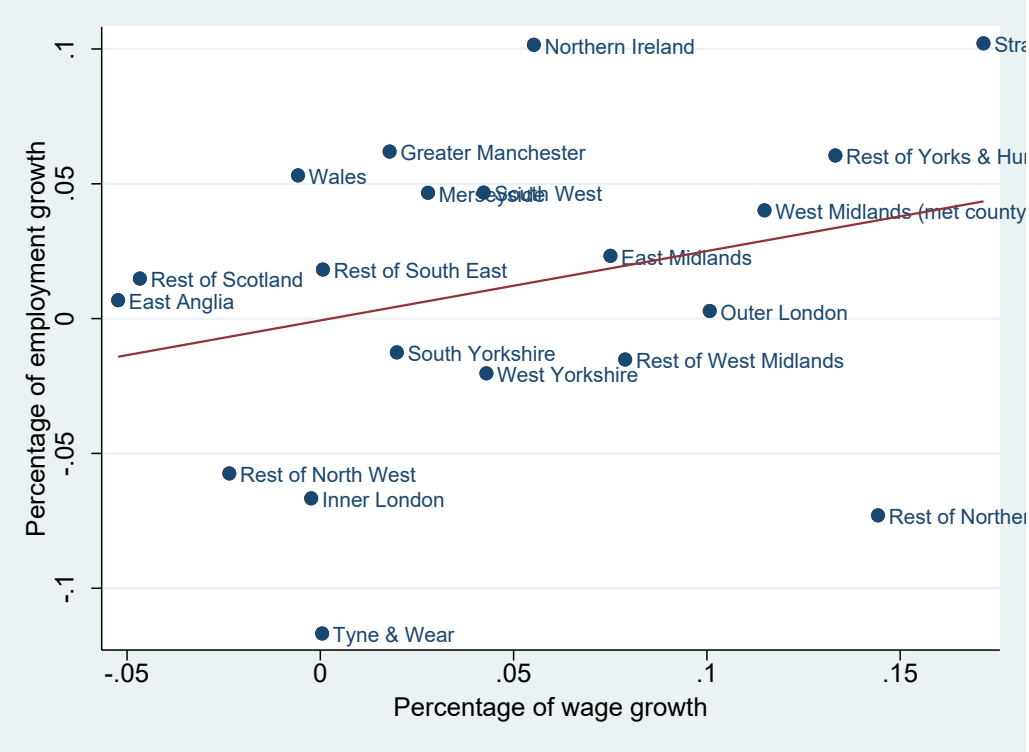
Figure 4. Correlation between wage growth and wages before birthday



Notes: Figure 4 is based on the statistical results of Table 4.

Figure 5. Changes in percentage of workers below adult rate across regions.

Figure 6. Correlation between wage and employment growth.



Notes: The correlation is based on the third and sixth columns of Table 4.

Tables:

Table 1. Summary

Panel A, Summary of variables

VARIABLES	N	Mean	Sd
All observations			
Age left education	92,426	17.21	1.335
Employed	92,426	0.660	0.474
Local non-employment rate	92,426	0.265	0.0527
Male	92,426	0.488	0.500
Self-employed	92,426	0.0460	0.209
Low earners sample (highest qualification GCSE or below**)**			
Age left education	50,037	16.68	1.159
Full-time job	50,037	0.579	0.494
Permanent-job	50,037	0.486	0.500

Panel B, Differences between treatment and control group

	Control		Treat		
	Mean	Sd	Mean	Sd	difference
Age left education	17.19	1.325	17.17	1.350	-0.021**
Employed	0.636	0.481	0.650	0.477	0.003***
Unemployment rate	0.267	0.0527	0.267	0.0524	0.000
Male	0.493	0.500	0.480	0.500	-0.012***

Notes: Control group comprises observations up to 6 months before the NMW-relevant birthday. Treatment group comprises observables up to 6 months after birthday. Permanent job represents the ratio of permanent jobs among all jobs.

Table 2. Discontinuity without procyclicality.

Panel A. Discontinuity in employment.

Employment	(1)	(2)	(3)	(4)
Discontinuity	0.0229*	0.0376**	0.0324*	0.0462*
	(0.0131)	(0.0182)	(0.0175)	(0.0240)
Specifications:				
Window length	12 months	6 months	12 months	6 months
Age function	Quadratic	Quadratic	Cubic	Cubic
Observations	50,037	25,981	50,037	25,981
R-squared	0.023	0.023	0.023	0.023

Panel B. Discontinuity in employment during and outside the "Great Recession" period

Employment	(1)	(2)	(3)	(4)
Discontinuity	0.0346**	-0.0100	0.0515**	-0.00442
	(0.0150)	(0.0267)	(0.0208)	(0.0370)
Specifications:				
Window length	12 months	12 months	6 months	6 months
Age function	Quadratic	Quadratic	Quadratic	Quadratic
Sample period	Non-recession	Recession	Non-recession	Recession
Observations	37,707	12,330	19,584	6,397
R-squared	0.027	0.017	0.027	0.019

Notes: OLS estimates with robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1. Analytical sample with varying window lengths from 6 to 12 months. The age function consists of quadratic form of weeks if not specified otherwise. "Discontinuity" represents the discontinuity, which equals to one if the observation is eligible for higher minimum wage rate. Non-recession includes observations before year 2009 and after year 2014. Recession includes observations between 2009 and 2014.

Table 3. Discontinuity with procyclicality.

Employment	(1)	(2)	(3)	(4)	(5)	(6)
Discontinuity	0.0625***	0.0733***	0.0824***	0.0518*	0.0777**	0.0868**
	(0.0223)	(0.0255)	(0.0280)	(0.0309)	(0.0352)	(0.0386)
Non-employment	-1.019***	-0.714***	-0.714***	-1.042***	-0.756***	-0.755***
	(0.0583)	(0.0665)	(0.0665)	(0.0809)	(0.0919)	(0.0919)
Procyclicality	-0.201**	-0.185**	-0.186**	-0.170	-0.150	-0.150
	(0.0817)	(0.0813)	(0.0813)	(0.113)	(0.113)	(0.113)
Specifications:						
Age function	No	Quadratic	Cubic	No	Quadratic	Cubic
Window length	12 months	12 months	12 months	6 months	6 months	6 months
Controls	No	Yes	Yes	No	Yes	Yes
Observations	50,037	50,037	50,037	25,981	25,981	25,981
R-squared	0.015	0.028	0.028	0.015	0.028	0.028

Notes: OLS estimates with robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1. Analytical sample with varying window lengths from 6 to 12 months. "Discontinuity" represents the discontinuity, which equals to one if the observation is eligible for higher minimum wage rate. Non-employment measures the local non-employment rates of 25-65 years-old. Procyclicality is the interaction of treatment dummy and non-employment. The control variables include dummy for male, and these are the same in the following tables.

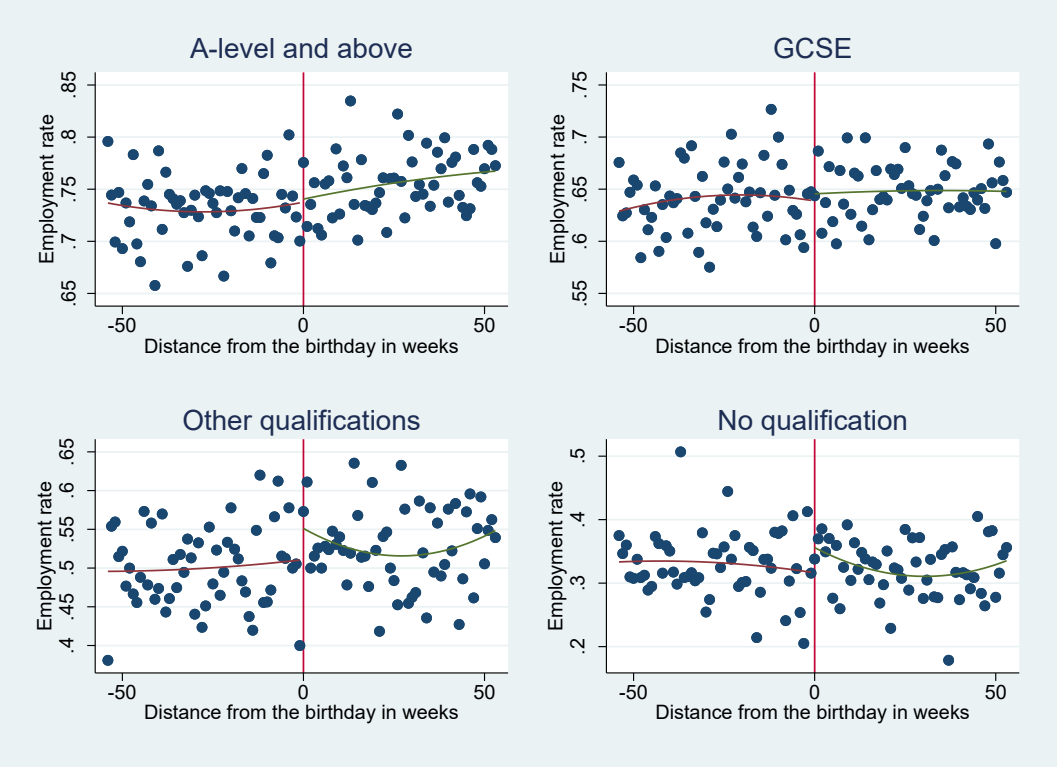
Table 4. Average changes in hourly pay across regions.

	Wage			Employment			Ratio of below NMW		
	Development rate (£)	Adult rate (£)	Increase in percentages	Development rate	Adult rate	Increase in percentages	Development rate	Adult rate	Increase in percentages
Rest of Northern region	6.84	7.83	14.47%	0.55	0.51	-7.27%	30.00%	31.00%	1.00%
Strathclyde	7.14	8.37	17.23%	0.44	0.49	11.36%	27.00%	24.00%	-3.00%
West Midlands	7.20	8.02	11.39%	0.48	0.50	4.17%	31.00%	34.00%	3.00%
Rest of Yorkshire	7.20	8.16	13.33%	0.61	0.64	4.92%	27.00%	25.00%	-2.00%
Northern Ireland	7.37	7.78	5.56%	0.52	0.57	9.62%	31.00%	24.00%	-7.00%
East Midlands	7.40	7.95	7.43%	0.61	0.62	1.64%	29.00%	13.00%	-16.00%
West Yorkshire	7.47	7.79	4.28%	0.55	0.54	-1.82%	25.00%	15.00%	-10.00%
Greater Manchester	7.51	7.64	1.73%	0.54	0.57	5.56%	32.00%	29.00%	-3.00%
Tyne & Wear	7.52	7.53	0.13%	0.59	0.52	-11.86%	37.00%	36.00%	-1.00%
Wales	7.55	7.51	-0.53%	0.52	0.55	5.77%	32.00%	33.00%	1.00%
Rest of West Midlands	7.58	8.18	7.92%	0.66	0.65	-1.52%	26.00%	20.00%	-6.00%
Rest of North West	7.66	7.48	-2.35%	0.62	0.59	-4.84%	28.00%	31.00%	3.00%
South Yorkshire	7.76	7.91	1.93%	0.50	0.49	-2.00%	24.00%	14.00%	-10.00%
Merseyside	7.80	8.02	2.82%	0.48	0.51	6.25%	23.00%	17.00%	-6.00%
South West	8.00	8.34	4.25%	0.62	0.65	4.84%	21.00%	14.00%	-7.00%
Outer London	8.07	8.89	10.16%	0.56	0.57	1.79%	17.00%	12.00%	-5.00%
Rest of Scotland	8.11	7.73	-4.69%	0.56	0.56	0.00%	29.00%	20.00%	-9.00%
Rest of South East	8.20	8.21	0.12%	0.63	0.64	1.59%	22.00%	16.00%	-6.00%
Inner London	8.32	8.30	-0.24%	0.46	0.42	-8.70%	21.00%	10.00%	-11.00%
East Anglia	9.06	8.58	-5.30%	0.60	0.60	0.00%	11.00%	14.00%	3.00%

Notes: The hourly pay includes observations who have highest qualification equivalent to or lower than GCSEs. The hourly wages are adjusted by CPI to year 2017 constant prices. The larger numbers might be because measurement errors in derived hourly wages as both wages and working hours are self-reported. Reportedly, there are lower earnings in Labour Force Survey (Skinner et al 2002; Dickens and Manning 2004).

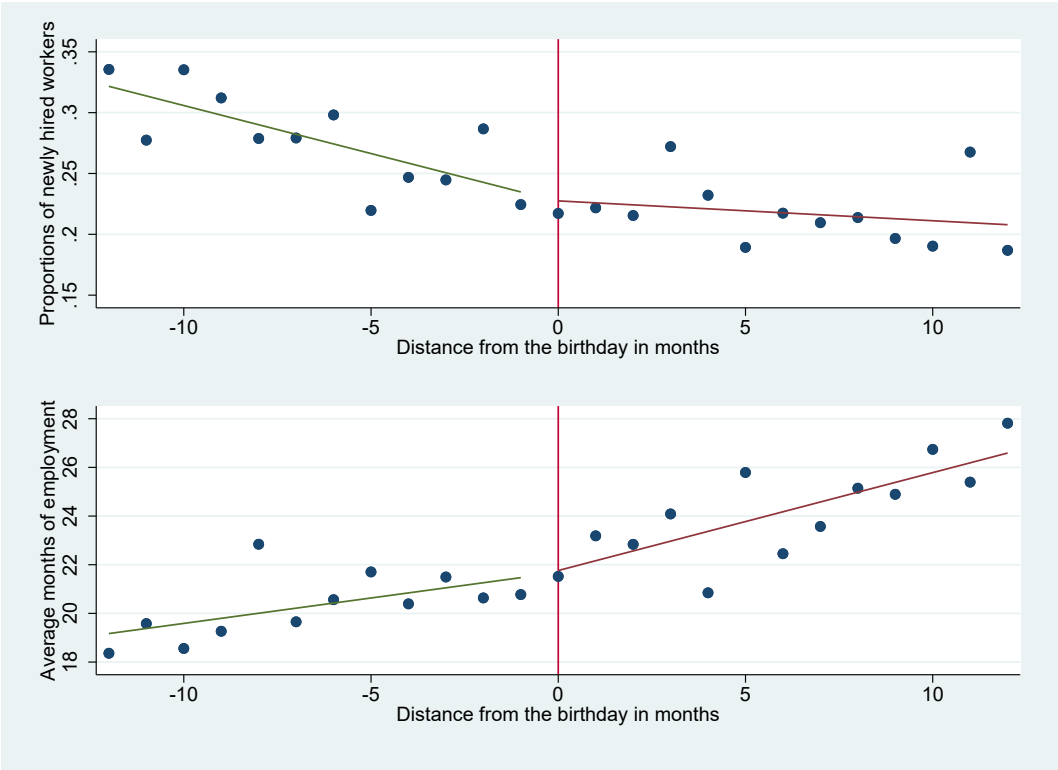
Appendix A:

Figure A.1. Heterogeneous discontinuity across qualifications.



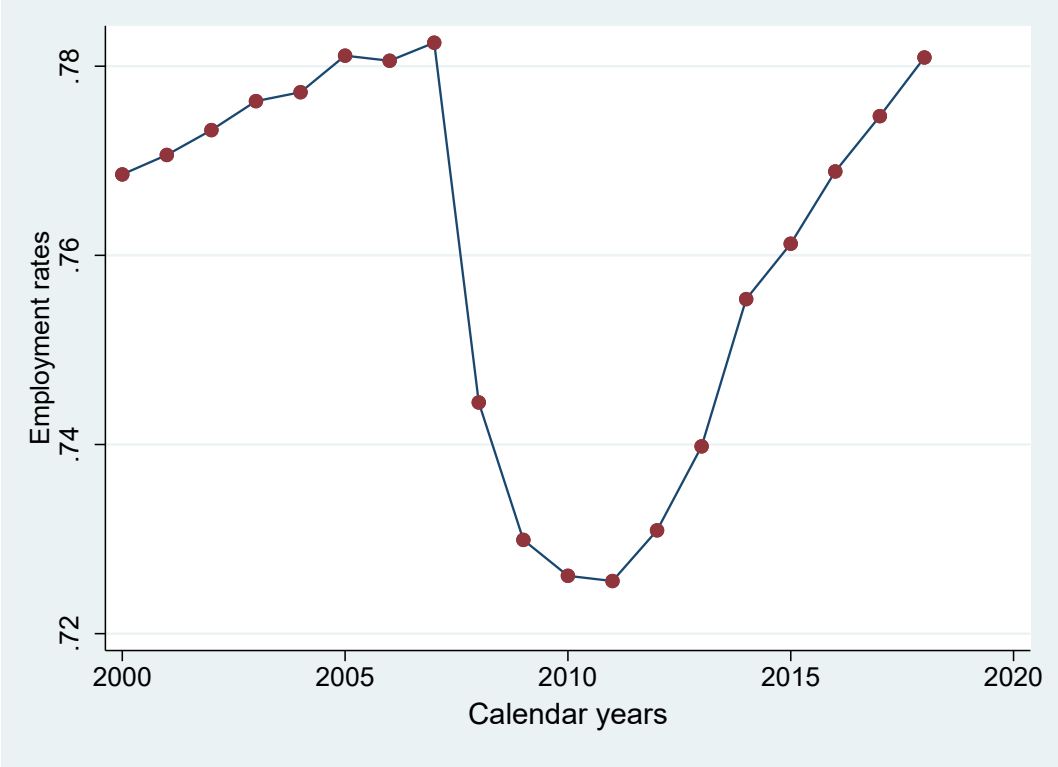
Notes: Analytical sample. The X-axis represents the week between date of birth and date of survey. Y-axis represents the employment rate. This figure plots the employment rates on the distance to the week of birth (which induces an increase in the age-dependent NMW).

Figure A.2. Employment rates based on tenure.



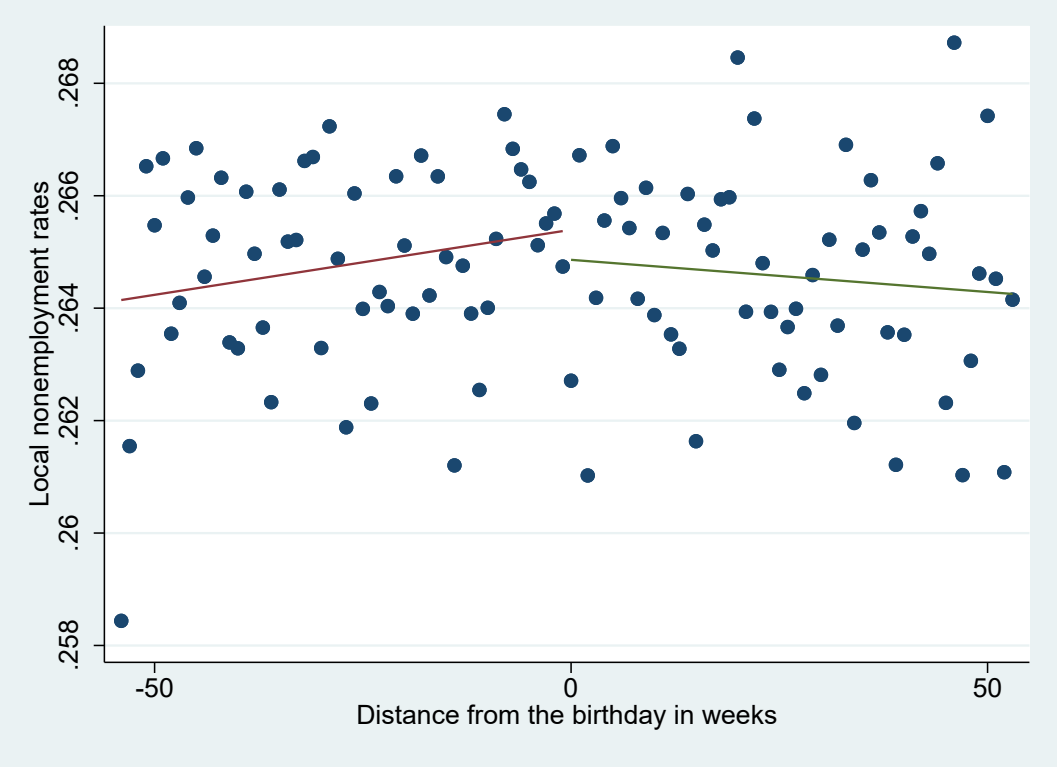
Notes: Analytical sample. The figure plots the proportions of newly hired workers and the average duration of employment against distances between month of survey and month of birth. Due to data limitations, we do not have accurate measures of when workers join or leave the same firms.

Figure A.3. Employment rate over time.



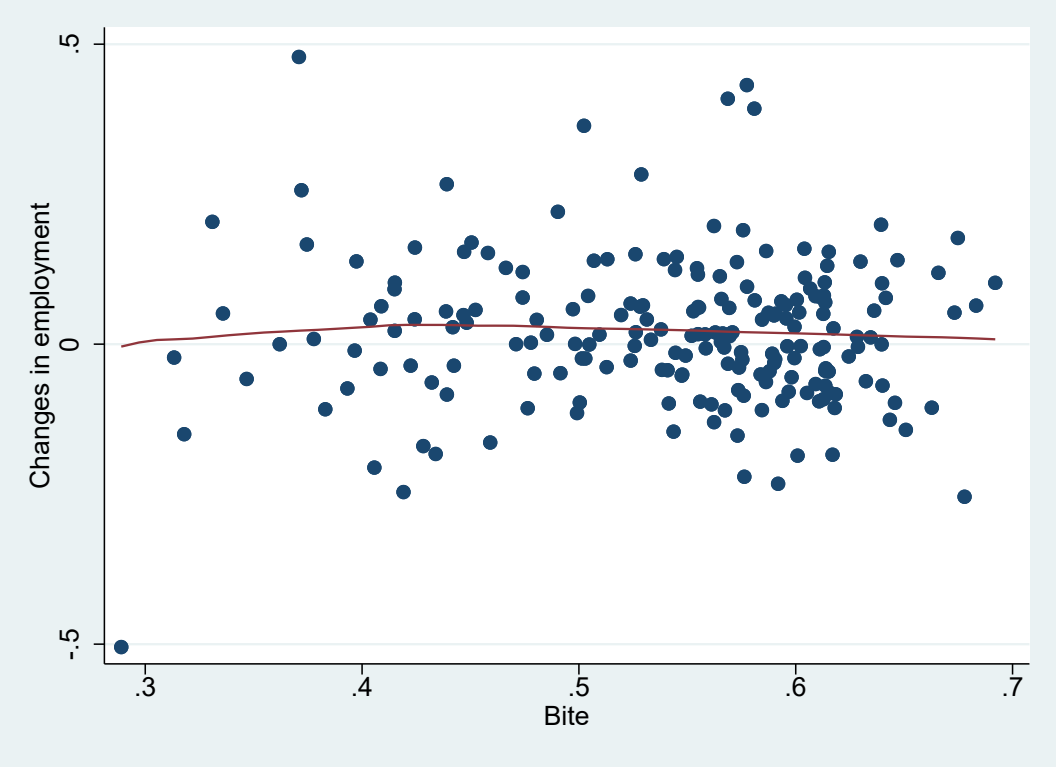
Notes: The employment rates are calculated for all workers between 25 and 65 years old.

Figure A.4. Discontinuity of non-employment rate.



Notes: Each point plots the average local non-employment rate against the distance from birthday in weeks.

Figure A.5. Relation between local "Bites" and changes in employment among low earners.



Notes: The graph plots changes in employment rate and local "bites" at the local authority level. We construct the average employment rate of low earners before and after increasing the minimum wage.

Table A.1. Discontinuity with procyclicality (excluding the month immediately preceding the cut-off).

Employ	(1)	(2)	(3)	(4)	(5)	(6)
Discontinuity	0.0697***	0.0675**	0.0734**	0.0652**	0.0751**	0.0843**
	(0.0228)	(0.0268)	(0.0299)	(0.0323)	(0.0377)	(0.0406)
Non-employment	-0.987***	-0.679***	-0.679***	-0.978***	-0.690***	-0.689***
	(0.0608)	(0.0690)	(0.0690)	(0.0882)	(0.0990)	(0.0990)
Procyclicality	-0.233***	-0.214**	-0.214**	-0.234**	-0.204*	-0.204*
	(0.0835)	(0.0831)	(0.0831)	(0.118)	(0.118)	(0.118)
Specifications:						
Age function	No	Quadratic	Cubic	No	Quadratic	Cubic
Window length	11 months	11 months	11 months	5 months	5 months	5 months
Controls	No	Yes	Yes	No	Yes	Yes
Observations	48,053	48,053	48,053	23,997	23,997	23,997
R-squared	0.015	0.027	0.027	0.015	0.028	0.028

Notes: The results are similar to Table 4, but excluding the month immediately preceding the cut-off point.

Table A.2. Discontinuity with procyclicality (excluding workers who are paid 20% above NMW).

Employ	(1)	(2)	(3)	(4)	(5)	(6)
Discontinuity	0.0665***	0.0853***	0.0950***	0.0643**	0.0990***	0.112***
	(0.0232)	(0.0265)	(0.0291)	(0.0322)	(0.0367)	(0.0402)
Non-employment	-0.972***	-0.703***	-0.703***	-0.979***	-0.730***	-0.730***
	(0.0603)	(0.0686)	(0.0686)	(0.0839)	(0.0950)	(0.0950)
Procyclicality	-0.226***	-0.215**	-0.215**	-0.220*	-0.201*	-0.201*
	(0.0846)	(0.0843)	(0.0843)	(0.117)	(0.117)	(0.117)
Specifications:						
Age function	No	Quadratic	Cubic	No	Quadratic	Cubic
Window length	12 months	12 months	12 months	6 months	6 months	6 months
Controls	No	Yes	Yes	No	Yes	Yes
Observations	45,191	45,191	45,191	22,550	22,550	22,550
R-squared	0.014	0.026	0.026	0.014	0.026	0.026

Table A.3. Discontinuity with procyclicality with varying window lengths (excluding the month immediately preceding the cut-off).

Employ	(1)	(2)	(3)	(4)	(5)
Discontinuity	0.0990***	0.104***	0.0798**	0.0835***	0.0864***
	(0.0368)	(0.0342)	(0.0322)	(0.0305)	(0.0290)
Non-employment	-0.717***	-0.723***	-0.768***	-0.711***	-0.706***
	(0.0951)	(0.0884)	(0.0831)	(0.0787)	(0.0747)
Procyclicality	-0.201*	-0.250**	-0.178*	-0.208**	-0.217**
	(0.117)	(0.109)	(0.102)	(0.0968)	(0.0920)
Specifications:					
Window length	6 months	7 months	8 months	9 months	10 months
Observations	24,390	28,157	31,975	35,715	39,442
R-squared	0.026	0.027	0.027	0.026	0.026

Notes: The results are based on quadratic term and full controls across various window lengths.

Table A.4. Placebo Test with regard to age cut-off

Panel A: Employment effect at 21 when 22 was the threshold (before 2010)

Employ	(1) 12 months at 21 when 22	(2) 6 months at 21 when 22	(3) 12 months at 21 when 22	(4) 6 months at 21 when 22
Discontinuity	0.000477	0.00324	-0.0190	-0.0181
	(0.0109)	(0.0156)	(0.0290)	(0.0415)
Non-employment			-0.917***	-0.923***
			(0.0842)	(0.122)
Procyclical			0.0759	0.0855
			(0.0988)	(0.142)
Observations	32,257	15,715	32,257	15,715
R-squared	0.022	0.021	0.028	0.027

Panel B: Employment effect at 22 when 21 was the threshold (2010 onwards).

Employ	(1) 12 months at 21 when 22	(2) 6 months at 21 when 22	(3) 12 months at 21 when 22	(4) 6 months at 21 when 22
Discontinuity	0.0171	0.0150	0.0151	0.0602
	(0.0183)	(0.0262)	(0.0530)	(0.0749)
Non-employment			-0.769***	-0.633***
			(0.149)	(0.209)
Procyclical			0.00393	-0.183
			(0.191)	(0.271)
Observations	11,306	5,673	11,306	5,673
R-squared	0.028	0.027	0.031	0.031

Panel C: Employment effect at one year before the threshold.

	(1)	(2)	(3)	(4)
Employ	12 months	6 months	12 months	6 months
Discontinuity	-0.00909	-0.00840	-0.0153	-0.0222
	(0.0143)	(0.0210)	(0.0279)	(0.0410)
Non-employment			-0.550***	-0.593***
			(0.0726)	(0.109)
Procyclical			0.0263	0.0563
			(0.0886)	(0.130)
Observations	42,592	19,775	42,592	19,775
R-squared	0.019	0.017	0.021	0.020

Panel D: Employment effect at one year after the threshold.

	(1)	(2)	(3)	(4)
Employ	12 months	6 months	12 months	6 months
Discontinuity	0.0197	0.0221	-0.0292	-0.0292
	(0.0140)	(0.0204)	(0.0405)	(0.0405)
Non-employment			-0.842***	-0.842***
			(0.105)	(0.105)
Procyclical			0.182	0.182
			(0.131)	(0.131)
Observations	41,921	19,995	19,995	19,995
R-squared	0.034	0.030	0.034	0.034

Notes: The placebo test is based on the change in the National Minimum Wage policy in 2010 which moved the age threshold from 22 years old to 21 year old. Panel A uses a false age threshold of 21 where the actual NMW age threshold is 22 for observations before 2010. Panel B uses a false age threshold of 22 when it should be 21 years for observations from 2010 onwards. Panels C and D shift the actual age threshold forward and backward by one year, respectively.

Table A.5. Wage effect.

Panel A, probability of earning below the NMW.

	(1)	(2)	(3)	(4)
Hourly pay	zero month	zero month	one month	one month
Discontinuity	-0.0358	-0.0913	-0.0879**	-0.173***
	(0.0436)	(0.0601)	(0.0408)	(0.0555)
Specification	Quadratic	Cubic	Quadratic	Cubic

Panel B, probability of earning below the NMW with procyclicality.

	(1)	(2)	(3)	(4)
Hourly pay	zero month	zero month	one month	one month
Discontinuity	0.0448	-0.0106	-0.0791*	-0.170***
	(0.0855)	(0.0947)	(0.0438)	(0.0554)
Non-employment	0.129	0.126	0.0163	0.127
	(0.232)	(0.232)	(0.193)	(0.200)
Procyclical	-0.303	-0.305	-0.0867	-0.311*
	(0.276)	(0.276)	(0.161)	(0.189)
Specification	Quadratic	Cubic	Quadratic	Cubic

Panel C, wage increase.

	(1)	(2)	(3)	(4)
Hourly pay	zero month	zero month	one month	one month
Discontinuity	0.429	0.460	0.411*	0.397
	(0.261)	(0.350)	(0.248)	(0.320)
Specification	Quadratic	Cubic	Quadratic	Cubic

Panel D, wage increase with procyclicality.

	(1)	(2)	(3)	(4)
Hourly pay	zero month	zero month	one month	one month
Discontinuity	0.287	0.269	0.279	0.341
	(0.521)	(0.572)	(0.256)	(0.313)
Non-employment	-12.81***	-12.81***	-13.10***	-13.08***
	(1.327)	(1.328)	(1.137)	(1.159)
Procyclical	0.327	0.327	0.896	0.854
	(1.632)	(1.633)	(0.905)	(1.066)
Specification	Quadratic	Cubic	Quadratic	Cubic

Notes: N=3661. The dependent variables of Panel A and B are a dummy for whether an individual earn below adult rate. The dependent variable of Panel C and D are the hourly wage. The first two columns include a discontinuity

when individuals are eligible for adult rate and the last two columns include a discontinuity when individuals are one month after being eligible for adult rate. We use the self-reported hourly wage information which is available in LFS 2002 onwards. The variable is not derived by the reported weekly payment and working hours and is only available when an individual produces a payslip at the interview showing an hourly wage.

Table A.6. Heterogeneity in discontinuity.

Panel A, looking for job and full-time jobs

	(1)	(2)	(3)	(4)
VARIABLES	looking	looking	Work hours	Work hours
Discontinuity	-0.00746	-0.00497	-0.140	-0.00681
	(0.00951)	(0.0184)	(0.614)	(1.168)
Non-employment		0.273***		-15.02***
		(0.0504)		(3.031)
Procyclical		-0.00967		-0.429
		(0.0599)		(3.775)
Observations	50,037	50,037	24,413	24,413
R-squared	0.021	0.022	0.054	0.055

Panel B, permanent jobs and working hours

	(1)	(2)	(3)	(4)
VARIABLES	permanent	permanent	full	full
Discontinuity	0.0229*	0.0680***	0.0162	0.0209
	(0.0133)	(0.0258)	(0.0130)	(0.0254)
Non-employment		-0.686***		-0.647***
		(0.0669)		(0.0656)
Procyclical		-0.166**		-0.0162
		(0.0820)		(0.0804)
Observations	50,037	50,037	50,037	50,037
R-squared	0.019	0.023	0.063	0.067

Panel C, by firm sizes

	(1)	(2)	(3)	(4)
Employ	Small firms	Small firms	Large firms	Large firms
Discontinuity	0.0201	0.0643**	0.0248	0.0888***
	(0.0152)	(0.0295)	(0.0157)	(0.0308)
Non-employment		-0.785***		-0.551***
		(0.0749)		(0.0768)
Procyclical		-0.161*		-0.234**
		(0.0925)		(0.0956)
Observations	37,688	37,688	33,103	33,103
R-squared	0.023	0.029	0.028	0.032

Panel D, by Industry Sectors

	(1)	(2)	(3)	(4)
Employ	Service	Service	Non-service	Non-service
Discontinuity	0.0295**	0.0833***	0.00176	0.0441
	(0.0143)	(0.0276)	(0.0144)	(0.0284)
Non-employment		-0.776***		-0.268***
		(0.0710)		(0.0687)
Procyclical		-0.197**		-0.154*
		(0.0873)		(0.0871)
Observations	43,728	43,728	27,219	27,219
R-squared	0.014	0.020	0.106	0.107

Notes: OLS estimates with robust standard errors based on analytical sample. Working hours refer to the actual working hours in a week. The age function is quadratic with full controls. Small firms include firms with less than 500 employees. Others belong to large firms. Non-service industry includes agriculture, production, and construction. Others belong to service business. *** p<0.01, ** p<0.05, * p<0.1.

Table A.7. Characteristics by regions.

Regions	Rate of Employment	Rate of Self-employment	Average Age	Age left full-time continuous education	Share of Whites
Tyne&Wear	0.633	0.033	21.174	17.055	0.923
Rest of Northern region	0.64	0.043	21.17	16.984	0.91
South Yorkshire	0.59	0.05	21.192	17.059	0.859
West Yorkshire	0.62	0.035	21.154	17.163	0.786
Rest of Yorks	0.684	0.033	21.177	17.21	0.927
East Midlands	0.695	0.041	21.148	17.098	0.863
East Anglia	0.683	0.059	21.144	17.205	0.9
Inner London	0.499	0.041	21.215	17.693	0.501
Outer London	0.634	0.057	21.19	17.514	0.648
Rest of South East	0.708	0.053	21.162	17.324	0.876
South West	0.711	0.063	21.148	17.321	0.909
West Midlands	0.567	0.033	21.167	17.09	0.718
Rest of West Midlands	0.725	0.045	21.154	17.212	0.906
Greater Manchester	0.642	0.041	21.151	17.07	0.842
Merseyside	0.611	0.029	21.183	16.952	0.903
Rest of North West	0.68	0.047	21.163	17.105	0.892
Wales	0.614	0.038	21.148	17.106	0.909
Strathclyde	0.631	0.028	21.191	17.106	0.905
Rest of Scotland	0.69	0.032	21.209	17.082	0.909
Northern Ireland	0.614	0.068	21.18	17.163	0.931
Total	0.66	0.046	21.167	17.205	0.855

Notes: The regions are the place where respondents usually live. “Age left full-time education” is the average age when leaving full time education.

Table A.8. Bite changes across regions.

	Bite (>25, all qualifications)			Bite (20-21, analytical sample)		
Regions	Before	After	Change	Before	After	Change
Tyne & Wear	0.6	0.61	0.01	0.72	0.87	0.15
Rest of Northern	0.59	0.6	0.01	0.7	0.88	0.18
South Yorkshire	0.6	0.61	0.01	0.7	0.86	0.16
West Yorkshire	0.59	0.58	-0.01	0.7	0.83	0.13
Rest of Yorkshire	0.62	0.61	-0.01	0.71	0.88	0.17
East Midlands	0.59	0.58	-0.01	0.71	0.87	0.16
East Anglia	0.58	0.58	0	0.69	0.84	0.15
Inner London	0.38	0.39	0.01	0.56	0.71	0.15
Outer London	0.44	0.43	-0.01	0.58	0.71	0.13
Rest of South East	0.48	0.49	0.01	0.65	0.79	0.14
South West	0.56	0.56	0	0.69	0.85	0.16
West Midlands	0.57	0.58	0.01	0.7	0.87	0.17
Rest of West Midland	0.57	0.57	0	0.7	0.86	0.16
Greater Manchester	0.57	0.58	0.01	0.7	0.87	0.17
Merseyside	0.57	0.57	0	0.74	0.88	0.14
Rest of North West	0.58	0.57	-0.01	0.72	0.89	0.17
Wales	0.59	0.59	0	0.72	0.89	0.17
Strathclyde	0.56	0.57	0.01	0.69	0.87	0.18
Rest of Scotland	0.55	0.55	0	0.73	0.86	0.13
Northern Ireland	0.6	0.6	0	0.72	0.91	0.19
Total	0.55	0.55	0	0.69	0.84	0.15

Notes: The first three columns describe the bites based on all working people above 25 years old. The last three columns describe the bite based on our analytical sample between 20 and 21 years old. The NMW "bite" measures the rate of minimum wage relative to median earnings. The variations of bite are used to measure to what extent minimum wage impacts a local labour market in applied research (Machine et al., 2003; Dolton et al., 2015).

In this section, we discuss the heterogeneous effect of geographic variations in the bite on the effect of increasing minimum wage. Due to the nature of its definition, the bite varies with increase in minimum wage and median earnings in the area, suggesting that it is a compound element. There is empirical evidence that median earning is an endogenous variable and will cause serious bias when estimating the 50/10 income ratio (Autor et al., 2016). Therefore, we think the bite is not a good measurement for local business environment. Table A.8 describes the local bites based on the adult sample and the analytical sample. It is clear to see that there is a significant increase in bite after increasing minimum wage based on analytical sample, while there is no change if the bite is constructed using full sample. Figure A.5 describes the relationship between local bites and changes in employment, similar to Figure 4. We do not observe a clear correlation between those two. We do not find strong impacts of local bite on the effect of increasing minimum wage, compared to when we use the local non-employment rate. The effect is stronger when excluding higher earnings. We suspect that the bites are more

endogenous and the heterogeneous effects of bites are not linear. For instance, areas with higher bites might have low median earnings but also high income inequality. Compared to the non-employment rate, the bite is much more complex and might interact with the age-dependent NMW in unpredictable ways.

Appendix B:

Let y_{1i} and y_{0i} denote the outcome with and without treatment respectively. $T_i = 1$ if treatment is received. The probability of receiving treatment is determined by the forcing variable z_i, such that treatment is a deterministic function of $f(T_i|z_i)$ and the probability is discontinuous at z_0.

The model can be written as $y_i = \alpha_i + \beta T_i$, where $\alpha_i \equiv y_{0i}$, $\beta = y_{1i} - y_{0i}$. There are necessary assumptions to identify a causal relationship in a heterogeneous RD design (Hahn et al. (2001)):

A1: The limits $x^+ = lim_{z \to z_0^+} E[T_i|z_i = \mathrm{z}]$ and $x^- = lim_{z \to z_0^-} E[T_i|z_i = \mathrm{z}]$ exist.

A2: $E(\alpha_i|z_i = z)$ $is\ continuous\ in\ z\ at\ z_0$

A3: $(\beta, T_i(z))$ is jointly independent of z_i near z_0 and there exists $\varepsilon > 0$ such that $T_i(z_0 + \mathrm{e}) \geq T_i(z_0 - \mathrm{e})$ for all $0 < e < \varepsilon$.

In a sharp design where all individuals respond to the treatment,

$$\beta = \frac{y^+ - y^-}{x^+ - x^-} \tag{B1}$$

where $y^+ = lim_{z \to z_0^+} E[y_i|z_i = \mathrm{z}]$ and $y^- = lim_{z \to z_0^-} E[y|z_i = \mathrm{z}]$

In most practical cases where only a proportion of observations will respond to the treatment, then the estimate becomes[17]

$$E[\beta|z_i = z_0] = \frac{y^+ - y^-}{x^+ - x^-} \tag{B2}$$

In a more general case where individuals are self-selected into a treatment, the treatment is assigned differently for different groups of people. Hahn et al. (2001) provide proof with a heterogeneous treatment. Then we have

$$lim_{e \to 0^+} E[\beta|T_i(z_0 + \mathrm{e}) - T_i(z_0 - \mathrm{e})] = \frac{y^+ - y^-}{x^+ - x^-} \tag{B3}$$

where $T_i(z_0 + \mathrm{e}) - T_i(z_0 - \mathrm{e})$ denotes the individual for whom treatment causes discontinuity at z_0. The estimate varies with different samples which include different observations having treatment changes at the threshold.

In a more general case, the estimate might be heterogenous even after controlling for covariates. It is related to the idea of "Essential Heterogeneity" from Heckman et al. (2006). The estimate would vary based on the willingness of receiving treatment in a self-selection scenario, leading to heterogeneous results. Lee (2008) argues that the discontinuity could be biased if unobserved factors affect the forcing variable and then the probability of taking treatment in a RD with non-random selection.

We introduce an external variable U_i that is independent from the treatment assignment D_i which it is only determined by the forcing variable. But it affects the expectation of people who eventually

[17] See Hahn et al. (2001) for the details.

respond to the treatment. In other words, it affects the probability of actually taking the treatment. In a scenario where treatment assignment is different from treatment response, results could be heterogenous without adjustment of taking the treatment. We allow the probability of taking the treatment to vary with the external factors.

$$y_i = \alpha_i + \beta T_i + U_i \tag{B4}$$

$$T_i = D_i + c_i U_i \tag{B5}$$

and assume c is consistent across individuals. D_i denotes the treatment assignment and is completely determined by the forcing variable. T_i denotes an individual receives the treatment and also is affected by the treatment. T_i can't be directly observed in the data. c_i has two values c_0 and c_1, denoting the impacts of exogeneous factor before and after the discontinuity respectively. They are constant, suggesting that an external factor affects the participation consistently. Equation (B5) is the responsiveness equation which is a function of the eligibility for treatment and the factors U_i which may affect the takeup of the treatment. A good example of such external factors is the local non-employment rate which reflects the tightness of the local labour market conditions.[18]

Together with the three assumption above, there are two more assumptions in our model.

A4: $E[U_i|z_i = \mathrm{z}]$ is continuous $in\ z\ at\ z_0$.

A5: The relationship between external factors and probability of taking treatment is linear, $E[T_i|z_i = \mathrm{z} + \mathrm{e}] = E[D_i|z_i = \mathrm{z} + \mathrm{e}] + E[c_1 U_i|z_i = \mathrm{z} + \mathrm{e}]$ and $E[T_i|z_i = \mathrm{z} - \mathrm{e}] = E[D_i|z_i = \mathrm{z} - \mathrm{e}] + E[c_0 U_i|z_i = \mathrm{z} - \mathrm{e}]$.

We extend the heterogeneous model (B3) to

$$E[\alpha_i + \beta T_i + U_i|z_i = z_0 + \mathrm{e}] - E[\alpha_i + \beta T_i + U_i|z_i = z_0 - \mathrm{e}]$$

$$= E[\beta T_i|z_i = z_0 + \mathrm{e}] - E[\beta T_i|z_i = z_0 - \mathrm{e}] + E[U_i|z_i = z_0 + \mathrm{e}] - E[U_i|z_i = z_0 - \mathrm{e}] + E[\alpha_i|z_i = z_0 + \mathrm{e}] - E[\alpha_i|z_i = z_0 - \mathrm{e}]$$

With A2, A4, and A5 assumptions, the equation leads to,

$$E[\beta T_i|z_i = z_0 + \mathrm{e}] - E[\beta T_i|z_i = z_0 - \mathrm{e},]$$

$$= E[\beta|T_i(z_0 + \mathrm{e}) - T_i(z_0 - \mathrm{e}) = 1]*\{E[D_i|z_i = z_0 + \mathrm{e}] - E[D_i|z_i = z_0 - \mathrm{e}] + E[c_1 U_i|z_i = z_0 + \mathrm{e}] - E[c_0 U_i|z_i = z_0 - \mathrm{e}]\}$$

And with A4, the equation leads to,

$$= E[\beta|T_i(z_0 + \mathrm{e}) - T_i(z_0 - \mathrm{e}) = 1]*\{E[D_i|z_i = z_0 + \mathrm{e}] - E[D_i|z_i = z_0 - \mathrm{e}] + E[(c_1 - c_0)U_i|z_i = z_0]\}$$

[18] The term non-employment differs from unemployment, as it captures all states other than paid employment. Importantly, it captures economically inactive and full-time education (Blondal and Pearson 1995).

Then we have

$$lim_{e\to 0^+} E[\beta | T_i(z_0 + \mathrm{e}) - T_i(z_0 - \mathrm{e}) = 1] = \frac{y^+ - y^-}{(d^+ - d^-) + E[(c_1 - c_0)U_i | z_i = z_0]} \quad \text{(B6)}$$

where $d^+ = lim_{z\to z_0^+} E[D_i | z_i = \mathrm{z}]$ and $d^- = lim_{z\to z_0^-} E[D_i | z_i = \mathrm{z}]$

$$lim_{e\to 0^+} E[\beta(1+\theta) | T_i(z_0 + \mathrm{e}) - T_i(z_0 - \mathrm{e}) = 1] = \frac{y^+ - y^-}{(d^+ - d^-)} = \hat{\beta} \quad \text{(B7)}$$

where we assume there is a linear relationship $(d^+ - d^-) + E[(c_1 - c_0)U_i | z_i = z_0] = (1 + \theta_i)(d^+ - d^-)$.

θ represents the correlation coefficient between response and the covariate and is negative because the response sample is no more than the sample which receives the treatment. c_1 is larger than c_0 because it is expected that U_i and T_i are positively correlated since higher non-employment rate may lead to more workers seeking a minimum wage related job. Moreover, other factors such as personal motivation may also make c_1 different than c_0. On the other hand, if c_1 equals to c_0, we may not observe the discontinuity to change.

Therefore, we can see the final sample as a heterogenous sample of $(d^+ - d^-)$, which suggests the actual affected sample is different in areas with different non-employment rate. The real heterogenous discontinuity is estimated by the individuals who change the treatment status discontinuously around the threshold, which consists of individuals who respond to the treatment status and take up the treatment $(T_i(z_0 + \mathrm{e}) - T_i(z_0 - \mathrm{e}) = 1)$.

The effect of treatment is determined by the individuals for whom treatment changes at z_0. And the effect $E[\hat{\beta}] = E[\beta^*] + E[\theta_i] * E[\beta^*]$. We only observe people who receive the treatment not the actual people who are eligible for the treatment. Hence, $\hat{\beta}$ is estimated based on D_i and it is correctly estimated only when $E(\theta)$ equals to 0. We argue that β is still unbiased if external factors are continuous at the threshold, such that external factors will not affect the outcome directly due to discontinuity, except for the fact that analytical sample could be affected, leading to heterogenous results. The estimated estimator could be decomposed into an average mean and heterogenous effect.

The model suggests that external variable can upward and downward affect the results if there is a change around the threshold in terms of the correlation between the probability of taking up treatment and external factors are positively or negatively correlated. In order to correctly specify the discontinuity, the external factors which could increase the heterogeneity should be addressed. It also suggests that the results would be still the same as when the external factors affect the responsiveness equation but the impacts remain the same before and after the threshold $(E[\theta] = 0)$. Failure to control for the unobserved factors which affect the response of treatment may lead to heterogeneous estimate of discontinuity.