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Do tax incentives for research increase firm innovation? An RD Design for R&D

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Abstract

We present the first evidence showing causal impact of research and development (R&D) tax incentives on innovation outcomes. We exploit a change in the asset-based size thresholds for eligibility for R&D tax subsidies and implement a Regression Discontinuity Design using administrative tax data on the population of UK firms. There are statistically and economically significant effects of the tax change on both R&D and patenting, with no evidence of a decline in the quality of innovation. R&D tax price elasticities are large at about 2.6, probably because the treated group is from a sub-population subject to financial constraints. There does not appear to be pre-policy manipulation of assets around the thresholds that could undermine our design, but firms do adjust assets to take advantage of the subsidy post-policy. We estimate that over 2006-11 business R&D would be around 10% lower in the absence of the tax relief scheme.

Keywords: R&D, patents, tax, innovation, Regression Discontinuity design

JEL codes: O31, O32, H23, H25, H32.

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1. Introduction

Innovation is recognized as the major source of growth in modern economies. But because of knowledge externalities, private returns on research and development (R&D) are typically much lower than their social returns, hence the need for some public subsidy.[1] As a consequence, every country treats R&D investments more generously than capital investment, but the majority of OECD countries (and many developing countries) also have additional fiscal incentives such as enhanced deductions for R&D. Over the last two decades, these tax incentives have grown more popular compared to more direct R&D subsidies to firms.[2] One reason for this shift is that subsidizing R&D through the tax system rather than direct grants reduces administrative burden and mitigates the risk of "picking losers" (i.e. choosing firms with low private and social returns due to political connections).

But do R&D tax incentives actually work? The existing literature has several serious shortcomings that we seek to address in this paper. First, researchers have mainly focused on the effects of taxes on *R&D* whereas the point of the policy is to try and stimulate *innovation.*[3] The tax incentive could increase observed R&D without having much effect on innovation if, for example, firms re-labeled existing activities as R&D to take advantage of the tax credits or only expanded very low quality R&D projects. We address this issue by analyzing the effect of R&D tax incentives not only on R&D expenditures but also on patenting activity (and other outcome measures such as firm size). We also look at the quality of these additional innovations through various commonly used measures of patent value.

A second problem with the literature it that it has proven difficult to come up with compelling causal designs to evaluate the impact of R&D tax policies. Evaluations at the macro-economic

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[1] Typical results find marginal social rates of return to R&D between 30% and 50% compared to private returns between from 7% to 15% (Hall, Mairesse and Mohnen, 2010). Endogenous growth theories (Romer 1990, Aghion and Howitt 1992) provide several reasons why private innovative activities do not take into account externalities over producers and consumers, and produce less than optimal innovations and growth. For evidence showing R&D externalities, see for example Bloom, Schankerman, and Van Reenen (2013). There is also evidence that these spillovers are partially localized geographically, so the country where the R&D is performed obtains a disproportionate share of the productivity benefits, at least initially.

[2] Over the period 2001-2011, R&D tax incentives were expanded in 19 out of 27 OECD countries (OECD 2014).

[3] There is a large literature on the effects of public R&D grants on firm and industry outcomes such as Einiö (2014), González, Jamandreu and Pazó (2005), Goodridge et al. (2015), Jaffe and Lee (2015), Lach (2002), Moretti, Steinwender and Van Reenen (2015) and Takalo, Tanayama, Toivanen (2013). The earlier literature is surveyed in David, Hall and Toole (2000).

(e.g. Bloom, Griffith and Van Reenen, 2002; Corrado et al., 2015) or state level (Wilson, 2009; Moretti and Wilson, 2015) face the problem that changes of policies are likely to be coincident with many unobserved factors that may influence R&D. On the other hand, variation at the firm level is often limited as the tax rules apply to all firms and the heterogeneity in tax prices that does exist are driven by firm choices (e.g. R&D spending, tax exhaustion, etc.).

To address this identification problem, we exploit a policy reform in the UK which raised the size threshold under which firms can access the more generous tax regime for small- and medium-sized enterprises (SME). Importantly, the new tax threshold introduced was unique to the R&D tax policy so it did not overlap with access to other programs or taxes. Prior to the major change in 2008 the threshold was based on the European Commission definition of an SME. Given this change in tax thresholds, we can implement a Regression Discontinuity (RD) Design (e.g. Lee and Lemieux 2010) looking at differences in R&D and innovation around the new SME threshold, which was based on accounting data pre-dating the policy change. To assess the validity of our design we confirm covariate balance and the absence of bunching of the running variable (assets) around the threshold prior to the policy change. And we can show that there were no discontinuities in R&D, patents or any other outcomes in the years prior to the policy change.

Third, data limitations have meant that the R&D tax credit literature focuses on large firms. Since R&D is concentrated, aggregated data will also be effectively dominated by large firms. Accounting regulations in most countries only insist on larger (usually public listed) firms reporting R&D, hence there has been a particular focus on US Compustat firms.[4] But since at least Arrow (1962) it is recognized that financial markets may under-supply credit for R&D and these problems are likely to be particularly acute for SMEs.[5] Hence, extrapolating from the innovation response of large firms to policy changes may be misleading. We use a new merged dataset containing the universe of UK firms. This combines confidential HMRC data (the UK equivalent of the US IRS) on R&D levels with firm accounts from the population of public and private firms as well as patents from 60 patent offices. The data is available before and after the R&D tax change.

We find large effects of the R&D Tax Scheme on R&D and patents. As a result of the

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[4] Rao (2014) has used US administrative tax data on the firm population to look at the impact of tax credits on R&D and Agrawal, Rosell and Simcoe (2014) look at the tax effect on investment for small private Canadian firms.

[5] Since R&D is mainly people, it is hard to post collateral to borrow against. Furthermore, asking outsiders for finance may reveal the innovation and so undermine its value.

policy, R&D approximately doubled in the treated firms and patenting rose by about 60% (and there is no evidence that these innovations were of lower value). We estimate an elasticity of R&D with respect to its tax-adjusted user cost of about 2.6 – higher than the values typical in the recent literature of between one and two.[6] We argue that the higher elasticity is likely to be because the sub-population "randomized in" by the RD Design is composed of smaller firms than have usually been examined and so are more likely to be credit constrained and therefore are also more responsive to R&D tax credits. We confirm this intuition by showing the response is particularly strong for young firms, presumably because they are more subject to credit constraints. Back of the envelope calculations suggest that between 2006 and 2011 the UK R&D Tax Relief Scheme induces £1.7 of private R&D for every £1 of taxpayer money and that aggregate UK R&D would have been about 16% lower in the absence of the policy. Given that we confirm the importance of positive R&D spillover effects to the innovation of neighboring firms, the policy appears to have succeeded in its intentions.

In terms of the existing literature, some papers have examined the causal impact of other types of innovation policy on R&D and other outcomes. These have used ratings given to grant applications as a way of generating exogenous variation around funding thresholds. Jacob and Lefgren (2010) and Azoulay et al. (2014) examine the impact of NIH grants. Bronzini and Iachini (2014) and Bronzini and Piselli (2014) use an RD Design for R&D subsidies in Italy.[7] Probably closest to our paper is Howell (2015) who uses the ranking of SBIR proposals for energy R&D. She finds significant effects of subsidies on future venture capital funding, especially for small firms.[8] Some papers have looked at the impact of R&D tax credits on non-R&D outcomes without an RD Design. For example, Bøler, Moxnes and Ulltveit-Moe (2015) employ a difference-in-differences strategy to investigate how the introduction of R&D tax credit in Norway affects profits, intermediate imports and R&D.[9]

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[6] See surveys by Becker (2015), OECD (2013) or Hall and Van Reenen (2000).

[7] The authors look at the impacts of R&D subsidies on investment and patents in Northern Italy in an RD Design (they do not have R&D data). In their setting the running variable is determined on the basis of scoring the project applications by a committee of experts. They observe a discontinuity in the score distribution around the eligibility cut-off, which they interpret as a sign of programme managers being able to assign higher scores for projects just below the cut-off to avoid appeals.

[8] She also finds effects on patents, but not on citations from Phase 1 funding.

[9] See also Czarnitki, Hanel, and Rosa (2011), Cappelen, Raknerud, and Rybalka (2012) and Bérubé and Mohnen (2009) who look at the effects of R&D tax credits on patents and/or new products. Branstetter and Sakakibara (2002) examine Research Joint Ventures and patents.

Our paper also contributes to the literature on the effects of R&D on innovation (e.g. Hall, Mairesse, and Mohnen, 2010). We find that R&D has a positive causal effect on innovation, with elasticities that are underestimated in conventional OLS approaches. More broadly, we provide evidence on the role of tax on a particular kind of investment (Hall and Jorgenson, 1967; Hassett and Hubbard, 2002).

The paper is organized as follows. Section 2 details the institutional setting of the tax relief policy; Section 3 explains the empirical design; Section 4 describes the data; Section 5 presents the main results and Section 6 some extensions. Section 7 concludes.

2. Institutional setting

We give more details of the institutional setting and tax policies in Appendix A (Table A1 details the policy changes over time), but summarize the most important features in this section. From the early 1980s the UK business R&D to GDP ratio fell, whereas it rose in most other OECD countries. In 2000, an R&D Tax Relief Scheme was introduced for small and medium enterprises (SMEs). It was extended to cover large companies in 2002, even though SMEs continued to enjoy more generous R&D tax relief. The policy costs the UK government £1.4bn in 2013 alone (Fowkes, Sousa and Duncan, 2015).

The tax policy is based on the total amount of R&D, i.e. it is volume-based rather than calculated as an increment over past spending like the US R&D tax credit. It works mostly through enhanced deduction of R&D from taxable income, thus reducing corporate tax liabilities. Only current R&D expenditures, such as labor and materials, qualify for the scheme, but since capital only accounts for about 10% of total R&D, this is less important (e.g. Cameron, 1996). At the time of its introduction, the scheme allowed SMEs to deduct an additional 50% of qualifying R&D expenditure from taxable profits (on top of the 100% that applies to any form of current expenditure). If an SME was not making profits, it could surrender enhanced losses in return for a payable *tax credit*[10] amounting to 16% of enhanced R&D.[11] This design feature was aimed at dealing with the well-known problem that smaller companies may not be making enough profits to benefit from

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[10] Throughout we will use "tax credit" to refer to this refundable element of the scheme as distinct from the "enhancement" element.

[11] Or equivalently, 24% (=16% x 150%) of total R&D expenditure. See Finance Act 2000 (Chapter 17, Schedule 20).

the *enhancement rate*. Large companies had a less generous deduction rate of 25% of their R&D and could not claim the refundable tax credits in the case of losses (Finance Act, 2002). The refundable aspect of the scheme is particularly beneficial to firms who are liquidity constrained and we will present evidence in line with the idea that the large responses we observe are related to the alleviation of financial constraints.

Aggregate business R&D intensity stabilized after the introduction of this R&D tax policy and Bond and Guceri (2012) suggest that these are causally connected. Guceri (2015) uses a difference-in-differences method across firm size classes to look at the effect of the introduction of the program and argues that the policy raised R&D by 20% in the affected firms. Fowkes et al. (2015) calculate the firm-specific user cost and instrument this with lagged values, also finding positive effects on R&D.

The policy used the SME definition recommended by the European Commission (EC) throughout most of the 2000s. This definition was based on employment, total assets, and sales[12] from the last two accounting years. It also takes into consideration company ownership structure and constrains variation in the SME status over time by requiring that in order to change its SME status, a company must fall in the new category two consecutive accounting periods (two-year rule). If a firm is below the threshold in year t, it must be above the threshold in both years $t+1$ and $t+2$ to lose its SME status in year $t+2$. Otherwise, it remains an SME in both subsequent years as it has been in year t.[13]

We focus on the major change to the scheme that commenced from August 2008. The SME assets threshold was increased from €43m to €86m, the employment threshold from 249 to 499 and the sales threshold from €50m to €100m.[14] As a result of these changes, a substantial proportion of companies that were eligible for the large company rate according to the old definition became eligible for the SME rate. In addition to the change in SME definition, the UK government also increased the enhancement rate for both SMEs and large companies in the same year. The

[12] We use the terms "sales", "turnover" and "revenue" interchangeably in the paper, except when more precise definitions are needed.
[13] For further details of the EC criteria see Recommendations 1996/280/EC and 2003/361/EC, summarized in Appendix A1.
[14] The other criteria laid down in the EC 2003 recommendation (e.g. two-year rule) were maintained in the new provision in Finance Act 2007 (Chapter 11). This act did not appoint a date on which new ceilings became effective. The date was appointed in the Finance Act 2007, Section 50 (Appointed Day) Order 2008 of July 16th 2008.

SME enhancement rate increased from 50% to 75%.[15] For large companies, the rate changed from 25% to 30%. The policy change implies a reduction in the tax-adjusted user cost of R&D from 0.19 to 0.15 for the newly-eligible SMEs whereas the user cost for large companies was basically unchanged (see sub-section 5.2 below and Table A11).

We examine the impact of this jump in tax-adjusted user cost of R&D at the new SME thresholds. The advantage of employing this reform instead of the other changes in the SME definition is twofold. First, unlike the previous thresholds based on the EU definition, which were extensively used in many other support programs targeting SMEs, the thresholds introduced in 2008 were specific to the R&D Tax Relief Scheme. This allows us to recover the effects of the R&D Tax Relief Scheme without confounding them with the impact of other SME schemes. Second, identifying the impacts around newly introduced thresholds mitigates biases arising from tax planning of R&D intensive firms which may cause endogenous bunching of firms around the thresholds. We show that firms did respond rationally by starting to bunch around the new thresholds in 2009 and afterwards. But we also demonstrate that there was no bunching around the threshold in 2007 (or earlier) and covariates were all balanced at the cutoff. This is important as although the policy was not completely detailed until July 2008 (and implemented in August 2008), aspects of the policy were understood in 2007 so firms may in principle have responded in advance. Information frictions, adjustment costs and policy uncertainty mean that this adjustment is likely to be sluggish, especially for the SMEs we study here.[16]

We will focus on assets as our key running variable. This is one of the three determinants of SME status and, unlike employment and sales, it does not suffer from missing values. We discuss this in detail in Section 4 and also consider using employment and sales in sub-section 6.4. We use the 2007 value of assets as this will matter for SME tax status in 2009 which depends on the past two accounting years as discussed above. Since the policy only began mid-way through 2008, it is inappropriate to use values in 2008 as a running variable. Nevertheless, we examine what happens when we consider other years for the running variable in robustness tests.

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[15] In parallel, the SME payable credit rate was reduced to 14% of enhanced R&D expenditure (i.e. 24.5% of R&D expenditure) to ensure that R&D tax credit falls below the 25% limit for state aid.
[16] Sluggish adjustment to policy announcements is consistent with many papers in the public finance literature (e.g. Kleven and Waseem, 2013).

3. Empirical strategy

We start with a simple R&D equation:

$$rd_{i,t} = \alpha_{1,t} + \beta_{FS,t}E_{i,2007} + f_{1,t}(z_{i,2007}) + \varepsilon_{1i,t} \quad (1)$$

where t = 2009, 2010, 2011 and $\varepsilon_{1i,t}$ is an error term. $rd_{i,t}$ is R&D the expenditure of firm i in year t and $E_{i,2007} = I\{z_{i,2007} \leq \tilde{z}\}$ is a binary indicator equal to one if assets in 2007 ($z_{i,2007}$) is equal to or less than the corresponding new SME threshold, $\tilde{z}$. The coefficient of interest β_{FS} estimates the effect of the difference in tax relief schemes between SMEs and large firms on firms' R&D spending. In an RD Design framework, the identification assumption requires that the distribution of all predetermined variables is smooth around the threshold, which is testable on observables. The identification is guaranteed when firms cannot manipulate their running variable, $z_{i,2007}$ (Lee, 2008). Under this assumption, eligibility, $E_{i,2007}$, is as good as randomly assigned at the cutoff. We consider year by year regressions of equation (1) as well as averaging over three post-policy years.

Equation (1) can be derived from the static first order condition of a firm with an R&D augmented CES production function (see Appendix A). We show how the elasticity of R&D with respect to its user cost can be derived in Section 5 below.

As is standard in RD Designs, we control for separate polynomials of the running variable on both sides of the assets threshold of €86m.[17] As noted above, because of the two-year rule, a firm's SME status in 2009 is partly based on its financials in 2007. These are unlikely to be manipulated by firms for tax planning purpose since the start date of the new SME definition (August 1st 2008) was only announced on July 16th 2008.[18] Using total assets in 2007 as our primary running variable thus mitigates the concern that there may have been endogenous sorting of firms across the threshold. Nevertheless, since there were discussions of the change in thresholds in late 2006 we are careful to check for continuity of observables around the thresholds even in 2007.

Notice that the "new SMEs", i.e. those who became SMEs only under the new definition,

[17] We also follow Gelman and Imbens's (2014) warning against using higher order polynomials, especially when higher order coefficients are not significant. We show in robustness checks that including higher order polynomials produce qualitatively similar results across all specifications.
[18] Finance Act 2007, Section 50 (Appointed Day) Order 2008 of July 16th 2008.

could only obtain the higher tax deduction rates on R&D performed after August 2008. Hence, to the extent that firms could predict the change in thresholds in early 2008 (or they could manipulate the reported timing of within year R&D), such companies would have an incentive to *reduce* 2008 R&D expenditures before August and increase them afterwards. To avoid these complexities with the transition year of 2008, we focus on 2009 and afterwards as full post-policy years.

Figure 1 shows that the distribution of firms' 2007 assets appears continuous around the new 2008 SME threshold of €86m. The McCrary test gives a discontinuity estimate (log difference in density height at the SME threshold) of -0.026 with a standard error of 0.088, which is close to and not significantly different from zero. Sub-section 6.3 discusses how there is also continuity in earlier years, but how this changes in later years in response to the policy switch.

In terms of innovative outputs we consider the following patent equation analogous to the R&D equation (1):

$$pat_{i,t} = \alpha_{2,t} + \beta_{RF,t}E_{i,2007} + f_{2,t}(z_{i,2007}) + \varepsilon_{2i,t} \tag{2}$$

where the dependent variable is the number of patents, $pat_{i,t}$. Under the same identification assumptions discussed above, β_{RF} estimates the causal effect of the policy on patents.

Finally we consider the "structural" patents equation:

$$pat_{i,t} = \alpha_{3,t} + \gamma_{3,t}rd_{i,t} + f_{3,t}(z_{i,2007}) + \varepsilon_{3i,t} \tag{3}$$

which can interpreted as a "knowledge production function" as introduced by Griliches (1979). Equations (1) and (3) correspond to a fuzzy RD model identifying the impact of additional R&D spending induced by the difference in tax relief schemes on firms' innovation output, using $E_{i,2007}$ as the instrument for R&D. With homogenous treatment effects, IV delivers the causal effect of R&D on patents under the exclusion restriction that the threshold indicator $E_{i,2007}$ does not affect innovation outputs through any other channel. With heterogeneous treatment effects, IV requires a monotonicity assumption that moving a firm's size slightly below the threshold always increases R&D. In this case, γ_3 is the Average Causal Response (Angrist and Imbens 1995), a generalization of the Local Average Treatment Effect that averages (with weights) over firms' causal responses of innovation outputs to small changes in R&D spending due to the IV.

4. Data

4.1 Data sources

Our data comes from three main sources: (1) HMRC Corporate Tax returns (CT600) and its extension, the Research and Development Tax Credits (RDTC) dataset, which provide data on the universe of UK firms and importantly includes firm's R&D expenditures as claimed under the R&D Tax Relief Scheme, (2) Bureau Van Dijk's FAME company dataset which provides data on the accounts of the universe of incorporated firms, and (3) PATSTAT which has patent information on all patents filed by UK companies in the main 60 patent offices across the world.

CT600 is a confidential administrative panel dataset provided by HMRC Datalab (the UK IRS) which consists of tax assessments made from the returns for all UK companies liable for corporation tax. It is made accessible to researchers only since 2011 and ours is among the first papers to use this dataset. The dataset covers financial years 2000-01 to 2011-12[19], with close to 16 million firm by year observations, and contains all information provided by firms in their annual corporate tax returns. We are specifically interested in CT600's RDTC Tax Credits dataset, which consists of all information related to the R&D Tax Relief Scheme including the amount of qualifying R&D expenditure each firm has in a year and the scheme under which it makes the claim (SME vs. Large Company Scheme).

Firms made a total of 53,000 claims between 2006 and 2011 (22,000 claims over 2006-08 and 31,000 claims over 2009-11), about 80% of which are under the SME Scheme. Total claims amounted to £2.5bn in R&D tax relief in total between 2006 and 2008 and £3.3bn between 2009 and 2011.[20]

We only observe R&D when firms seek to claim R&D tax relief and all the firms in the sample are eligible for some sort of R&D tax relief (it is just that the generosity differs depending on size). Ideally, we would also use R&D data from other sources, but UK accounting regulations (like the US regulation of privately listed firms) do not insist on SMEs reporting their R&D, so

[19] The UK fiscal year runs from April 1st to March 31st so 2001-02 refers to data between April 1st 2001 and March 31st 2002. In the text we refer to the financial years by their first year, so 2011-2012 is denoted "2011".

[20] It is currently not possible to merge CT600 with the BERD firm survey which is used to build the national estimate of R&D. The BERD survey (like US BERDIS) is a stratified random sample with very partial coverage of SMEs, however, so there would again be partial coverage.

there are many missing values. Statistics provided by internal HMRC analysis indicate that qualifying R&D expenditure amounts to 70% of total business R&D (BERD).[21] Note that the other outcomes (like patents) are observed for all firms, regardless of R&D status.

CT600 makes it possible to determine the SME status of firms who claim the R&D tax relief, but not the SME status of firms who are *not* claiming (the vast majority of firms). Employment and total assets are not available because such information is not directly required on corporate tax forms. Furthermore, only tax-accounting sales is reported in CT600, while the SME definition is based on financial-accounting sales as reported in company accounts.[22] Consequently, we turn to a second dataset, FAME, which contains all UK company accounts since about the mid-1980s. We match CT600 to FAME by an HMRC-anonymized version of company registration number (CRN), which is a unique regulatory identifier in both datasets. We merged 95% of CT600 firms between 2006 and 2011 with FAME and these firms cover close to 100% of R&D performing firms and patenting firms. Unmatched firms are slightly smaller but not statistically different from matched ones across different variables reported in CT600, including sales, gross trading profits, and gross and net corporate tax chargeable (see Appendix B4).

All firms are required to report their total assets in company accounts, but reporting of revenues and employment is mandatory only for larger firms. In our 2006 to 2011 FAME sample, only 5% of firms reported employment and only 15% reported sales. By comparison 97% reported assets. Even in our baseline sample of relatively larger firms around the SME asset threshold of €86m, employment and sales coverage is still only reported by 55% and 67% of firms respectively. For this reason, we only focus on exploiting the SME asset threshold with respect to total assets and use this as the key running variable in our baseline specification. Financial variables are reported in sterling while the SME thresholds are set in euros, so we convert assets and sales using exactly the same tax rules used by HMRC for this purpose. In addition, FAME provides industry, location, capital investment, profits, remuneration, etc., though coverage differs across variables.

We use assets from FAME as our key running variable, but also experiment with using

[21] There are various reasons for this difference, including the fact that BERD includes R&D spending on capital investment whereas qualified R&D does not (only current expenses are liable). It is also the case that HMRC defines R&D more narrowly for tax purposes that BERD which is based on the Frascati definition.

[22] Tax-accounting sales turnover is calculated using the cash-based method, which focuses on actual cash receipts rather than their related sale transactions. Financial-accounting turnover is calculated using the accrual method, which records sale revenues when they are earned, regardless of whether cash from sales has been collected.

sales to determine SME status, despite the greater number of missing values. In principle, using both running variables should increase efficiency, but in practice (as we explain in sub-section 6.4) it buys us less than what we hoped for. There are too many missing values on employment to use this as an alternative running variable. Note that these are all efficiency issue. The fact that we use only one of the three criteria for determining eligibility does not violate the assumptions for RD Design, it just reduces the precision of our estimates (and changes the interpretation of the estimate in the heterogeneous treatment model).

The third dataset we exploit is PATSTAT, a database curated by the European Patent Office (EPO). PATSTAT is the largest available international patent database and covers close to the population of all worldwide patents since the 1980s. It brings together nearly 70 million patent documents from over 60 patent offices, including all of the major offices such as the European Patent Office, the United States Patent and Trademark office (USPTO) and the Japan Patent Office (JPO). Patents filed with the UK Intellectual Property Office (UK IPO) are also included. To assign patents to UK-based companies we use the matching between PATSTAT and FAME implemented by Bureau Van Dijk and available from the ORBIS database. The quality of the matching is excellent: over our sample period, 94% of patents filed in the UK and 96% of patents filed at the EPO have been successfully associated with their owning company. We select all patents filed by UK companies between 1980 and 2013.[23] Our dataset contains comprehensive information from the patent record, including application date, citations, and technology class. Importantly, PATSTAT includes information on patent families, which are sets of patents protecting the same invention across several jurisdictions. This allows us to identify all patent applications filed worldwide by UK-based companies and to avoid double-counting inventions that are protected in several countries.[24]

In our baseline results, we use the number of patent families – irrespective of where the patents are filed – as a measure of the number of inventions for which patent protection has been sought. This means that we count the number of patents filed anywhere in the world by firms in our sample, whether at the UK, European or US patent office, but we use information on patent

[23] To avoid double counting, a patent filed by more than one firm is distributed equally among the firms. For example, a patent filed by 2 firms is counted as 0.5 for each of the firms.

[24] This means that thanks to patent family information our dataset includes patents filed by foreign affiliates of UK companies overseas that relate to an invention filed by the UK-based mother company. However, patents filed independently by foreign affiliates of UK companies overseas are not included.

families to make sure that an invention patented in multiple jurisdictions is only counted once. Patents are sorted by application year. Our measures use all patent application to avoid artificially truncating the sample, as the granting of a patent is a long administrative process (3.3 years on average in the UK, see Dechezleprêtre, 2013).

Numerous studies have demonstrated a strong link between patenting and firm performance.[25] Nevertheless, patents have their limitations (e.g. Hall et al., 2013). To tackle the problem that the value of individual patents is highly heterogeneous, we (i) show results separately for high value EPO patents vs. UK patents, (ii) use data on patent families and (iii) weight by patent citations. It has been demonstrated that the number of countries in which a patent is filed and the number of citations received by a patent in subsequent patents are both correlated with other indicators of patent value.[26]

4.2 Baseline sample descriptive statistics

We construct our baseline sample from the above three datasets. Our baseline sample contains 5,888 firms with total assets in 2007 between €61m and €111m which survive[27] at least until 2008 based on a €25m bandwidth around the threshold, with 3,651 firms under the €86m SME asset threshold and 2,327 firms above the threshold. The bandwidth of €25m is somewhat arbitrary, so we show robustness to a range of alternative bandwidths.[28] Our key outcome variables include amount of qualifying R&D expenditure, and number of patents filed. All nominal variables are converted to 2007 price using the UK Consumer Price Index (CPI), and all outcome variables are winsorized at 2.5% of non-zero values to mitigate the leverage of outliers.[29] In 2006-08 224 of these firms had positive R&D and this number rose to 254 over 2009-11 (roughly 5% of aggregate R&D expenditure). 210 firms filed 327 patents over 2006-08, and 157 firms filed 285 patents over 2009-11.

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[25] For example, see Hall, Jaffe and Trajtenberg (2005) on US firms or Blundell, Griffith and Van Reenen (1999) on UK firms.
[26] Lanjouw et al. (1998), Harhoff et al. (2003), Squicciarini et al. (2013), Hall et al. (2005), Lanjouw and Schankerman (2004).
[27] Firms who die are kept in the sample to avoid selection bias, but are given zero R&D.
[28] The Imbens and Kalyanaraman (2011) optimal bandwidth for using R&D as the outcome variable is 22, which is close to our baseline choice of 25.
[29] This is equivalent to "winsorizing" the R&D of the top 5 to 6 R&D spenders and the number of patents of the top 2 to 4 patenters in the baseline sample each year. We also show robustness to excluding outliers instead of winsorizing outcome variables.

In the 2006-2008 period firms below the threshold spent on average £57,800 per annum on R&D and firms above the threshold spent an average of £94,500 (with an overall average of £72,300). After the policy between 2009 and 2011 these numbers changed to £72,000 and £93,600. In other words, the gap in R&D spending between the two groups of firms almost halved from £36,700 pre-policy to £21,600 post-policy. In terms of innovation outputs, the average number of patents per annum was similar between the two groups of firms before the policy change (0.06), while after the policy change, firms below the SME asset threshold filed 30% more patents than those above the threshold (0.06 vs. 0.04). Detailed descriptive statistics by year across the two groups are in Table 1.

These "difference in differences" estimates are consistent with our hypothesis that the 2008 policy change induces firms below the new SME asset threshold, which are more likely to benefit from more generous tax relief under the SME scheme, to increase their R&D and patents. Gureci (2015) and Guceri and Li (2015) come to the same conclusion using a difference in difference approach.[30] However, there could be differential time trends correlated with size which could confound these simple comparisons between smaller and larger firms. We now turn to implementing the RD Design of equations (1)-(3) to investigate the causal effects directly.

5. Results

5.1 Main results

Table 2 reports R&D regressions (equation (1)). The key explanatory variable is whether the firm's total assets in 2007 was below the new SME asset threshold of €86m. The sample is limited to firms with total assets in 2007 between €61m and €111m (a €25m bandwidth around the threshold), and the running variable is the firms' total assets in 2007. Looking at each of the three "pre-policy" years 2006-2008 in columns (1) to (3), we find that as expected there is no significant discontinuity in R&D at the asset threshold before the new SME definition became effective toward the end of 2008.[31] In the next three columns we observe that from 2009 onward, firms just

[30] Unlike our paper they look only at R&D, however, and not patents or other firm performance outcomes. Furthermore, they condition on R&D performing firms which (i) creates selection issues and (ii) means that they cannot look at the extensive margin (i.e. they cannot examine whether any firms start or stop performing R&D as a result of the tax changes).

[31] The point estimate of 32 in 2008 is a third smaller than in 2007 (although both are insignificant). This could be

below the SME threshold have significantly more R&D than firms just above the threshold. Column (7) averages the three pre-policy years and column (8) the three post policy years. The discontinuity implies a causal annual effect of £138,500 per firm, compared to an insignificant effect pre-policy. Column (9) presents the difference between columns (8) and (7) and even in this specification there is a causal effect of £75,300. Although formally, the absence of a pre-policy trend implies that we do not need to take account of the trend, we consider this a conservative approach.[32] An effect of £75,300 per annum about doubles the average R&D per annum observed in the pre-policy period (£72,300), suggesting that the policy had a substantial impact from an economic as well as statistical perspective.

Figure 2 shows visually the discontinuous jumps in R&D at the SME asset threshold of €86m. While total assets correlate positively with both outcome variables in the regions just above and just below the threshold, as shown by the upward sloping regression lines, right across the threshold, there is a sudden jump in R&D expenditure. The size of the jump corresponds to the estimate in column (8) of Table 2 and is statistically significant at the 5% level.

Table 3 directly checks our RD identification assumption by looking at covariate balance. Firms right below and above the threshold are similar to one another in their observable characteristics prior to the policy change. The differences in sales, capital, and employment between the two groups of firms in 2006 and 2007 are both small and statistically insignificant in columns (1) through (6). After the policy change, we should not observe any discontinuity in R&D around any asset threshold other than the true SME asset threshold of €86m. To test this we ran a series of placebo tests on "pseudo" thresholds and found no significant effects. In column (7) we use a lower threshold of €71m with as an upper bound the true threshold of €86m and as a lower bound €46m (€25m below the lower pseudo-threshold as in the baseline). In column (8) we use a higher threshold of €101m with as a lower bound the true threshold of €86m and as an upper bound €116m (€25m above the higher pseudo-threshold). Neither experiment yield statistically significant effects. We also run similar placebo tests using all possible integer "pseudo" thresholds between

because firms were delaying their R&D in the start of 2008 (before the R&D threshold was changed) to the latter part of 2008 or even 2009. The fact that the policy effect in 2010 and 2011 are larger than 2009 makes this somewhat unlikely, but does highlight the difficulty of interpreting the 2008 data (which is another reason for using 2007 as the running variable).

[32] Alternatively we can condition directly on lagged R&D in the regressions. In Table A3, column (4) shows that we obtain treatment effects (standard error) of £82,000 (36,400) when we do this over the 2009-11 period.

€71m and €101m with a bandwidth of €25m as in the baseline specification (we allow the true threshold of €86m to be included in some samples in this experiment). Figure A1, which plots the resulting coefficients and their 95% confidence interval against the corresponding thresholds, shows that the estimated discontinuities in R&D peaks at the true threshold of €86m, while they are almost not statistically different from zero anywhere else.

Our results are robust to a wide range of robustness tests (see Table A3). We follow Gelman and Imbens' (2014) advice in using a first order polynomial for the running variable, especially as higher order terms are insignificant. If we add a second order polynomial to the baseline specification of column (8) in Table 2, the treatment effect (standard error) is larger at 171.2 (87.4) and the coefficient (standard error) on the first and second order assets terms are 0.1 (0.6) and 0.3 (0.7).[33] Second, the discontinuity is also robust to adding lagged dependent variable controls, industry and/or location fixed effects.[34] Third, we obtain statistically significant effects of comparable magnitude when using a Poisson specification instead of OLS.[35] Fourth, the discontinuity remains significant when we narrow the sample bandwidth or when we give more weights to firms closer to the asset threshold.[36] Finally, our estimates are robust to the choice of winsorization.

Table 4 reports the patent regressions (equation (2)) using the same specification and sample as Table 2. As with R&D, the first three columns show no significant discontinuity around the threshold for patenting activity prior to the policy 2006-08. By contrast, there is a significant increase in patenting in the post-policy period from 2009 onward (columns (3) to (6)). According to column (8) there is a significant average increase of 0.073 patents per year per firm as a result of the policy. The coefficient for the pre-policy period is half the size and statistically insignificant (column (7)). If we use the before and after differences, this is still significant at 0.035, and is a

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[33] If we add a third order polynomial the treatment effect rises further to 175.3, but is no longer statistically significant. The F-test on joint significance of the four higher order terms, however, is 1.05 (corresponding p-value of 0.38), suggesting they are not needed (they are all individually insignificant as well).

[34] Adding R&D in 2007 or average R&D over 2006-08 as a control variable gives coefficients (standard error) of 75.5 (37.6) and 82.0 (36.4) respectively, similar to result from the baseline after-before design. Adding industry (4-digit SIC) fixed effects or location (2-digit postcode) fixed effects gives coefficients (standard errors) of 125.6 (61.2) and 107.4 (49.5) respectively.

[35] We do this to allow for a proportionate effect on R&D (as in a semi-log specification). Using Poisson specification gives treatment effects (standard errors) of 1.62 (0.57) without lagged dependent variable control and 1.08 (0.54) when controlling for R&D in 2007. This is similar to the proportionate effects in Table 2.

[36] Using bandwidths of €35m or €15m gives coefficients (standard errors) of 43.6 (43.5) and 182.0 (73.5) respectively. Using Epanechnikov-kernel weights or triangular-kernel weights gives coefficients (standard errors) of 148.6 (57.8) and 151.9 (60.8).

substantial increase over the pre-policy sample mean of 0.060 (i.e. 58% more patents). This is a key result, as the R&D policy was not based on patents, so there is no danger similar to the case of relabeling existing activities as research. It may be surprising that the patent response is so speedy, but patent applications are usually timed quite closely to research expenditures in most sectors (e.g. Hausman, Hall and Griliches, 1984).

Figure 3 illustrates the discontinuity in the total number of patents filed over 2009-11 at the SME asset threshold of €86m, which corresponds to the estimate column (8) of Table 4. As with R&D there is clear evidence of the discontinuity in innovation outcomes at directly the point of the tax threshold. Furthermore, "pseudo" threshold tests similar to those discussed in Table 3 show that the estimated discontinuities in patent counts peak at the real SME threshold of €86m and are not statistically different from zero elsewhere (Figure A2).

We ran all the robustness tests discussed for the R&D equation also on the patent regressions (see Table A4), including adding higher order polynomials of the running variables, lagged dependent variables, industry and location controls, using the Poisson specification, widening or narrowing the sample bandwidth, giving more weights to firms closer to the SME asset threshold, changing the winsorization parameter, etc. The results were robust.[37]

As patents vary widely in quality, one important concern is that the additional patents induced by the policy could be of lower value. Table 5 investigates this possibility by considering different ways to control for quality. Column (1) reproduces our baseline results of patent counts. Column (2) counts only patents that are filed at the European Patent Office (EPO). It is around six times more costly to file a patent at the EPO than just at the UK patent office.[38] Consequently, EPO patents are likely to be of higher value – only about a third of firms who filed UK patents in our sample also filed at the EPO. It is clear that there is a significant and positive effect on these high value patents and on the lower value patents filed in the UK (but not necessarily elsewhere)

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[37] Adding patents in 2007 or average patents over 2006-08 as a control variable gives coefficients (standard errors) of 0.041 (0.021) and 0.043 (0.018) respectively, similar to result from the baseline after-before design. Adding industry (4-digit SIC) fixed effects or location (2-digit postcode) fixed effects gives coefficients (standard errors) of 0.069 (0.035) and 0.075 (0.027) respectively. Using Poisson specification gives treatment effect (standard errors) of 1.52 (0.50). Using bandwidths of €35m or €15m gives coefficients (standard errors) of 0.045 (0.025) and 0.071 (0.049) respectively. Using Epanechnikov-kernel weights or triangular-kernel weights gives coefficients (standard errors) of 0.071 (0.027) and 0.070 (0.029).

[38] Filing a patent at the European Patent Office costs around €30,000 (Roland Berger, 2005). In contrast, filing a patent at the UK IPO costs £3,000 to £5,000 (i.e. €4,000 to €6,000).

as shown in column (3). Although the point estimate is larger for UK patents than EPO patents (0.094 vs. 0.37), so is the mean (see base of the column), so the proportionate increase in patents is by a factor of about 1.2 in both columns (0.037/0.031 and 0.094/0.077).

As an alternative measure of patent value, we use data on family size, i.e. we count the number of jurisdictions in which each invention is patented (see Lanjouw, Pakes and Putnam, 1998). Since firms have to bear administrative costs for taking out intellectual protection in each country, the larger the family size, the more valuable the patent is likely to be (Harhoff et al., 2003). Compared to citations (see below), an advantage of patent family as a quality indicator is that all patent applications of the same invention need to be filed within (at most) 30 months after the first filing date. Hence, information on family size is available more quickly than patent citations. Column (4) of Table 5 uses this measure as a dependent variable and again finds a significant causal effect, showing almost a doubling of patenting activity.[39]

Concerns have been raised, especially in the US, that many patents are of dubious value and standards have slackened (e.g. business processing methods like Amazon's "one click" patent). It is generally agreed though, that patents in chemicals (such as biotechnology or pharmaceutical patents) remain of high value. Consequently, column (5) looks at chemical patents as an outcome and column (6) at non-chemical patents. Both dependent variables show a positive and significant effect of the policy with proportionate effects which are, if anything, larger in the "high quality" chemical patent sector.[40]

Finally, counting citations made by subsequent patents are a popular method of accounting for patent value (Lanjouw and Schankerman, 2004; Hall et al., 2005). If we weight EPO patents by future citations we obtain a coefficient (standard error) of 0.004 (0.002) as shown in column (7) of Table 5. In column (8), the UK measures are similar in proportionate terms, but insignificant at conventional levels. [41] However, we need to keep in mind that our data is very recent. For example, patents applied for in 2011 will have been published in 2012 or 2013 and hence will have

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[39] We also look at average family size per patent as a measure of patent value (we assign average family size value of zero to firms with no patents). The resulting coefficient (standard error) of 0.0038 (0.0314) is also positive, although not statistically significant.

[40] If we narrow the outcome still further to only bio-pharmaceutical patents the coefficient (standard error) is even larger in proportionate terms: 0.013 (0.006) on a pre-policy mean of 0.005.

[41] The coefficients (standard errors) obtained when we weight UK patents or all patents by future citations are 0.023 (0.021) and 0.012 (0.012) respectively. We also look at average citations per patent as a measure of patent value (again, we assign average citations value of zero to firms with no patents). This gives coefficients (standard errors) of 0.0010

had very little time to be cited.[42]

In summary, there is no strong evidence from Table 5 of any fall in innovation quality as a result of the policy.

Table 6 reports IV patents regressions where the key right hand side variable, R&D, is instrumented by the discontinuity in the tax threshold.[43] Column (1) presents the OLS version which shows a positive association between patents and R&D. Column (2) presents the IV results which increases the coefficient substantially (although the two estimates are not statistically different on the basis of the Hausman test presented at the base of the column). The IV estimate implies that one additional patent costs on average £1.9m (= 1/0.53) in additional qualifying R&D expenditure. Columns (3) and (4) show OLS and IV results for EPO and the final two for UK patents. All have significant effects, though larger for IV than OLS. The corresponding costs for one additional UK patent or one additional EPO patent is £1.5m and £3.7m respectively (columns (4) and (6)), which reflects that fact that only inventions of higher value typically get patented at the EPO. These figures are broadly in line with the existing estimates for R&D costs per patent of \$1m to \$5m.[44] We again subject these IV regression to the robustness tests discussed for the first stage and reduced form regressions to show that the magnitudes are robust (Table A5).

5.2 Magnitudes and tax-price elasticities

What is the implied elasticity of R&D with respect to its tax-adjusted user cost? Following the existing literature,[45] we define the elasticity as the percentage increase in R&D capital with respect to the percentage increase in the tax-adjusted user cost of R&D capital. In our setting, the tax-price elasticity of R&D η is given by:

$$\eta = \frac{\ln(rd_{SME}/rd_{LCO})}{\ln(\rho_{SME}/\rho_{LCO})}$$

(0.0010) for EPO patents and -0.0015 (0.0028) for UK patents. Both estimates are statistically insignificant.

42 Patents are published 18 months after the application date.

43 In the corresponding IV model, the estimate of the first-stage effect of the instrument on R&D is the coefficient on the threshold dummy in column (8) of Table 2.

44 Hall and Ziedonis (2001); Arora, Ceccagnoli, and Cohen (2008); Gurmu and Pérez-Sebastián (2008); Dernis et al. (2015).

45 For example, Hall and Jorgenson (1967) or Bloom, Griffith, and Van Reenen (2002).

where rd_{SME} and rd_{LCO} are the R&D of a firm under the SME scheme and under the large companies ("LCO") scheme respectively,[46] and ρ_{SME} and p_{LCO} are the tax-adjusted user cost of R&D facing the firm faces under the corresponding schemes.

Table 2 column (9) generates a treatment effect of £75,300, about a doubling over the pre-policy average R&D of £72,300.[47] Using these figures for our baseline tax-price elasticity calculation gives us a log difference in R&D of $\ln(rd_{SME}) - \ln(rd_{LCO}) = \ln(75.3 + 72.3) - \ln(72.3) = 0.71$.[48] We calculate the tax-adjusted user cost, ρ_f, based on the actual design of the R&D Tax Relief Scheme (see Table A1 and Appendix A4 for more details):

$$\rho_f = \frac{(1 - A_f)}{(1 - \tau_f)}(r + \delta)$$

where sub-script f denotes whether the firm is an SME or larger firm, A is the value of R&D tax relief, τ is the effective corporate tax rate, r is the real interest rate and δ is the depreciation rate. As described in Section 2, the R&D Tax Relief Scheme includes a tax deduction feature for firms with corporate tax liability with different enhancement rates under the SME and large company schemes and a payable tax credit feature for firms with no corporate tax liability only under the SME scheme.[49] In the case of tax deduction, the value of the tax relief A_d is $A_d = \tau(1+e)$ where e is the enhancement rate (which is 75% for SMEs and 30% for large companies in 2009-10 and 100% for SMEs and 30% for large companies in 2011). In the case of payable tax credit, the value of the tax relief A_c is $A_c = c(1+e)$ where c is the payable tax credit rate (which is 14% for SMEs in 2009-11 and 12.5% for SMEs in 2011 and always zero for large companies). Finally, the average tax-adjusted user cost of R&D under each scheme is an average of the user costs under each case,

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[46] Formally, the numerator of the tax price elasticity should be the R&D capital stock rather than flow expenditure. However, in steady state the R&D flow will be equal to R&D stock multiplied by the depreciation rate. Since the depreciation rate is the same for large and small firms around the discontinuity, it cancels out (see Appendix A).

[47] As the tax-adjusted user cost of R&D for large companies remains unchanged over 2006-11 (Table A11), it seems reasonable to use the average R&D over 2006-08 as a proxy for how much an average firm would spend on R&D if it remained a large company over 2009-11.

[48] For robustness checks, we use estimates from various alternative first stage specifications, including both OLS and Poisson specifications, and derive estimates for log difference in R&D investment in the range of 0.69 to 1.08 (see Appendix B).

[49] In some situations, a firm can first use the tax deduction feature to reduce its chargeable profits to zero, then claim the rest of the enhanced qualifying R&D expenditure using the payable tax credit feature. This is called a combination claim. However, given the very few number of combination claims in our baseline sample, we ignore this case for simplicity.

weighted by the probability, $\Pr(.)$, that a firm will have no corporate tax liability:

$$\rho_f = \Pr(Has\ tax\ liability) \times \rho_{scheme}^{deduction} + \Pr(No\ tax\ liability) \times \rho_{scheme}^{credit}.$$

To calculate this we use the share of firms in the sample with corporate tax liabilities in 2006 and 2007, which is 45%, as a proxy for $\Pr(Has\ tax\ liability)$. The effective tax rate τ is 28% in 2009-10 and 26% in 2011.[50] The average tax-adjusted user cost of R&D is 0.15 under the SME scheme and 0.19 under the large company scheme over 2009-11, which translates into a log difference in user cost of 0.27.

Putting all these elements together we obtain a tax-price elasticity of R&D of 2.6 (= 0.71/0.27). This is somewhat higher than the typical values of between 1 and 2 found in other studies.[51] However, almost all previous studies have effectively focused on larger firms such as publicly listed firms or using state/macro data which will be dominated by the expenditures of larger firms (due to the concentration of R&D). Our sample, by contrast, is predominantly of SMEs around the €86m threshold. As these firms are more likely to be credit constrained (especially during and after the global financial crisis), they are likely to be more responsive to R&D tax incentives.

Some evidence for the hypothesis that there are larger treatment effects for the more financially constrained firms is presented in Table 7. First, we split the sample by firm age, as younger firms are much more likely to be credit constrained than older ones. Splitting by median age we find that although the effect of the policy is significant in both sub-samples, it is proportionately larger for the young firms. R&D rises by a factor of 2.4 for the young and only 1.9 for the old (columns (1) and (2)). Furthermore, when we use the after-before design, the treatment effect is significant for young firms, but smaller and insignificant for older firms (columns (3) and (4)). Estimates from the after-before design gives a treatment effect to baseline ratio of 2.6 for young firms and 0.5 for old firms, a difference that is significant at the 10% level (the implied tax price elasticities are 4.7 and 1.6 respectively).[52]

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[50] We set the real interest rate r to 5% and depreciation rate δ to 15%. As $\ln(r+\delta)$ cancels out in $\ln(\rho_{SME}/\rho_{LCO})$, the value of these two last parameters do not affect our final tax-price elasticity estimate.

[51] See the surveys in Becker (2015), OECD (2014), Fowkes, Sousa, and Duncan (2015), Hall and Van Reenen (2000).

[52] The log difference in the user cost of R&D among younger firms is 0.274, as the probability of payable tax credits is 67%. The log difference in the user cost among older firms is 0.267, as the probability of the payable tax credits is 44%.

One concern is that young firms respond more to the R&D tax policy not because they are financially constrained, but because they are more likely to have zero corporate tax liabilities and therefore benefit more from the SME scheme via payable tax credit. We directly address this concern by comparing the responses of young and old firms only among firms with corporate tax liabilities for at least one year between 2005 and 2007 (columns (5) to (8) of Table 6). As before, we find that young firms still have a much higher treatment effect to baseline ratio in this subsample: 2.4 to 0.5 among old firms, implying tax price elasticities of 4.8 and 1.6 respectively. Though these differences are not statistically significant due to smaller sample size, they support our hypothesis that the larger treatment effects we find are driven by financially constrained firms.[53]

5.3 Cost effectiveness of the R&D Tax Relief Scheme

A full welfare analysis of the R&D policy is complex as one needs to take into account general equilibrium effects through spillovers (see below) and possibly aggregate effects on scientists' wages (Goolsbee, 1998). We take one step in this direction by implementing a simple "value for money" calculation based on how much additional R&D is generated per pound sterling of taxpayer money ("Exchequer Costs"). The details of the calculations are in Appendix A5, but we summarize them here.

As described in the previous sub-section, we obtain empirical estimates of the tax-price elasticity from the 2008 policy change. In addition, for every year we can also calculate the difference in the user costs of R&D generated by the policy parameters of the tax system. We do this separately for each of the three R&D schemes: SME deductible, SME payable tax credit and large company scheme. This allows us to calculate the value for money ratio, $\frac{\Delta_{RD}}{\Delta_{EC}}$ separately for each scheme in each year. From the HMRC data (HMRC 2015) we also know the amount given out in each of the three schemes by the government (ΔEC). Combining this with the value for money ratio (derived from the tax elasticity and the user costs) enables us to calculate the counterfactual level of aggregate R&D.

The estimated R&D tax-price elasticity of 2.6 implies that a firm entering the SME scheme

[53] Replicating the exercise using the sub-sample of firms with no corporate tax liabilities 2005-07 gives a treatment effect (relative to baseline R&D) ratios of 2.8 for young firms and 0.5 for older firms, implying tax price elasticities of 4.7 and 1.5 respectively.

as a result of the new threshold increases its R&D by 84% of its pre-policy level in the tax deduction case, and 109% of its pre-policy R&D in the payable tax credit case. The corresponding increase in Exchequer costs by the same firm is 31% of its pre-policy R&D in the tax deduction case, and 51% of its pre-policy R&D in the payable tax credit case. In both cases, roughly half of this increase is to cover more generous tax relief applied to the firm's old level of R&D, while the other half covers tax relief applied to the firm's additional R&D. The implied "value for the money" ratio of the 2008 policy change, as measured by additional R&D over additional Exchequer costs, thus ranges from 2.1 in the payable tax credit case to 2.7 in the tax deduction case.

If we generalize the estimated R&D tax-price elasticity of 2.6 to the whole population of SMEs, we can do a similar calculation for the overall SME scheme between 2006 and 2011. Value for money ratios are on average 2.79 for the deduction scheme and 2.13 for the tax credit scheme. Combining these ratios with Exchequer costs statistics gives us estimates of the additional SME R&D induced which averages at £719m per year (£321m from the deductible and £398m from payable tax credit). Total SME qualified R&D averaged £1,745m, so this is a substantial fraction. SME R&D would have been 41% lower in the absence of the UK R&D tax credit system.

We also repeat the exercise for the population of large companies, but with more conservative R&D tax-price elasticity of 1.0[54] as these firms are likely less responsive to tax incentives, and obtain value for the money ratios of around 1.4. These translate into an average of £919m additional R&D (about 11% of total large firm's qualified R&D spending).

Putting these figures together suggests that the R&D Tax Relief Scheme induced an average of £1.64bn per year 2006-11, while costing the Exchequer £0.96bn in lost tax revenue – a value for money ratio of 1.7. The UK's qualifying R&D spending would have been about 16% lower in the absence of this fiscal support. This suggests that the tax policy was important in the macro-economic performance of UK R&D. In Figure 4 we show estimates of the counterfactual business R&D (BERD) to GDP ratio estimated in the absence of the tax relief scheme (see Appendix A.5 for details). It is striking that since the early 1980s UK BERD became an increasingly small share of GDP, whereas it generally rose in other major economies. According to our estimates

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[54] This follows the conclusions from literature surveys (e.g. Becker, 2014). These elasticity assumptions are likely to *underestimate* the benefits of the policy as (i) the literature may have under-estimated the elasticity due to weaker identification approached and (ii) since we find larger elasticities for medium sized firms, the responsiveness may be even larger for the much smaller firms who are well below the asset thresholds we consider.

this decline would have continued were it not for the introduction and extension of a more generous fiscal regime in the 2000s.[55] Business R&D would have been 10% lower over the 2006-2011 period (total BERD is larger than tax qualifying R&D).

A full welfare analysis would likely produce even larger benefit to cost ratios than 1.7. First, since the taxpayer costs are transfers, only the deadweight cost of tax should be considered (e.g. Gruber, 2011, uses 40%). Second, the additional R&D is likely to have technological spillovers to other firms, raising their innovation rates (e.g. Bloom et al. 2013). We examine these spillover effects in sub-section 6.5.

6. Extensions and Robustness

6.1 Intensive versus extensive margins

The additional amount of R&D induced by the policy could come from firms which would not have done any R&D without the scheme (i.e. the extensive margin) or from firms which would have done R&D, although in smaller amounts (i.e. the intensive margin). It turns out that the main R&D effects are coming from the intensive margin (Table A6). Estimating the R&D equation where the outcome is a dummy for whether the firm performs R&D produces insignificant effects. By contrast, when the outcome is whether a firm patents there remains a positive and significant effect.[56] Similarly, if we split by industry, the strongest effects of the policy come from those sectors that are more intensive in R&D and patents (Table A8).[57]

We also split the baseline sample into firms which made some capital investment in the 2005-07 pre-policy period, and firms that did not (Table A9).[58] The policy effect on R&D and innovation is larger among firms who had invested, suggesting that current R&D and capital investments are more likely to be complements than substitutes. This result is consistent with the

[55] The trend annual decline in business R&D intensity was 1.9% between 1981 and 1999. We estimate that in the absence of the policy change the decline would have continued at 1.7% a year 1999 to 2012.

[56] Table A7 shows similar findings by splitting the sample by firms with and without R&D or patents in the past. Both R&D and patent effects come mainly through the intensive margin, driven by firms with past R&D or patents.

[57] These are shown by splitting at median of industry patent intensity, and we generate the same qualitative pattern if we repeat the exercise using R&D intensity. Examples of high-patenting industries include electric domestic appliances, basic pharmaceutical products, medical and surgical equipment, organic and inorganic basic chemicals, optical and photographic equipment, etc.

[58] Due to limited coverage of investments in FAME, we use data on machinery and plant expenditure reported in CT600 as a proxy for capital investments.

idea that firms having previously made R&D capital investments have lower adjustment costs and therefore respond more to R&D tax incentives (Agrawal, Rosell, and Simcoe 2014).

6.2 R&D tax effects on other aspects of firm performance

We also examined several other measures of firm performance such as size and productivity using the baseline specification. These results are to be taken with caution. First, there are many missing values on accounting values of employment and sales as UK accounting regulations do not insist on these being reported for smaller and medium sized enterprises (as in the US). Second, our available panel ends in 2011 and so we will not capture all the long-run effects. Table 8 shows that there does appear to be some positive effect on sales (Panel A) and employment (Panel C),[59] but not on capital (Panel B), although the standard errors are large. There is a slight tendency for the policy impact on sales and employment to become stronger over time (e.g. the coefficients are insignificant in 2009, but larger and significant in 2010). The estimates of the policy effect on total factor productivity (TFP, Panel D)[60] are very imprecise but there is a significant effect in the final column. We should not read too much into this given the smaller sample sizes, but there is a hint of the policy effect starting with R&D which shifts patents then finally affects productivity.

6.3 How firms cluster around the threshold in later years

As discussed in Section 3, we chose total assets in 2007 as our primary running variable to avoid potential endogenous sorting of firms across the threshold once the policy effective date was announced in 2008. We test the validity of our primary running variable choice and our concern by performing the McCrary test for each year from 2006 to 2011,[61] which estimates the discontinuity in firms' total asset distribution at the SME threshold of €86m. The respective McCrary tests for 2006 and 2007 (Figure A3) confirm that firms did not manipulate their total assets to benefit

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[59] If we subtract imputed R&D staff count from employment to net out the impact of the policy on raising R&D, the effects are smaller but qualitatively similar. The effects in log term (standard errors) on adjusted employment in 2010 and 2011 on adjusted employment are 0.24 (0.15), and 0.27 (0.15) respectively.

[60] TFP is calculated as $\ln(sales) - (1{-}\propto_l)\ln(capital) - \propto_l \ln(employment)$, where $\propto_l$ is the share of labor costs in total revenue at the two-digit industry level across all firms in the FAME dataset averaged across the 2006-11 period. Material share is not included due to very limited reporting of material costs in FAME.

[61] We exclude 2008 as the increase in deduction rate for large companies became effective before the effective date for the changes in the SME scheme (including increase in deduction rate for SMEs and SME definition change) was announced much later in the year. As such, it is hard to predict which way the bunching would happen in this year, or if it would happen at all.

from the SME scheme before 2008.[62] On the other hand, there is some graphical evidence of firms' bunching right below the €86m from 2009 onward, which is most obvious in 2009 and 2011. Finally, Figure A4 pools together the two years before the policy change (2006-07) and Figure A5 the three years after the change (2009-11). Again, it is apparent from these graphs that endogenous sorting does seem to happen, but only from 2009 onward after the policy became effective.

6.4 Exploiting other elements of the SME definition

We also explored using other elements of SME definition (sales and employment) to estimate the impacts of the policy and R&D and innovation outputs (Table A10). We must interpret this with caution because, as noted above, there are many missing values on sales and employment. Furthermore, we also find evidence that the asset criterion is more binding than the sales criterion. As a firm is considered an SME if it meets either the asset or the sales criterion, the asset criterion is binding only when the firm already fails the sales one and vice versa. The binding/non-binding ratio for the asset criterion is 0.36, considerably higher than the binding/non-binding ratio of 0.20 for sales criterion (Figure A6).[63]

As expected, while we still find positive effects on R&D and innovation outputs using the sales or employment criterion (Table A10) but these effects are not always statistically significant. They are also of smaller magnitude compared to our baseline effects estimated using the asset criterion when taking into consideration the baseline R&D and patent count of the respective sample. The treatment effect to baseline ratios for R&D using asset, sales, and employment criteria are 1.92, 1.27, and 0.39 respectively, and the same set of ratios for patent count are 1.22, 0.42, and

[62] This is the log difference in density height at the SME threshold. The coefficient (standard error) is 0.029 (0.065) in 2006 and -0.026 (0.088) in 2007.

[63] Binding/non-binding ratio for the asset criterion is calculated as number of firms with sales in 2007 between €100m and €180m/number of firms with sales in 2007 between €20m and €100m, conditioned on firms' total assets in 2007 being between €36m and €136m (i.e. +/-€50m window around the asset threshold of €86m). Binding/non-binding ratio for the sales criterion is calculated as the number of firms with total assets in 2008 between €6m and €86m/number of firms with total assets in 2007 between €86m and €166m, conditioned on firms' sales in 2007 being between €50m and €150m (i.e. +/-€50m window around the sales threshold of €100m). The qualitative result that the asset criterion is more binding than the sales criterion does not change when we pick different windows to calculate the binding/non-binding ratios.

0.85.[64] We also examined whether combining the different SME criteria could increase the efficiency of our estimates, but found no significant improvement.[65]

6.5 R&D technology spillovers

The main economic rationale usually given for more generous tax treatment of R&D is that there are technological externalities, so the social return to R&D exceeds the private return. Our study design allows us to estimate the causal impact of R&D spillovers on innovation by *other* firms. Following the work of Jaffe (1986) we calculate the knowledge spillover pool available to firm i as $SpilltechRD_{i,09\text{-}11} = \sum_{j \neq i} \omega_{ij} rd_{j,09-11}$ where $rd_{j,09\text{-}11}$ is the average R&D of firm j over 2009-11 and ω_{ij} is measure of technological "proximity" between firms i and j as indicated by which technology classes a firm patents in (e.g. if two firms have identical distributions of patent classes then proximity is 1 and if they are in entirely different patent classes the proximity is zero).[66] We follow our earlier approach of using $E_{j,\,2007}$ as instrument for $rd_{j,09\text{-}11}$ where $E_{j,2007}$ is the below-asset-threshold dummy in 2007 for firm j.[67] Consequently, we construct $SpilltechSME_{i,09\text{-}11}$ =

[64] Even when we restrict the sample to firms for which the sales criterion binds when using the sales running variable, the percentage effects are still lower than our baseline results, and are not statistically significant.

[65] The asset threshold almost always generates large and statistically significant effects on both R&D and patents, while the sales threshold does not (columns (1)-(2) and (4)-(5) in Panel B of Table A10). Joint F-statistics for *below-asset-threshold dummy* and *below-sales-threshold dummy* indicate that their effects on both R&D and innovation outputs are jointly significant in all cases. Finally, the estimated effects of R&D on innovation outputs using both criteria as instrumental variables for R&D are of similar magnitude to our baseline effect of 0.530 (0.698 and 0.410 in columns (3) and (6) respectively). However, these estimates are less precise due to the inclusion of an additional weak *below-sales-threshold dummy* instrument.

[66] Following Jaffe (1986) we define proximity as the uncentered angular correlation between the vectors of the proportion of patents taken out in each technology class $\omega_{ij} = \frac{F_i F_j'}{(F_i F_i')^{\frac{1}{2}} (F_j F_j')^{\frac{1}{2}}}$. $F_i = (F_{i1}, \dots, F_{i\Upsilon})$ is a $1 \times \Upsilon$ vector where $F_{i\tau} = \frac{n_{i\tau}}{n_i}$ is firm i's number of patents in technology field τ as a share of firm i's total number of patents. To calculate $F_{i\tau}$, we use information on all patents filed between 1900 and 2011 (80% of these patents are filed after 1980) and their 3-digit International Patent Classification (IPC), which classifies patents into 123 different technology fields. These data are available from PATSTAT. Bloom et al. (2013) show that the Jaffe measure delivers similar results to more sophisticated measures of proximity.

[67] More generally, $E_{i,2007} = I\{\, z_{i,2007} \leq \tilde{z} \,\}$ is a binary indicator equal to one if the 2007 financial variable $z_{i,2007}$ is equal to or less than the corresponding new SME threshold for it, $\tilde{z}$.

$\sum_{j \neq i} \omega_{ij} E_{j,2007}$ as instrument for *SpilltechRD$_{i,09\text{-}11}$*. The exclusion restriction requires that the discontinuity induced random fluctuations in firm *j's* eligibility would only affect connected firm *i*'s R&D and innovation outputs through R&D spillovers.

Our main spillover IV regression estimates the impact of *SpilltechRD$_{i,09\text{-}11}$* on firm *i*'s innovation, *pat$_{i,09\text{-}11}$* controlling for firm *i*'s own R&D, *rd$_{j,09\text{-}11}$*:

$$pat_{i,09-11} = \alpha_4 + \delta spilltechRD_{i,09-11} + \theta rd_{i,09-11} + G\big(z_{j,2007}\big) + f_4\big(z_{i,2007}\big) + \varepsilon_{4i} \quad (4)$$

where $G\big(z_{j,2007}\big) = \sum_{j \neq i} \omega_{ij} g(z_{j,2007})$ and $f_4(z_{i,2007})$ and $g(z_{j,2007})$ are polynomials of total assets in 2007.[68] We instrument $spilltechRD_{i,09-11}$ with $spilltechSME_{i,2007}$ and we instrument own R&D, $rd_{i,09-11}$, with $E_{i,2007}$ exactly as we did earlier in the paper.

We estimate equation (4) on the sample of firms with total assets in 2007 between €46m and €126m (as in Figure 1). This is a larger sample than in the baseline sample as the policy-induced R&D can have spillovers on firms well beyond the policy threshold.[69]

Column (1) of Table 9 reports the first stage for the R&D spillover term and column (2) the first stage for own R&D. As expected the instrument $spilltechSME_{i,2007}$ significantly predicts $spilltechRD_{i,09-11}$, in the first column and the instrument $E_{i,2007}$ significantly predicts firm i's R&D expenditure in the second column. More interestingly, we see that in the reduced form patent model of column (3) the R&D spillover term $spilltechSME_{i,2007}$ has a large and significant positive effect on firm i's patents. The spillover term is in fact statistically stronger than the own R&D effect, due to collinearity issues. If we drop the spillover measure from column (3) for example, the coefficient on $E_{i,2007}$ becomes significant on own patents as in our baseline regressions.

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[68] An RD Design model for firm j's R&D yields $rd_{j,09-11} = \alpha + \beta_{FS} E_{i,2007} + g\big(z_{j,2007}\big) + \varepsilon_j$. Aggregating this equation across all connected firm j's around the SME asset threshold, using ω_{ij} as weights, yields $\sum_{j \neq i} \omega_{ij} rd_{j,09-11} = \alpha \sum_{j \neq i} \omega_{ij} + \beta_{FS} \sum_{j \neq i} \omega_{ij} E_{i,2007} + \sum_{j \neq i} \omega_{ij} g\big(z_{j,2007}\big) + \sum_{j \neq i} \omega_{ij} \varepsilon_j$. Rewriting the latter equation then yields $spilltechRD_{i,09-11} = \alpha \sum_{j \neq i} \omega_{ij} + \beta_{FS} spilltechSME_{i,2007} + G\big(z_{j,2007}\big) + \eta_i$, which shows that $G(z_{j.2007})$ is the appropriate "RD-style" polynomial control when using $spilltechSME_{i,2007}$ as instrument for $spilltechRD_{i,2007}$.

[69] Note that $spilltechRD_{i,09-11}$ is calculated using the population of all possible firm j's, while $spilltechSME_{i,2007}$ and $G(z_{j,2007})$ are calculated using all firm j's with total assets in 2007 between €61m and €111m (our baseline RD sample), as the RD Design works best in samples of firms around the relevant threshold. Also, in all reported results, we use third order polynomial controls separately on each side of the threshold for $g(z_{j,2007})$ and $f_4(z_{i,2007})$. In this larger sample we found that higher order terms were significant (unlike in the earlier Tables on smaller samples). However, using different orders of polynomial controls does not change our qualitative findings.

Turning to the IV results column (4) shows that there appears to be no significant effect of other firms' R&D on own R&D. By contrast, the last two columns show that R&D by a firm's technological neighbors ($spilltechRD_{i,09-11}$) *does* have a causal impact on patenting consistent with the patent reduced form of column (4). In addition to the instrumented spillover term, column (5) includes the instrument for own R&D and in column (6) we instrument own R&D by the usual own asset threshold. The magnitude of the spillover coefficient is similar in both specifications. In column (6) a £1m increase in R&D by a firm with an identical technological profile will increase patenting by 0.009, which is 3.3% of an equivalent R&D increase by the firm itself (=0.009/0.273).

These findings are broadly consistent with Bloom et al.'s (2013) theoretical predictions that R&D technology spillovers should positively affect innovations, but have an ambiguous effect on own R&D. Finally, estimates from our baseline spillover regression (column (6)) again suggest the presence of positive R&D spillovers on innovations.

There may be some negative R&D spillovers through business stealing effects among firms in similar product markets. To address this concern, we follow Bloom et al. (2013) and construct $spillsicRD_{i,09-11} = \sum_{j \neq i} \phi_{ij} rd_{j,09-11}$ that captures the R&D spillovers in product market space, where ϕ_{ij} is a measure of product market distance between firms i and j.[70] Similar to the above, we also construct $spillsicSME_{i,2007} = \sum_{j \neq i} \phi_{ij} E_{i,2007}$ as instrument for $spillsicRD_{i,09-11}$. We found some evidence for strategic complementarity in R&D, but there were no significant effects of $spillsicRD_{i,09-11}$ on patents.

Together, these findings provide evidence that policy-induced R&D have sizable positive impacts on not only R&D performing firms but also other firms operating in similar technology areas, as measured by innovation outputs, which further supports the use of R&D subsidies in the UK context.

7. Conclusion

Fiscal incentives for R&D have become an increasingly popular policy of supporting innovation across the world. But little is known about whether these costly tax breaks causally raise

[70] $\phi_{ij} = 1$ if firm i operates in the same industry as firm j and $\phi_{ij} = 0$ otherwise. To calculate ϕ_{ij}, we use firms' primary industry codes at 3-digit Standard Industry Classification (SIC). These data are available from FAME.

innovation. We address this issue by exploiting a change in the UK R&D tax regime in 2008 which raised the size threshold determining whether a firm was eligible for the more generous "SME" tax regime. This enables us to implement a Regression Discontinuity Design and assess impact of the policy on R&D and innovation (as measured by patenting). Using total assets in the pre-policy period of 2007 we show that there was no evidence of discontinuities around the threshold prior to the policy, which is unsurprising as the new threshold was only relevant for the R&D tax incentive scheme and not for other programs targeting SMEs.

The policy caused an economically and statistically significant increase in R&D and patenting, and there is no evidence that the new patenting was of significantly lower value. Hence R&D tax policies do seem effective in increasing innovation, they are not simply devices for relabeling existing spending. The elasticity of R&D with respect to changes in its (tax adjusted) user cost is around 2.6. We argue that this is higher than existing estimates because we focus on firms that are smaller than those conventionally used in the extant literature and are more likely to be subject to financial constraints. The policy seems to be cost effective, in aggregate stimulating £1.7 of R&D for every £1 of taxpayer subsidy. Over the 2006-2011 period we calculate that the tax scheme meant aggregate R&D was 16% higher than it would otherwise have been, halting the secular decline of the UK's share of business R&D in GDP.

There are many caveats when moving from these results to policy. Although the results are optimistic about the efficacy of tax incentives, the large effects come from smaller firms and should not be generalized across the entire size distribution – this does imply that targeting R&D policy on financially constrained SMEs is worthwhile (although a first best policy would be to deal directly with credit market imperfections).

We have partially examined general equilibrium effects by demonstrating that the R&D tax policy stimulated patenting activity not only for the firms directly affected, but also created spillovers for other firms who were indirectly affected. However, there may be other equilibrium effects that reduce innovation. For example, subsidies are captured in the form of higher wages rather than a higher volume of R&D, especially in the short-run. We believe that this is less likely to be a first order problem when there is large international mobility of inventors, as is the case in the UK (e.g. e.g. Akcigit, Baslandze and Stantcheva, 2015, and within the US see Moretti and Wilson, 2015). Finally, it is unclear if tax breaks are the optimal form of support for innovation. Direct support of basic R&D in the science base and increasing the supply of future talent into the innovation sector (e.g. Bell et al., 2015) are policies that may have more powerful effects on innovation and growth in the long term.

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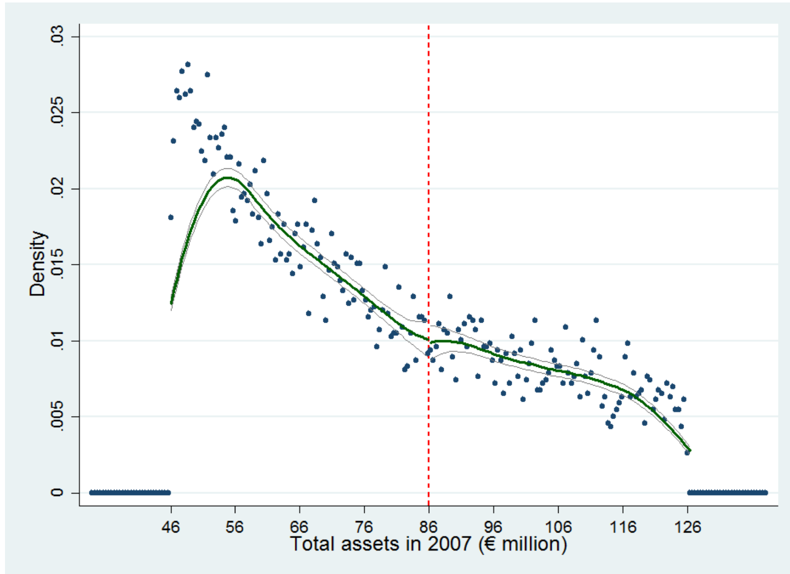
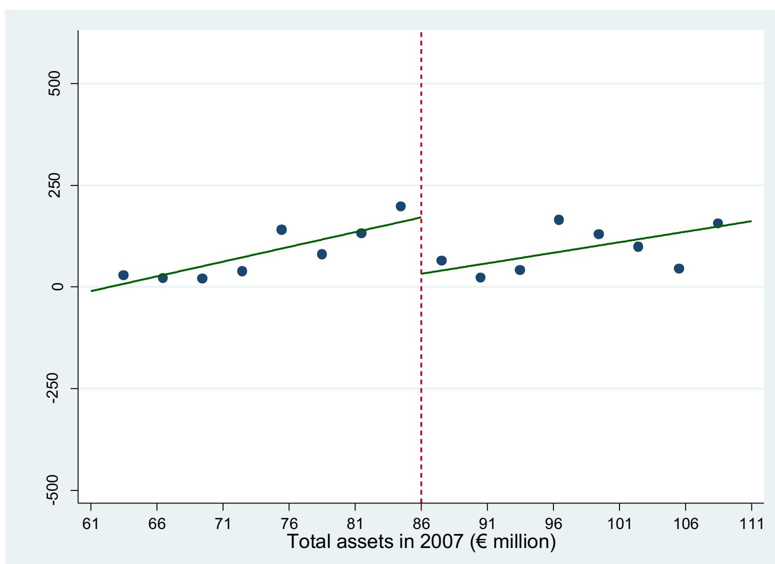
Figure 1. McCrary test for no manipulation at the SME asset threshold in 2007



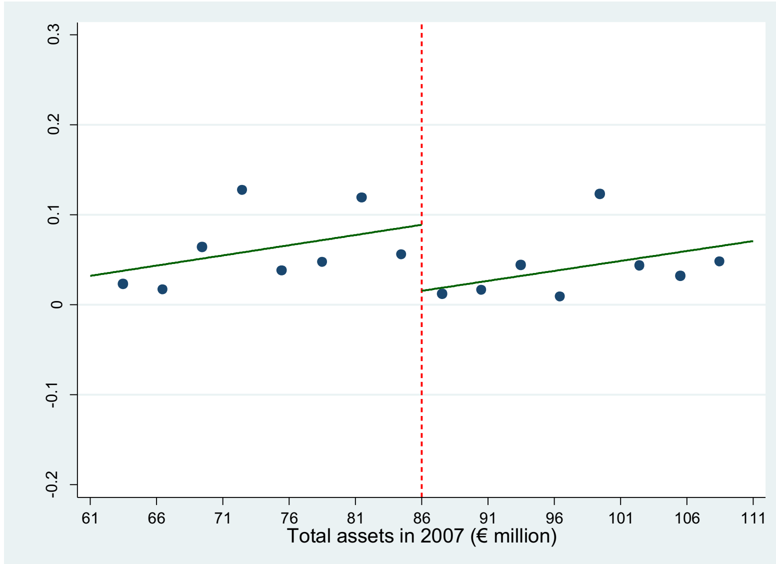
Note: McCrary test for discontinuity in distribution density of total assets in 2007 at the SME asset threshold of €86m. Sample includes firms with total assets in 2007 between €46m and €126m. The discontinuity estimate (log difference in density height at the SME threshold) is -0.026, with standard error of 0.088.

Figure 2. Discontinuity in average R&D expenditure over 2009-11



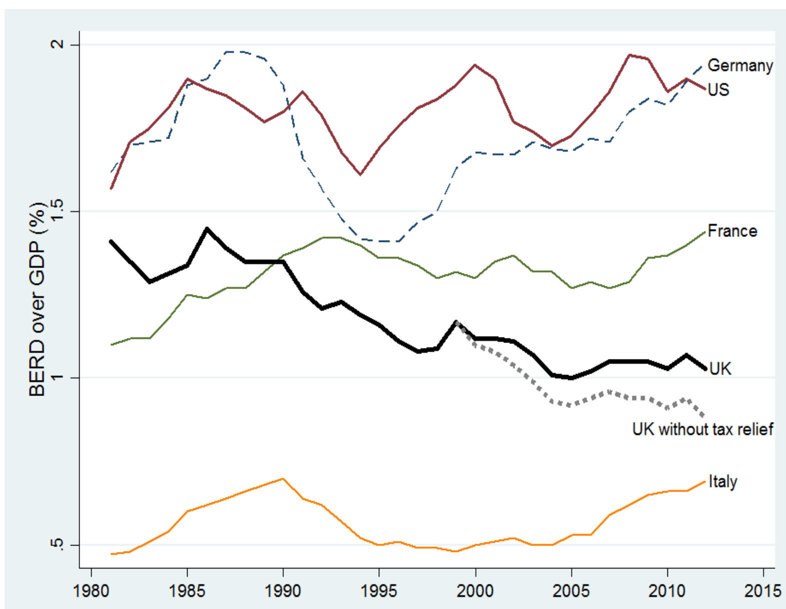
Note: The figure corresponds to the baseline R&D expenditure regression using a Regression Discontinuity (RD) Design. The dependent variable is average R&D expenditure over 2009-11. The running variable is total assets in 2007 with a threshold of €86m. The baseline sample includes firms with total assets in 2007 €25m above and €25m below the cut-off (i.e. between €61m and €111m). Controls for the running variable are estimated separately on each side of the threshold. The OLS discontinuity estimate at the €86m threshold is 138,540 with a standard error of 55,318. Bin size for the scatter plot is €3m.

Figure 3. Discontinuity in average number of patents over 2009-11



Note: The figure corresponds to our baseline reduced-form patent regression using an RD Design. The dependent variable is average number of patents over 2009-11. The running variable is total assets in 2007 with a threshold of €86m. Baseline sample includes firms with total assets in 2007 €25m above and below the cut-off (i.e. between €61m and €111m). Controls for running variable separately for each side of the threshold are included. The OLS discontinuity estimate at the €86m threshold is 0.073 with a standard error of 0.026. Bin size for the scatter plot is €3m.

Figure 4. Business Enterprise R&D over GDP, selected countries



Note: The data is from OECD MSTI downloaded February 9th 2016. The dotted line is the counterfactual R&D intensity in the UK that we estimate in the absence of the R&D Tax Relief Scheme (see sub-section 5.3 and Appendix A.5 for details).

Table 1. Baseline sample descriptive statistics

Sample	Firms with total assets in 2007 between €61m and €86m								Firms with total assets in 2007 between €86m and €111m							
Year	2006	2007	2008	2009	2010	2011	06-08 avg.	09-11 avg.	2006	2007	2008	2009	2010	2011	06-08 avg.	09-11 avg.
Total no. firms in the subsample	3,561								2,327							
Mean qual. R&D exp. *(£ '000)*	50.0	70.9	52.6	68.9	71.8	75.3	57.8	72.0	87.1	110.6	85.7	100.5	91.9	88.4	94.5	93.6
Mean patents	0.065	0.059	0.060	0.060	0.058	0.056	0.061	0.058	0.056	0.066	0.053	0.041	0.040	0.044	0.058	0.042
Mean UK patents	0.078	0.084	0.078	0.072	0.067	0.070	0.080	0.070	0.062	0.081	0.074	0.056	0.045	0.050	0.072	0.050
Mean EPO patents	0.028	0.032	0.036	0.031	0.028	0.024	0.032	0.028	0.029	0.029	0.033	0.020	0.025	0.023	0.030	0.023

Note: The baseline sample includes 5,888 firms with total assets in 2007 between €61m and €111m. Total assets are from FAME and are converted to € from £ using HMRC rules. Qualifying R&D expenditure comes from CT600 panel dataset and are converted to 2007 prices. Patent counts come from PATSTAT.

Table 2. R&D regressions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Dependent variable	**R&D expenditure *(£ '000)***								
	Before (pre-policy)			After (post-policy)			Before	After	Difference
Year	2006	2007	2008	2009	2010	2011	2006-08 average	2009-11 average	After - Before
Below asset threshold dummy (in 2007)	61.5	96.1	32.0	120.7**	157.8***	137.2**	63.2	138.5**	75.3**
	(58.5)	(72.1)	(40.4)	(59.0)	(58.6)	(53.7)	(53.4)	(55.3)	(36.3)
Firms	5,888	5,888	5,888	5,888	5,888	5,888	5,888	5,888	5,888

Note: *** significant at 1% level, ** 5% level, * 10% level. OLS estimates based on the RD Design. The running variable is total assets in 2007 with a threshold of €86m. Baseline sample includes firms with total assets in 2007 within €25m below and above the cut-off (i.e. between €61m and €111m). Controls for first order polynomials of the running variable separately for each side of the threshold are included. Robust standard errors are in brackets. Mean R&D between 2006 and 2008 was £72,312 and between 2009 and 2011 was £80,545. 2007 real prices.

Table 3. Pre-treatment covariate balance tests and placebo tests

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent variable	**Ln(Sales)**		**Ln(Fixed assets)**		**Ln(Employment)**		**R&D exp. *(£ '000)***	
Year	2006	2007	2006	2007	2006	2007	2009-11 average	
Below asset threshold dummy (in 2007)	-0.08	0.02	0.04	0.02	0.12	0.15	-16.5	48.6
	(0.12)	(0.12)	(0.10)	(0.10)	(0.13)	(0.13)	(41.7)	(77.1)
SME threshold (€)	86m	86m	86m	86m	86m	86m	71m	101m
Sample bandwidth	61-111m	61-111m	61-111m	61-111m	61-111m	61-111m	46-86m	86-126m
Firms	3,650	3,848	4,771	5,083	2,972	3,089	7,095	3,354

Note: *** significant at 1% level, ** 5% level, * 10% level. OLS estimates based on the RD Design. The running variable is total assets in 2007 with a threshold of €86m. Baseline sample includes firms with total assets in 2007 within €25m below and above the cut-off (i.e. between €61m and €111m). Controls for first order polynomials of the running variable separately for each side of the threshold are included. Robust standard errors are in brackets. Columns 1-6 report pre-treatment covariate tests for sales, employment, and capital. Columns (7) and (8) report placebo tests using placebo asset threshold of €71m and €101m.

Table 4: Reduced-form patent regressions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Dependent variable	**All patent count**								
	Before (pre-policy)			After (post-policy)			Before	After	Difference
Year	2006	2007	2008	2009	2010	2011	2006-08 average	2009-11 average	After - Before
Below asset threshold dummy (in 2007)	0.026	0.043	0.045	0.081***	0.066**	0.074**	0.038	0.073***	0.035*
	(0.028)	(0.030)	(0.032)	(0.029)	(0.027)	(0.031)	(0.027)	(0.026)	(0.020)
Firms	5,888	5,888	5,888	5,888	5,888	5,888	5,888	5,888	5,888

Note: *** significant at 1% level, ** 5% level, * 10% level. OLS estimates based on the RD Design. The running variable is total assets in 2007 with a threshold of €86m. Baseline sample includes firm's total assets in 2007 within €25m below and above the cut-off (i.e. between €61m and €111m). Controls for first order polynomials of the running variable separately for each side of the threshold are included. Robust standard errors are in brackets. Mean patent count between 2006 and 2008 was 0.060 and between 2009 and 2011 was 0.052.

Table 5: The effects of R&D tax policy on patent quality

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent variable	Baseline	EPO patents	UK patents	Family size (i.e. countries)	Chemistry/pharma patents	Non-chem/pharma patents	EPO patent citations	UK patent citations
Below asset threshold dummy (in 2007)	0.073***	0.037**	0.094***	0.214**	0.024*	0.050**	0.004**	0.023
	(0.026)	(0.016)	(0.033)	(0.085)	(0.014)	(0.022)	(0.002)	(0.021)
Dependent variable mean over 2006-08	*0.060*	*0.031*	*0.077*	*0.222*	*0.015*	*0.045*	*0.013*	*0.062*
Firms	5,888	5,888	5,888	5,888	5,888	5,888	5,888	5,888

Note: *** significant at 1% level, ** 5% level, * 10% level. OLS estimates based on the RD Design. The running variable is total assets in 2007 with a threshold of €86m. Baseline sample includes firms with total assets in 2007 within €25m below and above the cut-off (i.e. between €61m and €111m). Controls for first order polynomials of the running variable separately for each side of the threshold are included. Robust standard errors are in brackets. Quality measures are baseline patent count (column 1), EPO patent count (column 2), UK patent count (column 3), patent by family count (i.e. patent by country count) (column 4), chemistry/pharmaceutical patent count (column 5), and non-chemistry/pharmaceutical patent count (column 6), EPO patent by citation count (column 7), and UK patent by citation count (column 8).

Table 6. Effects of R&D on patents (IV regressions)

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable (2009-11 average)	**All patent count**		**EPO patent count**		**UK patent count**	
Specification	OLS	IV	OLS	IV	OLS	IV
R&D expenditure *(£ million)*, 2009-11 average	0.168**	0.530**	0.094**	0.268*	0.207**	0.680**
	(0.074)	(0.254)	(0.04)	(0.140)	(0.093)	(0.327)
Anderson-Rubin test p-value		0.005		0.024		0.004
Hausman test p-value	0.15		0.32		0.12	
Firms	5,888	5,888	5,888	5,888	5,888	5,888

Note: *** significant at 1% level, ** 5% level, * 10% level. Instrumental variable is the dummy whether total assets in 2007 is below €86m. Baseline sample includes firms with total assets in 2007 within €25m below and above the cut-off (i.e. between €61m and €111m). Controls for first order polynomials of the running variable (total assets in 2007) separately for each side of the threshold are included. Robust standard errors are in brackets. Adjusted first-stage F-statistic is 6.3. P-values of Anderson-Rubin weak-instrument-robust inference tests indicate that the IV estimates are statistically different from zero even in the possible case of weak IV.

Table 7. Heterogeneous effects of R&D Tax policy by firm age (as proxies for financial constraints)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent variable	**R&D expenditure *(£ '000)***							
Year	After (2009-11 avg.)		After - Before		After (2009-11 average)		After - Before	
Subsample	Young firms	Old firms	Young firms	Old firms	Young firms & profits > 0	Old firms & profits > 0	Young firms & profits > 0	Old firms & profits > 0
Below asset threshold dummy (in 2007)	92.3**	198.4*	97.9**	56.3	124.5*	107.7	111.0	46.0
	(42.1)	(104.2)	(42.2)	(59.4)	(70.0)	(120.7)	(93.2)	(79.6)
Mean over 2006-08	*37.9*	*107.1*			*46.2*	*90.6*		
Mean after - before			*2.8*	*46.8*			*-8.6*	*29.4*
Firms	2,928	2,955	2,928	2,955	956	1,585	956	1,585

Note: *** significant at 1% level, ** 5% level, * 10% level. OLS estimates based on the RD Design. The running variable is total assets in 2007 with a threshold of €86m. Baseline sample includes firms with total assets in 2007 within €25m below and above the cut-off (i.e. between €61m and €111m). Controls for the running variable separately for each side of the threshold are included. Robust standard errors are in brackets. Columns (1)-(4): Median firm age in 2007 is 12 years. Ratios of treatment effect to baseline mean R&D over 2006-08 for young and old firms are 2.6 and 0.5 respectively which are statistically different at the 10% level. The implied tax-price elasticities are 4.7 among young firms and 1.6 among old firms and these are also statistically different at 10% level. Columns (5)-(8): "Profits > 0" indicates that a firm had corporate tax liabilities at some point between 2005 and 2007. Ratios of treatment effect to baseline mean R&D over 2006-08 for young and old firms are 2.8 and 0.5 respectively. Implied tax-price elasticities are 4.8 among young firms and 1.6 among old firms.

Table 8. Effects of R&D Tax Relief Scheme on other measures of firms performance

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Panel A. Dependent variable: Ln(sales)									
	Before (pre-policy)			After (post-policy)			Before	After	Difference
Year	2006	2007	2008	2009	2010	2011	2006-08	2009-11	After - Before
Below asset threshold dummy (in 2007)	-0.187	0.029	-0.102	0.212	0.404**	0.297	-0.012	0.231	0.218*
	(0.170)	(0.167)	(0.162)	(0.180)	(0.187)	(0.192)	(0.154)	(0.177)	(0.114)
Firms	3,292	3,439	3,393	3,311	3,294	3,255	3,398	3,398	3,398
Panel B. Dependent variable: Ln(capital)									
Below asset threshold dummy (in 2007)	-0.017	-0.035	-0.0096	-0.020	-0.008	0.010	-0.077	-0.038	0.039
	(0.120)	(0.109)	(0.113)	(0.122)	(0.131)	(0.135)	(0.106)	(0.124)	(0.077)
Firms	3,721	3,958	3,791	3,608	3,451	3,316	3,651	3,651	3,651
Panel C. Dependent variable: Ln(employment)									
Below asset threshold dummy (in 2007)	-0.0118	0.102	0.0838	0.107	0.263*	0.292*	0.055	0.188	0.134
	(0.126)	(0.123)	(0.131)	(0.140)	(0.147)	(0.153)	(0.125)	(0.141)	(0.086)
Firms	2,468	2,550	2,431	2,445	2,551	2,469	2,387	2,387	2,387
Panel D. Dependent variable: Total factor productivity									
Below asset threshold dummy (in 2007)	-0.328	-0.106	-0.199	-0.0321	0.123	0.0239	-0.120	0.127	0.247**
	(0.255)	(0.237)	(0.235)	(0.245)	(0.258)	(0.264)	(0.234)	(0.245)	(0.118)
Firms	2,025	2,091	2,017	1,952	1,913	1,881	1,989	1,989	1,989

Note: *** significant at 1% level, ** 5% level, * 10% level. Regression Discontinuity Design (RDD) results (OLS). The running variable is total assets in 2007 with a threshold of €86m. Baseline sample includes firms with total assets in 2007 within €25m below and above the cut-off (i.e. between €61m and €111m). Controls for the running variable separately for each side of the threshold and two digit industry dummies are included. Standard errors are clustered by firm in brackets. Panel A uses sales from CT600. Panel B uses fixed assets (from FAME). Panel C uses employment (from FAME). Total factor productivity in Panel D is calculated as $\ln(sales) - (1-\propto_l)\ln(capital) - \propto_l \ln(employment)$, where $\propto_l$ is the share of labor costs in total revenue at the two-digit industry level across all firms in the FAME dataset averaged across the 2006-2011 period. Columns (7) – (9) condition on the "balanced" sample where we observe the outcome variable in at least one year of the pre-policy sample and one year of the post-policy sample (i.e. it is a sub-sample of the observations in columns (1) – (6)).

Table 9: Estimating R&D technology spillovers

	(1)	(2)	(3)	(4)	(5)	(6)
Specification	**First stage**		**Reduced form**	**IV**		
Dependent variable: (2009-2011 average)	***spill techRD***	**R&D exp. *(£ '000)***	**All patent count**	**R&D exp. *(£ '000)***	**All patent count**	**All patent count**
$spilltechSME$ *(sum tech. distance x dummy)*	35.9***	133.9	0.344**			
	(11.0)	(204.7)	(0.146)			
Below asset threshold dummy (in 2007)	-0.5	180.7**	0.045	182.4**	0.050	
	(4.1)	(83.8)	(0.052)	(80.1)	(0.063)	
$spilltechRD$ *(sum tech. distance x £ million)*				3.7	0.010**	0.009*
				(5.6)	(0.005)	(0.005)
R&D expenditure (*£ million)*, 2009-11 average						0.273
						(0.368)
Mean over 2006-08	*22.7*	*65.3*	*0.059*	*65.3*	*0.059*	*0.059*
Firms	10,449	10,449	10,449	10,440	10,449	10,449

Note: Sample of firms with total assets in 2007 between €46m and €126m. *** Significant at 1% level, ** 5% level, * 10% level. Standard errors clustered by firm in brackets. Controls include third order polynomials of total assets in 2007, separately for each side of the asset threshold of €86m, and $G(z_{j,2007}) = \sum_{j \neq i} \omega_{ij} g(z_{j,2007})$ as described in sub-section 5.8; $g(z_{j,2007})$ are third order polynomials of technology-connected firms' total assets in 2007, also separately for each side of the asset threshold. In column (6), the instrument variable for $spilltechRD$ is $spilltechSME$ and instrument variable for R&D expenditure is below-asset-threshold dummy.