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How cost-effective is public R&D in stimulating firm innovation?*

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Abstract

This paper assesses the impact of public R&D on firm R&D using patent application data on the county and firm level in Germany. We address the endogeneity of public R&D by employing an instrumental variable estimator that uses lagged institutional funding for research institutes and universities as excluded instruments. We find that one additional public patent application generates 3.5 firm patent applications in the median county, but also that the relationship turns negative for high levels of public R&D. We estimate the public costs per firm patent to be between 0.8 and 1.5 million EURO.

Keywords: R&D, university, research institutes, public spending.

JEL Classification: I23, O34, O38.

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1 Introduction

There is a clear consensus that stimulating R&D is welfare increasing due to positive externalities and uncertainty (Arrow, 1962; Nelson, 1959), but the question about the most efficient way is still open to debate. In principle, there are two ways to do so. First, governments can stimulate private R&D by increasing the profitability of R&D investment. This can be achieved by handing out cash payments or providing beneficial tax treatment, either in the form of super-deductions for R&D expenses or a lower tax rate on the returns from R&D. Second, governments can fund public R&D, which may stimulate (domestic) firm R&D due to local knowledge spillovers which are driven by personal interactions and workforce mobility. While there is a large body of empirical literature examining the impact of direct subsidies[1], causal empirical evidence on the magnitude of public R&D spillovers on firm R&D is limited and mainly focused on universities. Since universities engage, however, in both R&D as well as "degree" production, identifying the transmission channel at work is challenging. Our paper aims to fill this gap in the existing literature by investigating local knowledge spillovers of public R&D by universities *and* research institutes on firm R&D using firm and county level data for Germany between 2003 and 2010. To identify the causal effect and to calculate the cost-effectiveness of public R&D in stimulating firm innovation, we employ an instrumental variable estimator which exploits variation in lagged institutional funding for research institutes and universities as excluded instruments.

We believe that Germany provides an excellent set-up for our research question. First, Germany relies substantially on public R&D carried out by independent research institutes. These institutes spend together almost as much on R&D as the higher education sector in Germany. Figure 1 illustrates the international comparison. While Germany, Japan, the UK, the US and the average EU 28 country have similar R&D expenditures relative to GDP in the higher education sector, R&D spending in the government sector (including the research institutes) is highest in Germany among the selected countries. Second, the German firm R&D support strategy mainly consists of funding public R&D. In particular, Germany does not offer super-deductions for R&D expenditures or a lower tax rate on returns from R&D investment in the form of a patent box as recently introduced in several European countries (see, for example, Alstadsaeter et al., 2018). Thus, our focus on Germany mitigates concerns that the estimated spillovers of public R&D are driven by both, public R&D as well as generous direct subsidiaries. Third, German firms have comparably high R&D expenditures. As shown in Figure 1, the share of firm

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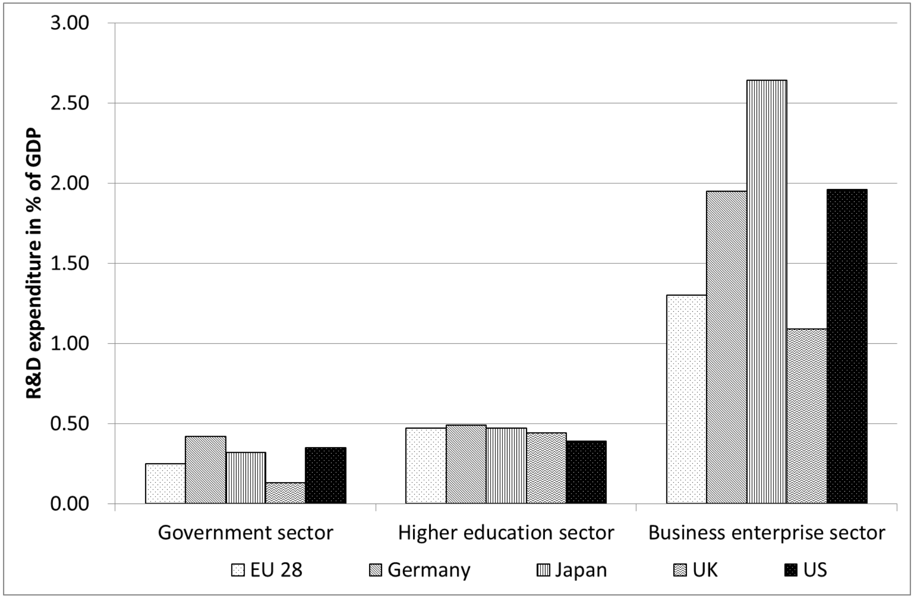
[1] See David et al. (2000) and Zúñiga-Vicente et al. (2014) for a literature review on the impact of cash subsidies on firm R&D and Hall and Van Reenen (2000) and Guceri and Liu (2017) for a literature review on the impact of R&D tax credits on firm R&D. In general, it seems to be the case that R&D tax credits are quite successful in stimulating firm R&D (e.g. Lokshin and Mohnen, 2012; Mulkay and Mairesse, 2013; Rao, 2016; Dechezlepretre et al., 2016; Guceri, 2018), while cash subsidies increase firm R&D in particular for smaller and younger firms (e.g. Bronzini and Iachini, 2014; Howell, 2017).

R&D expenditures in Germany is second largest among the selected countries. Thus, a no impact result cannot be explained by a general low R&D intensity of German firms.

Figure 1: Public R&D Expenditure as a Percentage of GDP



Source: Authors' calculations based on data from Eurostat 2014.

Our empirical strategy to quantify the local knowledge spillovers of public R&D on private R&D exploits county-level variation within Germany. This strategy has the benefit that all firms operate in the same institutional environment, but it comes at the cost that we are estimating a lower bound of the effect due to the potential presence of non-regional spillovers.[2] A minor concern for our analysis are, however, negative product-market related spillovers (due to competition) as identified by Branstetter and Sakakibara (2002) or Bloom et al. (2013) since public institutes do not compete for market shares with private firms. We focus on variation between counties - which have an approximately size of 1000 square kilometers in Germany - as this is likely to capture a large part of local knowledge spillovers given the results of prior literature (e.g. Andersson et al., 2009; Belenzon and Schankerman, 2013). Due to the lack of precise R&D expenditures for universities and (all) research institutes, we use patent applications from the OECD RegPat database as a proxy for public as well as firm R&D. This database covers all patents that are filed with the European Patent Office (EPO) and under the Patent Co-operation Treaty (PCT). It includes information on general patent characteristics as well as address information for inventors and applicants. We use the home address of inventors for the geographical mapping of patents as it allows a better approximation of where R&D takes place than using the location of the applicant. The latter would be in particular misleading for large firms that consist of several establishments or legally non-independent research institutes as for example the Fraunhofer institutes, for which

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[2] This assumes positive non-regional spillovers. In principle, non-regional spillovers could also be negative, if R&D activities are relocated. While we find some evidence for the latter, the effect is small.

the applicant is always the Fraunhofer Society. To address concerns about the use of patent data as a proxy for R&D activities (e.g. Griliches, 1998), we also use the number of firm R&D employees on the county level as a dependent variable in a robustness test. Further, we account for patent quality following the procedure outlined in Ernst et al. (2014) in another robustness check.

Although we are able to estimate the relationship of interest on the county as well as the firm level and are able to control for a wide range of county characteristics, a remaining concern regarding our empirical strategy is the potential endogeneity of public R&D. The level as well as the quality of public R&D may be influenced by private R&D. We address this concern by implementing an instrumental variable estimator (IV) using two excluded instruments. Our first excluded instrument is the 4-year-lagged institutional funding for Fraunhofer and Leibniz institutes. Using the 4-year lagged funding addresses the concern that private as well as public patent applications are driven by unobserved factors. Further, the use of solely institutional funding rules out that privately funded public R&D is driving the results. To address the persistence in public and private R&D, which could invalidate our instrument, we also solely exploit time-series variation in the instrument. Our second excluded instrument is institutional funding for central service staff of universities as librarians and administrators. This correlates with the generosity of funding for universities and thus the research undertaken, but avoids the direct link to the number of students which influence the local human capital stock and thus firm R&D as well. While we are convinced that the instruments are exogenous, we are also able to test this explicitly since we have identified two potential instruments. An additional benefit of our IV strategy is that it accounts also for a potential measurement error in the number (as well as the quality) of public patent applications and dynamic misspecification. Moreover, our focus on patent applications and institutional funding allows us to calculate the cost-effectiveness (institutional funding per firm patent) of this firm R&D support strategy and hence a comparison with other strategies, as for example R&D tax credits.

We obtain five main results from our empirical analysis. First, using our IV strategy we find a semi-elasticity of 0.09 for firm patents with respect to public patents in the median county with non-zero public patents. Thus, an increase in the number of public patent applications by one increases the number of firm patent applications by 9%, or by 3.5 patent applications (using the median number of firm patent applications in counties with non-zero public patents). The results are unchanged when including county-fixed effects and flexible state-trends or when estimating on the applicant-region level (including applicant-region-fixed effects). Further, the results are robust to our instrument choice. When using the number of firm R&D employees as a proxy for firms' R&D activities, we obtain a somewhat larger semi-elasticity. This is consistent with the argument that not all innovations are patentable. Accounting for patent quality leaves the results, however, mainly unchanged. Comparing IV to OLS estimates suggests that endogeneity is of minor importance as the point estimates are very similar when estimating without county-fixed effects. The OLS estimate is, however, strongly downward biased due to measurement error or dynamic mis-specification or both once we include county or application-region fixed effects.

We estimate the marginal costs of one additional public patent application to be between 2.7 and 5.3 million EURO. Hence, marginal institutional costs per firm patent application are between 0.8 and 1.5 million EURO in the median county with non-zero public patents. This is only half as large as the implied public costs for one firm patent application in the US or the UK using R&D tax credits as firm R&D support strategy based on the results by Dechezlepretre et al. (2016) and Rao (2016). Our estimated costs might even be lower as they ignore that an additional public patent has been generated and that positive non-regional spillovers might exist.

Second, we find evidence that the estimated semi-elasticity of firm R&D with respect to public R&D is non-monotone. The positive effect decreases with the level of public patents within a county and turns negative at a level of 21 public patents. This is, however, a relatively high level of public R&D as it suggests that the marginal effect is positive in 95% of the counties in Germany.

Our third main result is that public R&D affects in particular the number of patenting firms, but less the patent intensity of a firm (number of patents per firm). This contrasts with evidence on the impact of R&D tax credits on firm R&D as shown, for example, in Dechezlepretre et al. (2016). By using applicant level estimations, we further show that the extensive margin is not driven by previously non-patenting firms but “occasionally” patenting firms.

Our fourth result sheds some light on the existence of non-local spillovers due to *within* firm spillovers. Thus, we assess whether a firm that is active in two regions spends more in both regions or less in one and more in the other, if the number of public patents increases in the latter region. Our results suggests negative within firm spillovers, but the effect is quantitatively small.

Finally, we show that the transmission channel at work is indeed personal interactions and potentially workforce mobility as we find that firms that have jointly filed patents with universities or research institutes in a region in the past benefit the most from public R&D in this region. This is consistent with other results presented in this paper, e.g. (i) it is not public-private collaboration per se that drive the results, (ii) the impact of firm R&D does not occur through spin-offs as we show that firms with patent applications before our sample period react stronger and (iii) proximity does matter as firms do relocate R&D activities into regions with more public R&D.

Our work contributes to the literature on the relationship between public and private R&D in several ways. First, we provide evidence in line with several other studies on positive local knowledge spillovers of public R&D. The seminal paper in this field is Jaffe (1989). Using US state level data, Jaffe (1989) finds an elasticity of corporate patents to university R&D expenditure of around 0.1. Several studies have found similar empirical evidence for local knowledge spillovers. Audretsch and Feldman (1996) and Jaffe et al. (1993) find that spatial proximity matters for the diffusion of (private) knowledge. Belenzon and Schankerman (2013) confirm these results for university patents. In addition, Andersson et al. (2009) find that openings of higher education institutions in Sweden increased the number of patents in the same region.

While most of the recent studies have been able to use less aggregated data than Jaffe (1989), not all of them have been able to address the potential endogeneity of public R&D. The most convincing approach in the literature used to tackle the endogeneity of public research carried out by universities is by Kantor and Whalley (2014). They exploit the fact that US universities usually invest a fixed amount of their endowments' market value every year. Based on the argument that past university endowments are independent of the county's future economic performance, they use past university endowment in combination with variation in stock market returns as an instrument for university spending. They find a substantial downward bias in the OLS estimate using 3-year changes in labor income in the non-educational sector as the dependent variable. Our identification strategy is similar in a vein that variation in (lagged) institutional funding can also be seen as an endowment shock for research institutes and universities. Further, our results reveal an even larger downward bias.

Second, we bring the somewhat contrasting results in the literature on the impact of public on private R&D closer together. While all of the above mentioned studies find unambiguously positive effects, there are also a non-negligible number of papers finding negative effects of public R&D and thus a "crowding out" of private R&D (see David et al. (2000) for a literature review up to 2000 and Zúñiga-Vicente et al. (2014) for a more recent one). So far, three main channels have been suggested in the literature that may explain this result. First, the supply of R&D workers may be inelastic, which means more public R&D increases firms' R&D costs.[3] Second, public R&D might directly replace private R&D, if firms substitute public R&D for their own R&D. Third, public R&D could distort competition between firms by funding some firms at the cost of others. Although our paper cannot answer which of the three forces is the dominant one in the German context, we show that public R&D may have a positive or a negative impact on private R&D in Germany and that the sign of the effects depends on the level of public R&D

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[3] A similar argument has been raised with respect to the impact of public subsidies on private R&D spending. While earlier literature found positive effects, Goolsbee (1998) and David and Hall (2000) suggest that public R&D funding does not increase real private R&D spending, but solely raises researchers' wages. While there is evidence for this "wage inflation" effect (Aerts, 2008; Lokshin and Mohnen, 2013; Wolff and Reinthaler, 2008), recent literature confirms the existence of an additional positive effect on real R&D expenditures (Aerts, 2008; Görg and Strobl, 2007; Guellec and Van Pottelsberghe De La Potterie, 2003; Thomson and Jensen, 2013; Wolff and Reinthaler, 2008).

carried out in a region.

Our third contribution to the literature is that we provide robust evidence that it is indeed public R&D production that affects private R&D. One challenge regarding prior work is the identification of the driving force at work, as most of the studies focus on public R&D carried out by universities. Universities engage, however, in both "degree" as well as R&D production and both are likely to influence R&D activities by firms. Disentangling these two effects is challenging, as it necessarily relies on a parametrization. Abel and Deitz (2011) proxy the "degree production" dimension with the number of degrees per 100 working-age people and the research dimension by R&D expenditures per enrolled student. They find that it is in particular a university's research dimension that increases local human capital while the impact of the degree production dimension is limited due to labor force mobility. Some of the results by Kantor and Whalley (2014) can be read in a similar vein. They find that the effect is larger in counties with universities that have a higher research intensity and in counties with industries that cite university patents more often. However, while this seems conclusive, there are also other dimensions of universities as the quality of degrees, which is related to both, the research as well as the degree production of universities. We contribute to this stream of literature and the ongoing debate by applying an IV strategy that exploits variation in institutional funding of research institutes, which is undoubtedly unrelated to "degree" production.

The rest of this article is structured as follows. In section 2 we explain the German research system. Section 3 describes the data and the methodology employed. The empirical results are presented and discussed in section 4 and section 5 concludes.

2 R&D in the Public Sector in Germany

Since the drawing of the Lisbon strategy in 2000, the EU member countries aim to invest 3% of GDP in R&D. Compared to other EU countries Germany is close to this target with a sum of public and private R&D expenditures of 2.88% of GDP (based on 2014 data). Surprising is that Germany is also one of the few EU countries that offers only cash subsidies to the private sector and does not grant tax credits for R&D expenses or a lower tax rate on the return of R&D investment in the form of a patent box. Instead the German federal and the state governments heavily invest in public R&D carried out by independent research institutes and - similar to other countries - fund universities, which also engage in R&D activities. The majority of the independent research institutes belong to one of the following umbrella associations: the Max Planck Society, the Fraunhofer Society, the Leibniz Society and the Helmholtz Community.[4] As shown in Figure 1, R&D spending in the government sector (including the independent research institutes) is almost as high

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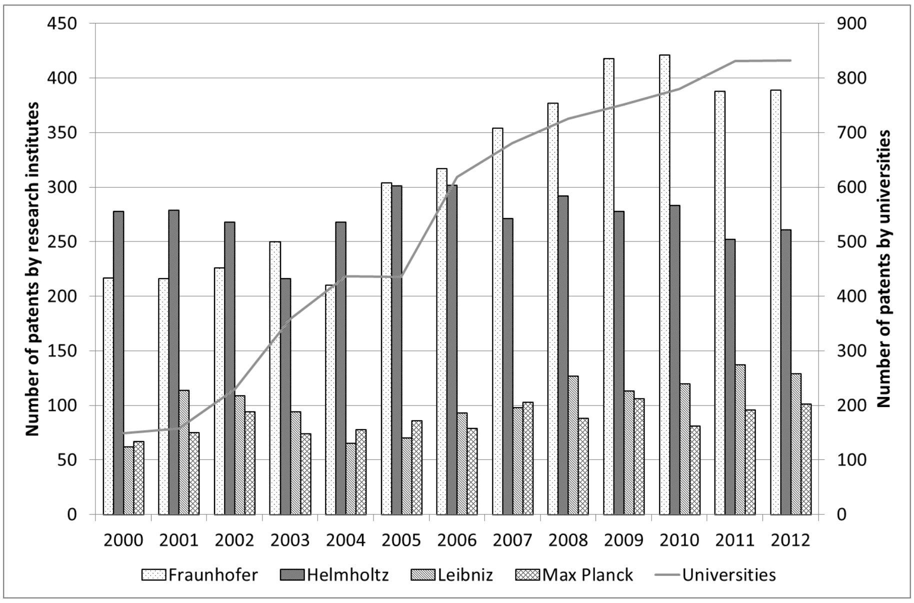
[4] Governmental research institutes exist in Germany as well, but they are of minor importance and conduct mainly departmental research for federal and state administration.

(12.5 billion EURO in 2014) as in the higher education sector (15.3 billion EURO).

Figure 2: Evolution of Public Patent Applications by Type of Applicant



Notes: Patent applications include only applications filed with the European Patent Office or under the Patent Co-operation Treaty. *Source:* Authors' calculation based on OECD RegPAT database 2000-2012.

The structure of the higher education sector in Germany is as follows. Overall, there are more than 400 higher education institutes but only about 25% of them are "real" universities (see also Table 1). The rest are universities of applied sciences (*Fachhochschulen*), which engage in research as well but to a much smaller extent, as they are usually highly specialized in one field. While the number of universities of applied sciences has increased over time, the number of universities has been stable. The state, in which the higher education institute is located, is responsible for 75% of the basic funding, which is usually a function of the number of students, the number of graduates and the amount of third party funding obtained. These criteria vary from state to state. The federal government and the private sector contribute in the form of public and private third party funding for specific research projects. Tuition fees are not a significant source of funding. The level of university R&D expenditures has increased in our sample period, from 8.4 billion EURO in 2000 to 12.7 billion EURO in 2010.[5] The main driver was an increase in third-party funding, which grew from 2.8 billion EURO (one fourth) in 2002 to 5.9 billion EURO (one half) in 2010. The number of university patent applications filed with the EPO or under the PCT also increased between 2000 to 2010 (see Figure 2).[6]

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[5] German Federal Ministry of Finance, Data portal, Table 1.6.2 (`http://www.datenportal.bmbf.de/portal/de/K16.html`, last accessed 02/08/2018).

[6] One factor which is likely to have contributed to the increase in university patent applications is a law change in 2002. Up to 2002, researchers who worked at a university were able to file patents as the sole applicant. After the reform, universities were mandated to register as the applicant and the researcher was only named as the inventor and compensated for his invention by the university.

The main players in the government sector are the research institutes that belong to one of the four research umbrella organizations named earlier. They account for roughly 75% of overall R&D expenditures in the government sector in Germany.[7] A large share of their income (60%) comes from the federal and the state governments in the form of institutional funding. There is, however, substantial heterogeneity between organizations. Further, the reader should note that the federal structure in Germany is also visible in public R&D funding as the state in which the institute is located does not bear the whole (state) burden, but all other states contribute to the funding as well.[8]

Table 1: Funding and Spending of Public R&D in 2010

	Higher Education	Fraunhofer	Max Planck	Helmholtz	Leibniz	Other
# Institutions	415 (106 Uni.)	60	75	17	86	./.
Share fundamental research	./.	5	100	71	75	30
Share natural sciences	30	30	83	52	57	27
Share engineering	20	64	0	34	10	22
Share humanities	22	2	11	1	20	31
# Overall patents	./.	502	87	approx. 400	approx. 120	./.
# EPO and PCT patents	780	421	81	283	120	./.
R&D budget (€bn)	12.7	1.62	1.54	3.20	1.41	5.2
Institutional funding (€bn)	6.8	0.55	1.23	2.04	0.91	./.
Own business income (€bn)	./.	0.5	0.07	0.6	0.01	./.
Institutional funding shares						
Federal gov.	25	90	50	90	50	./.
Home state gov.	75	6.7	25	5	25-50	./.
Other state gov.	0	3.3	25	5	25-50	./.

Notes: Federal and state funding shares are on average. Contribution of other states depends on *Koenigsteiner Schluessel*. Patent applications include only applications filed with the European Patent Office or under the Patent Co-operation Treaty. Humanities include social sciences.
Source: Authors' calculations based on German Federal Ministry of Finance, data portal, Table 1.6.1 and 1.2.2, German Statistical Office, 2012, Finance and Taxes (Fachserie 14), Reihe 3.6, Table 2.4, 3.8, 4, GWK - Pakt fuer Forschung und Innovation - Monitoring-Bericht 2018, Table 14, and OECD RegPat database, 2010.

The Fraunhofer Society (17,000 employees) consists of 60 legally non-independent institutes (in 2010) and is the largest organization for application-oriented research in Europe. Two third of their R&D expenditures comes from project funding or own income which is relatively high compared to the other research organizations, the remainder is institutional funding. The latter comes to 90% from the federal government, 3.3% from the "home" state and 6.6% from all other states. In 2010, the overall budget of the Fraunhofer Society amounted to 1.62 billion EURO and the Fraunhofer institutes filed 421 patent applications with the EPO (or under PCT) in out data, out of 502 patentable

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[7] German Federal Statistical Office, 2012, Finance and Taxation (Fachserie 14), Reihe 3.6, Table 1.3.

[8] The contribution of all non-home states follows the *Koenigsteiner Schluessel*, which is based on tax revenue after fiscal equalization (67%) and population size of the respective state (33%).

innovations in total in 2010.[9]

Researchers at the 75 Max Planck institutes (13,000 employees) conduct solely fundamental research. The majority of the organization's expenditures (1.54 billion EURO in 2010) is institutionally funded (around 80%) and stems equally from the federal government and the states. Half of the state share is funded by the "home" state and the rest by all other states. The Max Planck society registered 81 new patents with the EPO (or under the PCT) in our data and had in total 87 patent applications in 2010.[10] The relatively high expenditures per filed patent compared to the Fraunhofer institutes is due to a stronger focus on natural sciences (83% compared to 30%), humanities (11% compared to 2%) and fundamental research (100% compared to 5%).

The Helmholtz Community (32,000 employees) is the biggest research organization in Germany and consists of 17 research centers. They conduct fundamental research (71%) by employing large facilities. Institutional funding makes up around 75% of their total income (3.20 billion EURO in 2010) and public and private third party funding and own income around 25%. The institutional share is borne to 90% by the federal government, 5% by the "home" state and the rest by all other states. The Helmholtz institutes filed around 400 new patent applications in 2010.[11] We observe, however, only 70% of them in our data. This is slightly less than the share for the other associations and likely to be related to patents filed by subsidiaries of the institutes (which we do not consider) and patent applications filed by foreign institutes. While the ratio of expenditures per patent is closer to the one for the Fraunhofer institutes compared to the Max Planck institutes, it is still larger. The reasons is the stronger focus on natural sciences (52%) and fundamental research (71%).

The Leibniz Society (13,500 employees) has 86 independent member institutions that widely vary from academic service facilities to fundamental research institutes. Around 65% of their budget (1.41 billion EURO in 2010) is institutionally funded. Half of the institutional funding comes from the federal government, and on average 25% from the "home" and 25% from all other states, but this varies between institutes. The member institutions of the Leibniz society filed 120 patent applications in our data, out of around 120 in total in 2010.[12] The relatively higher expenditures per filed patent result from

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[9] GWK - Pakt fuer Forschung und Innovation - Monitoring-Bericht 2018, Table 14 (`https://www.gwk-bonn.de/fileadmin/Redaktion/Dokumente/Papers/GWK-Heft-58-Monitoring-Bericht-2018.pdf`, last accessed 02/08/2018).

[10] GWK - Pakt fuer Forschung und Innovation - Monitoring-Bericht 2018, Table 14 (`https://www.gwk-bonn.de/fileadmin/Redaktion/Dokumente/Papers/GWK-Heft-58-Monitoring-Bericht-2018.pdf`, last accessed 02/08/2018).

[11] No exact number is available for 2010. In 2012, 409 patents have been filed. (GWK - Pakt fuer Forschung und Innovation - Monitoring-Bericht 2018, Table 14 (`https://www.gwk-bonn.de/fileadmin/Redaktion/Dokumente/Papers/GWK-Heft-58-Monitoring-Bericht-2018.pdf`, last accessed 02/08/2018).)

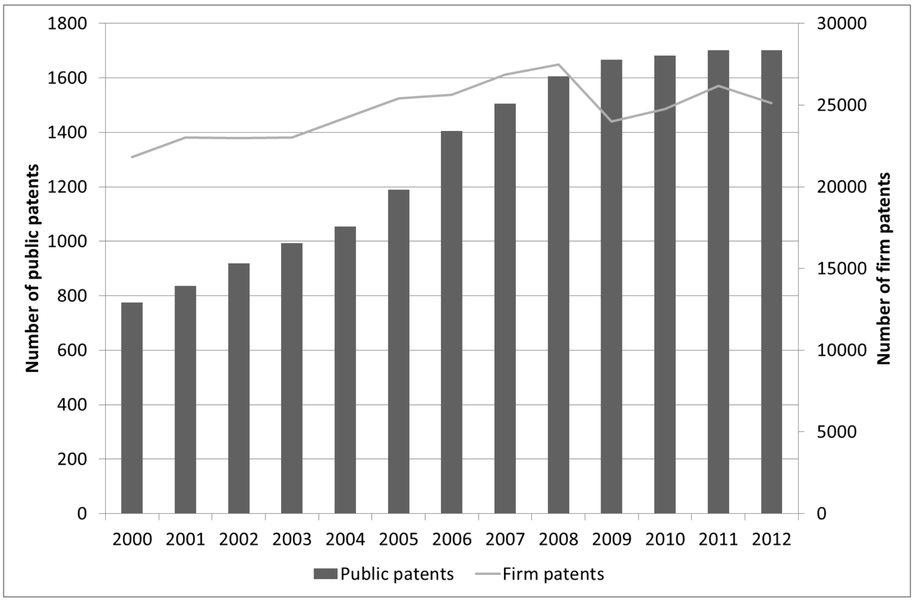
[12] No exact number is available for 2010. In 2012, 121 patents have been filed (GWK - Pakt fuer Forschung und Innovation - Monitoring-Bericht 2018, Table 14 (`https://www.gwk-bonn.de/fileadmin/Redaktion/Dokumente/Papers/GWK-Heft-58-Monitoring-Bericht-2018.pdf`, last acces-

a larger budget share for natural science (55%), humanities (20%) and for fundamental research (75%).

The funding for the research institutes is set for some years in advance in non-public committees, in which representatives of the umbrella organizations as well as of the federal and state governments take part. Institutional funding as well as overall funding increased over time, the latter from 5.4 billion EURO in 2002 to 7.8 billion EURO in 2010. Consistent with the budget increase, the number of patent applications by these research institutes observed in our data has - except for the Helmholtz institutes - increased between 2000 and 2010 (see Figure 2).

Figure 3 summarizes the evolution of the overall number of patent applications by universities and our considered research institutes. Further, the figure shows the evolution of private patents, which also increased between 2000 and 2010.

Figure 3: Evolution of Public and Firm Patent Applications



Notes: Patent applications include only applications filed with the European Patent Office or under the Patent Co-operation Treaty. Public patent applications include only applications filed by universities and the considered research institutes. *Source:* Authors' calculation based on OECD RegPAT database, 2000-2012.

3 Data and Empirical Methodology

3.1 General Estimation Strategy

Our empirical strategy assesses the impact of patent applications by universities and research institutes as a proxy for public R&D on patent applications by firms on the

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German county level between 2003 and 2010.[13] Our estimation equation reads as follows:

$$ln(CP_{i,t}) = \alpha_i + \beta_1 PP_{i,t} + \beta_2 PP_{i,t}^2 + \gamma X + \epsilon_{i,t} \tag{1}$$

The dependent variable is the logarithm of the number of patent applications filed by firms located in county i at time t. Since 99% of the county-year observations in the sample have non-zero firm patent applications, using the log-linear model is not restrictive compared to using a count-model. We prefer the log-linear model as it seems to be more robust. However, we report also the results of a Poisson model with the number of firm patent applications as dependent variable to convince the reader that the model choice is not driving the results.

Our main explanatory variable of interest is the number of public patent applications (PP) in county i at time t. To allow a flexible relationship, we include the number of public patents linear and squared.[14] An important assumption of our estimation strategy is that only firms active in region i benefit from public patents in region i. Hence, we are estimating a lower bound of the impact of public patents on firm patents, if positive non-local knowledge spillovers exist. Their magnitude is, however, likely to be small given that we estimate on the county level and the results of prior literature (e.g. Andersson et al., 2009; Belenzon and Schankerman, 2013). To rule out that we are overestimating the spillover effects due to a potential relocation of firm R&D activities into regions with high levels of public R&D within Germany, we investigate this channel explicitly in a robustness check.

Our two main variables are constructed using the OECD RegPat database. This database covers all patent applications filed with the European Patent Office (EPO) and under the Patent Co-operation Treaty (PCT) up to 2014.[15] The database includes general information about the patent as well as name, address and county codes of applicants and inventors. The address information for the inventors are particularly important for our analysis, as we use them to map patent applications to counties.[16] We believe this to be superior to using the applicants' address information, as the applicants' location may be very different from the location of the invention. This is particular true for large firms

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[13] While it is certainly of interest to investigate patent class heterogeneity, we are not able to do so in a credible way due to a lack of instruments.

[14] In a non-reported robustness test, we also include the number of public patents to the power of three. The estimated semi-elasticities are very similar. The main difference is that the semi-elasticity is larger for low levels of public patent applications and decreases stronger with the level of public patents. Results are available upon request. Including higher order polynomials is not possible, as the instrument strength is then not longer sufficient.

[15] A patent application filed under the PCT is similar to a patent application filed with the EPO. It allows to file one patent application to protect an invention in several (potentially all PCT contracting) states.

[16] This is also the reason why we cannot use PATSTAT. While for some countries PATSTAT includes also address information for inventors, it does not so for Germany.

that have several establishments and legally non-independent research institutes as, for example, the Frauhofer institutes. Given that we are estimating on the county level, we believe that most researchers live and work in the same county.[17]

One potential disadvantage of our data is that it does not include all patents filed by firms, universities and research institutes. The resulting bias is, however, likely to be small. First, according to the German Patent Office, roughly 660.000 patents were valid in Germany in 2017, 80% of them were granted by the EPO.[18] We observe a similar ratio of EPO and PCT patent applications to overall patents for the research institutes as shown in Table 1. Second, Dechezlepretre et al. (2016) study the impact of R&D tax credits on national and EPO patent applications by UK firms. They show that the EPO patents are of higher value but also that the relative impact of the UK R&D tax credit on the number of firms' national and EPO patent applications is of similar magnitude.

We identify patent applications by firms using the legal form of the applicant and public patents via the applicants' names in the database. To obtain a reasonable proxy for R&D activities, we adjust the raw number of patent applications as follows: First, we count patents only once independent of the number of patent classes they are filed. Second, we weight for the same reason patents by the number of inventors and applicants.[19] Thus, if a patent is filed by one applicant and invented by two researchers, one located in county A and the other in county B, county A and B get 0.5 patents. In the case of two applicants, one is a firm and the other an individual, county A and B would have 0.25 patents each.

The remaining parts in our estimation equation are a county specific effect (α_i) and our set of control variables, captured in the matrix X.[20] The latter includes the population in the county, linear and squared, the population density, linear and squared, the number of physicians per 100.000 inhabitants as well as the number of students per 1.000 inhabitants.[21] To account for the tax burden on firm profits, which affects innovation behavior as well, we include the business rate multiplier as well as the property tax multiplier. In addition, we include the seat share of the Social Democrat Party, the Greens, the Liberals, and the Christian Democrats in the community councils. Moreover, we account for the fact that during our sample period, several neighboring countries of Germany have introduced patent boxes. These patent boxes offer a substantially lower tax rate on profits from patents and thus might affect innovation behavior in particular in German coun-

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[17] To the extent that this is not the case, it will introduce measurement error, which is, however, addressed by our IV strategy outlined later.

[18] Press notice of the German Patent Office (`https://www.dpma.de/dpma/veroeffentlichungen/statistiken/patente/index.html`, last accessed 02/08/2018).

[19] In a sensitivity check we only weight by the number of inventors, the results are basically unchanged. This is not surprising since the majority of patents are filed by only one applicant.

[20] The control variables are obtained from the INKAR database as well as from Statistik Lokal, provided by the Federal Statistical Office. The tax rates as well as the political variable stem from the municipality level, we use them thus municipality-population weighted.

[21] In a robustness check, we also included the natural logarithm of the population, linear and squared, and the results are unchanged.

ties that are located close to those countries. Belgium and the Netherlands introduced a patent box in 2006 and Luxembourg in 2007. We define two dummy variables, one if the county belongs to the 25% closest counties to Belgium and the other if the county belongs to the 25% closest counties to the Netherlands or Luxembourg. The indicator variables are interacted with the respective reform dummy. Finally, we absorb business cycle effects as well as differences between states by including year and state fixed effects and in robustness test also linear and squared state trends.

Our estimation sample covers the years from 2003 to 2010 due to the availability of the data for our instruments, which are described below. From the overall 412 counties in Germany, we exclude the city states, which make up 4 counties in total (Berlin, Bremen, Bremerhaven and Hamburg), due to their larger size and 8 additional "outlier" counties. The latter are characterized by having a number of firm patents in the top 1% of the distribution. We remove them to rule out that a handful of large firms or large cities are driving the results. This leaves us with 3,208 county-year observations. In the log-linear model, only 3,188 county-year observations are used as 20 county-year observations have zero firm patent applications.

In additional specifications, we also estimate the relationship of interest on the applicant-region level while accounting for applicant region fixed effects. This allows us to explore heterogeneity between firms (applicants) with respect to their patenting behavior in the past. In addition, we investigate not only the overall response of firm R&D, but also the importance of the intensive margin, e.g. the number of patents per firm, and the extensive margin, e.g. the number of patenting firms. Finally, as mentioned above, we assess the role of within firm spillovers as one potential form of non-regional spillovers that could lead to an upward bias in our estimates. To do so, we include the number of public patent applications in all other regions, linear and squared, in which the applicant filed patents between 1999 and 2002.

3.2 Instrumental Variable Strategy

There are three main concerns regarding our outlined estimation strategy. These are (i) omitted variables that drive both private and public R&D, (ii) reverse causality, since public R&D may be influenced by private R&D, and (iii) the assumed immediate impact of public R&D on private R&D. The latter point is less severe when using cross-sectional and time-series variation, but highly restrictive when exploiting solely time-series variation. We address these three challenges by employing an IV estimator using two sets of excluded instruments.

Our first instrument is the 4-year lagged institutional funding for Fraunhofer and Leibniz institutes that engage in R&D activities.[22] We use solely institutional funding

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[22] The data for Leibniz institutes have been obtained from annual publications of the Leibniz Society.

instead of overall R&D expenditures to rule out a direct correlation of firm R&D with public R&D since the research institutes, in particular the Fraunhofer institutes, do carry out R&D on behalf of firms. Further, we exclude public project funding, as the likelihood of receiving it depends strongly on the success probability of a particular project. Since institutional funding may still correlate with firm R&D if governments take the level of firm R&D in a region into account when deciding about the level of institutional funding[23] or if both private and public R&D activities are driven by unobserved factors, we use lagged institutional funding. Our choice of the 4-year lagged institutional funding is motivated by ensuring a sufficiently long period to address a potential reverse causality or omitted variable bias on the one hand and by ensuring a sufficiently strong instrument on the other hand.[24] Since the use of lagged funding to address reverse causality fails if public and private R&D activities are highly persistent and cross-section variation is used for identification, we also solely exploit time-series variation by including county-fixed effects. To avoid that in this case a substantial part of the variation in the excluded instrument stems from institute openings or closures, which are likely to be even more endogenous, we consider only institutional funding for institutes that existed between 1999 and 2007 when constructing the instrument.

Our second instrument focuses on R&D expenditures in the higher education sector. More precisely, we use the 4-year lagged institutional funding for central service staff of universities that existed between 1999 and 2007.[25] The arguments for using lagged institutional funding and for focusing on higher education institutes that existed between 1999 and 2007 are the same as for the research institutes. Further, we focus solely on universities which are the main driver of R&D in the higher education sector in Germany. Since lagged institutional funding of universities is a function of the number of students and thus of the number of graduates in 3 to 5 years time, we consider only institutional funding for central service staff as administrators or librarians. This is substantially less correlated with the number of students, but still an indicator of the research activities

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The data for Fraunhofer institutes has been provided by the Fraunhofer Society. We also collected information for Helmholtz institutes and have been provided with data for Max Planck institutes by the Max Planck Society. For Max Planck institutes the data only starts in 2005 and for the Helmholtz institutes the data is less precise as Helmholtz institutes usually consist of several establishments and we were only able to collect institutional funding data on the institute level.

[23] For Fraunhofer institutes there is even a mechanical relationship, as their institutional funding depends explicitly on the level of third party funding.

[24] In a robustness check, we also use the 6 and 8-years lagged institutional funding. Results are very similar and available upon request.

[25] The data for the construction of the variable stems from the Employee-Statistic of the higher education sector in Germany, which is provided by the research data center of the Federal Statistical Office of the State and the Laender and can be assessed via remote access. The data includes information on all employees in the higher education sector, in particular their job description (professor, research assistant, administrator, etc.), the department they work for, the number of hours worked and the funding of the position (institutional, private or public third party). Since the data does not include information on salaries, we assume a yearly wage of 30.000 EURO per full-time employee when calculating the institutional funding for central service staff.

carried out by a university, as it correlates with the generosity of the institutional funding. In addition, more staff for central services reduces the administrative burden for researchers.

One remaining concern regarding our instruments is a potential correlation with direct subsidies given to firms. If the amount of firm R&D subsidies correlates with the institutional funding, the effect we are estimating may be driven by the subsidies *or* the funding of public R&D. Due to a lack of data for the regional distribution of firm R&D subsidies, we are not able to rule this out directly. However, there are at least two arguments why a co-founding is unlikely. First, the amount of direct subsidies is relatively small compared to public funding for research institutes and the higher education institutions. While the federal and the state governments fund 19 billion EURO R&D expenditures in the government and higher education sector, they fund only 2 billion EURO R&D expenditures in the business sector (out of 47 billion EURO).[26] Second, although we do observe a positive correlation of the growth rate of overall direct subsidies and the growth rate of overall public funding for research institutes (0.76, p-value: 0.03) and universities (0.42, p-value: 0.30), the correlation turns negative and insignificant for research institutes (-0.09, p-value: 0.82) and universities (-0.29, p-value: 0.48) once we use the 4-year lagged growth rate. Thus our estimates would only be biased if direct subsidies also need 4 years to stimulate patent applications by firms. This seems, however, rather unlikely.

We implement the IV strategy in the linear model as a two stage least square (2SLS) estimation and in the Poisson model via a control function approach. While the 2SLS model uses the predicted values for the endogenous explanatory variables based on control variables and excluded instruments (the first stage) to remove the endogeneity, the control function approach corrects for the endogeneity by including the predicted residuals of the same first stage regression as regressor. We report robust standard errors for the log-linear model and (county-block) bootstrapped standard errors (500 replications) for the Poisson model. To mitigate level differences in the amount of institutional funding, we use the logarithm of institutional funding plus one, linear and squared, as excluded instruments. Both instruments are highly relevant when estimating without county-fixed effects (see col. (1) and (2) in Table A.1 in the Appendix). If we include county-fixed effects, only the impact of institutional funding for research institutes remains statistically significant (see col. (3) and (4)).

3.3 Descriptive Statistics and Graphical Analysis

Descriptive statistics for the variables used in the empirical analysis are shown in Table 2. The average number of patents per county is 54 and the number of firm patents 47.

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[26] German Federal Ministry of Finance, Data portal, Table 1.1.1 (`http://www.datenportal.bmbf.de/portal/de/K11.html`, last access 02/08/2018).

Table 2: Descriptive Statistics for County Level Estimation Sample

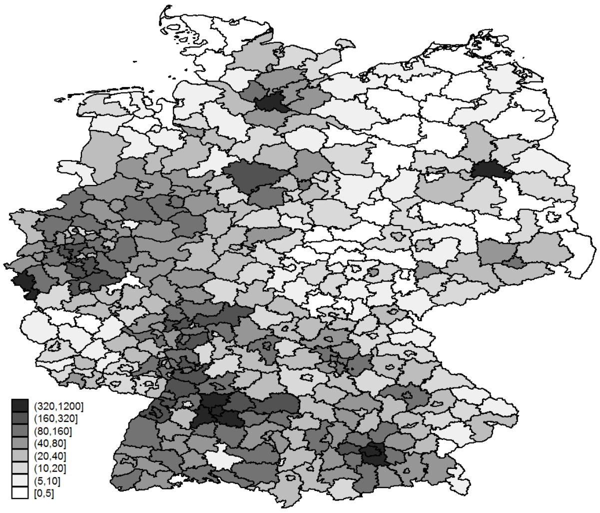
	mean	p25	p50	p75	sd
# Private patents	53.46	12.67	31.74	75.12	60.30
# Firm patents	46.99	10.85	27.60	65.91	52.21
# Public patents	2.11	0.00	0.50	1.79	4.95
# University patents	0.88	0.00	0.17	0.83	2.04
# Institute patents	1.24	0.00	0.17	0.83	3.54
Population in 1,000	175.13	99.59	137.96	219.00	128.30
Population density	474.43	112.00	189.00	562.30	606.06
Physicians per 100,000 capita	157.48	123.60	136.45	175.10	54.39
Students per 1,000 capita	27.48	0.00	0.90	35.05	50.09
Property tax multiplier	353.40	313.78	342.91	390.00	69.03
Business tax multiplier	361.92	329.38	349.65	397.12	49.31
Share SPD	0.24	0.15	0.23	0.32	0.12
Share Union	0.35	0.29	0.36	0.42	0.11
Share Greens	0.04	0.01	0.03	0.07	0.04
Share Liberals	0.04	0.01	0.03	0.06	0.03
Close to Luxembourg	0.24	0.00	0.00	0.00	0.43
Close to Belgium or the Netherlands	0.33	0.00	0.00	1.00	0.47
Observations	3,208				

Notes: Table reports descriptive statistics for our county level estimation sample. Property tax and business tax multiplier as well as the seat shares of the political parties are municipality-population weighted. *Source:* Authors' calculation based on Statistik Lokal, INKAR and OECD RegPAT database, 2003-2010.

In comparison, there are only 2.1 public patents on average, 1.24 are filed by research institutes and 0.88 filed by universities. The average county has 175,000 inhabitants.

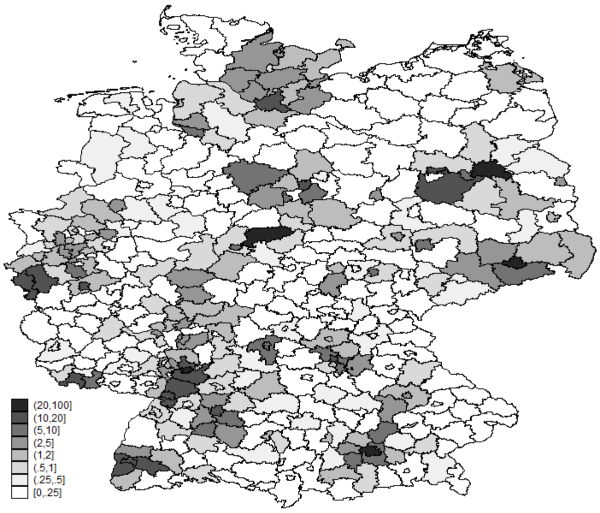
To assess some first evidence for our research question, we illustrate the distribution of firm and public patents within Germany (see Figure 4 and Figure 5, respectively). Counties with a darker color have more firm or public patent applications. There is some evidence that more public patents are linked to more firm patents. To inspect the relationship further, Figure 6 plots the average number of firm (white dots, left scale) and public patent applications (black square, right scale) for deciles of public patent applications. There is again evidence that counties with more public patent applications also have more firm patent applications. Interestingly, the pattern of public to private patents (which depends of course on the scales) is different in the 10th deciles. This could suggest a non-monotone relationship, for which we, however, account in our estimations. Finally, Figure 7 plots the number of firm patents in counties with and without public patents for population deciles. We do so to inspect whether the potential relationship is driven by differences in the size of counties. The figure does not suggest so, as for all population deciles the number of firm patents is larger in counties with public patents compared to counties with no public patents.

Figure 4: Number of Firm Patents 2003



Notes: Figure shows the number of firm patent applications per county in 2003. All counties are included. In the final estimation sample, city states and counties with firm patent applications in the top 1% of the distribution are excluded. *Source:* Authors' calculations based on OECD RegPat database, 2003.

Figure 5: Number of Public Patents 2003



Notes: Figure shows the number of public patent applications per county in 2003. All counties are included. In the final estimation sample, city states and counties with firm patent applications in the top 1% of the distribution are excluded. *Source:* Authors' calculations based on OECD RegPat database, 2003.

4 Empirical Results

Estimation Results without County Fixed Effects: We now present our regression results for the impact of the number of public patent applications on the number of firm patent applications.[27] We start with the results of the linear and the Poisson model without county-fixed effects (see Table 3). Col. (1) to (4) show the results of the linear model and col. (5) and (6) of the Poisson model. Col. (1) presents the OLS estimates. The point estimates for the linear as well as the squared number of public patents are statistical significant at the 1% level. Thus, this suggests a non-linear relationship. In col. (2) to (4) we employ the IV strategy. In col. (2) we only use the 4-year lagged institutional funding for Fraunhofer and Leibniz institutes and in col. (3) in addition the 4-year lagged institutional funding for central service staff of universities as excluded instrument. The test-statistics (reported in the bottom of the Table) confirm again the relevance of our excluded instruments. Further, the test of over-identifying restrictions cannot be rejected

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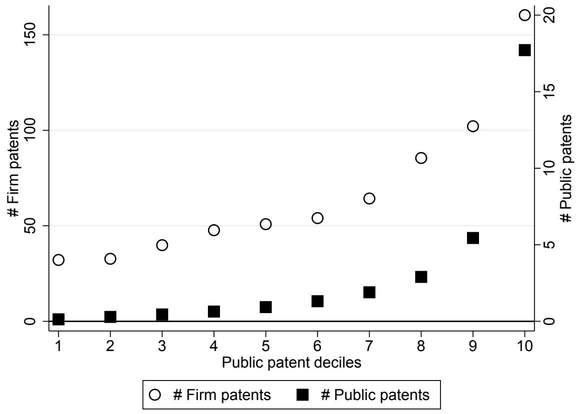
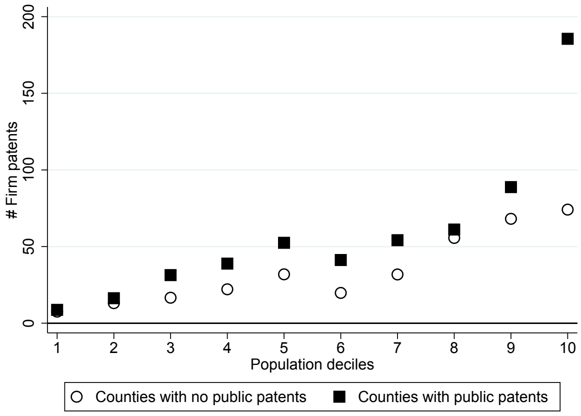
[27] We report the point estimates for our control variables only for our main specifications in Table A.2 in the Appendix. They are largely in line with our expectations with two exceptions. First, the point estimate of the local business tax turns positive once we include county-fixed effects which suggests endogeneity problems due to reverse causality. Second, the effect of health care provision is negative without including fixed effects which could suggest an omitted variable bias. This does, however, not affect the point estimates for our variable of interest as we rely on the IV strategy. One effect that is of interest relates to the impact of patent box introductions in Belgium, Luxembourg and the Netherlands. The interaction effects between the indicator variable that is one if a county is close to these counties and the reform dummies are negative in all specifications and for counties close to Luxembourg also statistically significant at least at the 10% level in all specifications. Thus, the result suggests that patent boxes are a beggar-thy-neighbor policy. The stronger effect for Luxembourg could relate to the fact that German is an official language in Luxembourg.

Figure 6: Number Firm Patents for Public Patent Deciles



Notes: Figure shows the number of public patent applications for public patent deciles. All counties are included. In the final estimation sample, city states and counties with firm patent applications in the 1% of the distribution are excluded. *Source:* Authors' calculation based on OECD RegPat database, 2003-2010.

Figure 7: Number Firm Patents for Population Deciles



Notes: Figure shows the number of public patent applications for population deciles. All counties are included. In the final estimation sample, city states and counties with firm patent applications in the 1% of the distribution are excluded. *Source:* Authors' calculation based on OECD RegPat database, 2003-2010.

when using both instruments, which lends support to the exogeneity of our instruments. The estimated coefficients are thus not surprisingly very similar in col. (2) and (3). We include state-trends, linear and squared, in col. (4), which leaves the point estimates again basically unchanged. Col. (5) presents the results of the baseline Poisson specification. In this specification only the point estimate for the linear term is significantly different from zero, but also much smaller than in the log-linear model. Additional unreported regression results suggest that the different point estimates of the Poisson and log-linear model are due to overdispersion. In col. (6) we address the potential endogeneity of public R&D using a control function approach. Similar to the results for the log-linear model, the point estimates change little. This suggests that there is either no endogeneity of public patents or that our excluded instruments are not able to address the endogeneity due to highly persistent public and private R&D activities. Thus, before interpreting our results, we address the persistence in public and private R&D activities by including county-fixed effects in our estimations.

Estimation Results with County Fixed Effects: The results for the same specifications but now with county-fixed effects are reported in Table 4. The OLS point estimates, shown in col. (1), are substantially lower and only marginally significant. When using solely lagged institutional funding for research institutes (col. (2)), both point estimates increase substantially and are significant at the 5% level. Results are again largely unaffected when additionally using institutional funding for universities as excluded instrument (col. (3)) or when accounting for state-trends (col. (4)). Further, the test of overidentifying restrictions cannot be rejected, suggesting again the validity of our excluded instruments. However, this test should be interpreted with caution as the

Table 3: Main Results for County Level Estimations without County Fixed Effects

Model	OLS				Poisson	
Dep. Var.	log(#patents)				#patents	
IV implemented as		2SLS	2SLS	2SLS		CF
Excluded instrument:						
L4.(ln) Institutional funding for						
research institutes		x	x	x		x
universities			x	x		x
	(1)	(2)	(3)	(4)	(5)	(6)
# Public patents	0.072***	0.086***	0.087***	0.089***	0.027***	0.025
	(0.008)	(0.021)	(0.020)	(0.019)	(0.006)	(0.023)
# Public patents, sqrd.	-0.001***	-0.001**	-0.001**	-0.001**	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)
Observations	3,188	3,188	3,188	3,188	3,208	3,208
Control variables	x	x	x	x	x	x
State-trends				x		
P-value Underidend.		0.000	0.000	0.000		
F-Stat. Weak ident.		43	15	16		
Shea R^2: I		0.088	0.106	0.106		
Shea R^2: II		0.099	0.108	0.109		
P-value Overidend.			0.696	0.657		

Notes: Table shows estimated coefficients for the impact of the number of public patent applications on the number of firm patent applications without county-fixed effects. Col. (1) to (4) show the point estimates of the linear model, which uses (ln) number of firm patent applications as dependent variable, and col. (5) and (6) the point estimates of the Poisson model, which uses the number of firm patent applications as dependent variable. In col. (2) to (4) and (6) we address the potential endogeneity of public patent applications using an IV approach. The excluded instruments in col. (2) are the 4-year lagged (ln) institutional funding for Fraunhofer and Leibniz institutes linear and squared. Col. (3), (4) and (6) employ the 4-year lagged (ln) institutional funding for Fraunhofer and Leibniz institutes, linear and squared, and the 4-year lagged (ln) institutional funding for central services staff of universities, linear and squared, as excluded instruments. The IV strategy is implemented as 2SLS in col. (2) to (4) and via a control function approach in col. (6). Robust (col. (1) to (5)) and block-bootstrapped (col. (6)) standard errors in parentheses. Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. *Source:* Author's calculation based on Statistik Lokal, INKAR and OECD RegPAT database, 2003-2010.

second instrument is not longer statistically significant in the first stage (see col. (4) in Table A.1), which is also indicated by the F-Statistic, which is below 10, and the p-value for the test of underidentification, which exceeds 5%. The point estimates of the baseline Poisson model are as for the linear model close to zero (col. (5)). When using the IV strategy the point estimates increase and are of similar size as for the log-linear model (col. (6)), although less precisely estimated. Overall, the IV results with county-fixed effects using the linear and the Poisson model are very similar to the results of the linear model without county-fixed effects. Thus, the similar magnitude of IV and non-IV estimates in the estimations without county-fixed effects point indeed to the fact that omitted variables and reverse causality are of minor importance. This suggests that public R&D is used by governments in a forward looking way. The downward bias in the specifications with county-fixed effects is thus due to dynamic mis-specification or measurement error (which is more severe in fixed effect estimations).

Sensitivity Analysis: Table A.3 presents robustness tests with respect to the dependent variable, the explanatory variable of interest as well as the control variables using our preferred specification, shown in col. (2) in Table 4. We prefer using only lagged

Table 4: Main Results for County Level Estimations with County Fixed Effects

Model	OLS				Poisson	
Dep. Var.	log(#patents)				#patents	
IV implemented as		2SLS	2SLS	2SLS		CF
Excluded instrument:						
L4.(ln) Institutional funding for						
research institutes		x	x	x		x
universities			x	x		x
	(1)	(2)	(3)	(4)	(5)	(6)
# Public patents	0.007	0.096**	0.111**	0.075**	0.003	0.089
	(0.004)	(0.045)	(0.045)	(0.034)	(0.003)	(0.079)
# Public patents, sqrd.	-0.000*	-0.002**	-0.002***	-0.002**	-0.000	-0.002
	(0.000)	(0.001)	(0.001)	(0.001)	(0.000)	(0.003)
Observations	3,188	3,188	3,188	3,188	3,208	3,208
County-FE	x	x	x	x	x	x
Control variables	x	x	x	x	x	x
State-trends				x		
P-value Underidend.		0.035	0.134	0.156		
F-Stat. Weak ident.		18	9	13		
Shea R^2: I		0.011	0.011	0.014		
Shea R^2: II		0.015	0.016	0.018		
P-value Overidend.			0.351	0.296		

Notes: Table shows estimated coefficients for the impact of the number of public patent applications on the number of firm patent applications with county-fixed effects. Col. (1) to (4) show the point estimates of the linear model, which uses (ln) number of firm patent applications as dependent variable, and col. (5) and (6) the point estimates of the Poisson model, which uses the number of firm patent applications as dependent variable. In col. (2) to (4) and (6) we address the potential endogeneity of public patent applications using an IV approach. The excluded instrument in col. (2) is the 4-year lagged (ln) institutional funding for Fraunhofer and Leibniz institutes, linear and squared. Col. (3), (4) and (6) employ the 4-year lagged (ln) institutional funding for Fraunhofer and Leibniz institutes, linear and squared, and the 4-year lagged (ln) institutional funding for central services staff of universities, linear and squared, as excluded instruments. The IV strategy is implemented as 2SLS in col. (2) to (4) and via a control function approach in col. (6). Robust (col. (1) to (5)) and block-bootstrapped (col. (6)) standard errors in parentheses. Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.
Source: Author's calculation based on INKAR and RegPAT 2003-2010.

institutional funding for Fraunhofer and Leibniz institutes as the excluded instrument, as it avoids the weak instrument problem. Further, the linear model seems to be more robust. In a first robustness test, we assess the role of weighting the number of patents by the number of applicants and the number of investors. We obtain very similar estimates when weighting only by the number of inventors (see col. (1) in Table A.3). This is not surprising given that most patents are filed by only one applicant. In col. (2) we exclude firm patent applications that are filed jointly with a research institute or an university to assess whether public-private collaborations are driving the results. We do not find evidence for that. In col. (3) we use (ln) number of firm R&D employees on the county level as the dependent variable to address the concern that not all inventions are patentable. The number of firm R&D employees is only available for 2003, 2005, and 2007 and 2009, but based on a full-assessment of firms' R&D activities in Germany. The point estimates increase by roughly 50% which is in line with the fact that not all inventions are patentable. In col. (4) we exclude medical patents filed by universities which often operate hospitals. Results are unchanged. Col. (5) and (6) show the results of two robustness tests with respect to the inclusion of control variables. In col. (5) we additionally include (ln) local gross domestic product as well as (ln) local gross-value added and in col. (6) we include (ln) number of firm patents filed between 1991 and 2000 interacted with year dummies to account for a potential agglomeration effect that could drive the results. In both specifications, the point estimates are very similar.

As a last robustness check, we investigate the impact of patent quality. We do so by constructing a quality weighted number of firm patent applications following the procedure outlined in Ernst et al. (2014).[28] Since we have the relevant data only for the EPO patent applications, we only use the subsample of EPO firm patent applications and exclude firm patent applications that were filed under the PCT. The regression results are shown in Table A.4 in the Appendix. We start assessing the impact of focusing solely on EPO firm patents (col. (1)). The point estimate for the linear number of public patents is with 0.076 smaller, but confidence intervals overlap with the point estimate in our preferred specification. In col. (2) we adjust the number of firm patent applications using the absolute quality indicator and in col. (3) using the relative quality indicator. Finally, we simply weight firm patent applications by the patent's family size (col. (4)). All point estimates are very similar which suggests no impact of patent quality heterogeneity on our IV estimates.

Effect Size: Given the robustness of our IV results, we now discuss the size of the impact of public on private R&D. Due to the non-linear and potentially even non-monotone relationship, we illustrate the effect of a marginal increase in public patents graphically based on the results of our preferred specification shown in col. (2) in Table 4. Our estimated semi-elasticity for a level of public patents from 0 to 26 is shown in Figure 8. The semi-elasticity is decreasing with the number of patents and turns negative at a level of around 21 public patents. For the median county with non-zero public patents we estimate a semi-elasticity of 0.09.[29] For the median county for which our instrument for research institutes is non-zero, we estimate a semi-elasticity of 0.07 which translates into an elasticity of 0.39.

In absolute terms, our results suggest that in the median county with non-zero public patents an increase in the number of public patents by one would generate 3.5 new firm patent applications (median patent applications is 38).[30] While the absolute number is interesting, even more important are the public costs to generate these additional patents.

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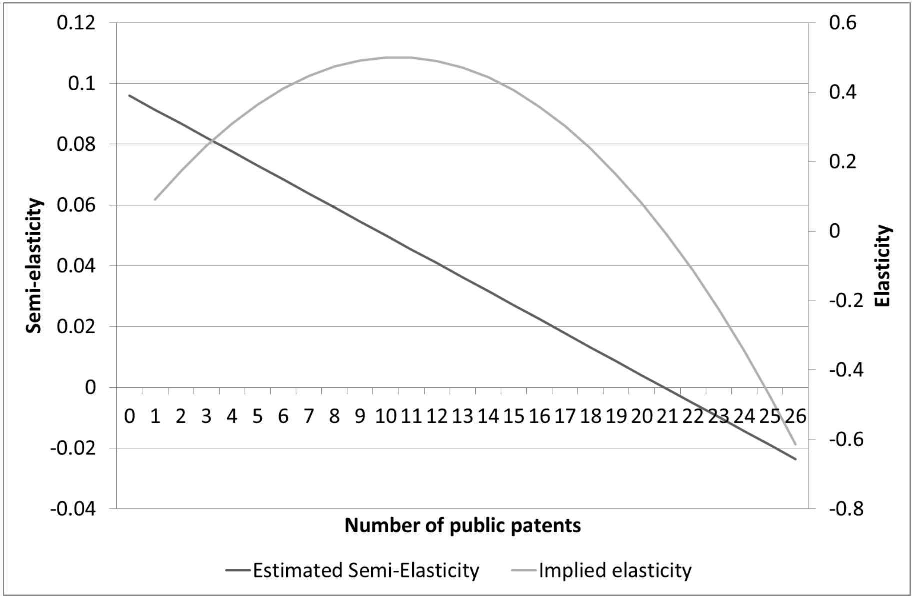
[28] The quality of a patent is based on three factors: a patent's forward citations, its family size, and its number of technical fields. The number of forward citations a patent receives within five years after the publication date signals if the patent has induced further innovations. The patent's family size which is the number of countries in which the firm files a patent application is an indicator for the patent's anticipated earnings potential. Lastly, the number of technical fields the patent is filed in presents a proxy for its technological quality (Lerner, 1994).

[29] We focus on the median as the distribution of patent applications is skewed.

[30] In the median county with non-zero lagged institutional funding for research institutes, 2.8 new firm patent applications are generated.

Figure 8: Semi-Elasticity and Elasticity of Firm Patents to Public Patents



Notes: The figure shows the estimated semi-elasticity of the number of firm patent applications with respect to public patent applications as well as the implied elasticity. Semi-elasticity and elasticity are based on the specification shown in col. (2) in Table 4.

Although our first stage provides a relationship between institutional funding and the number of public patents, this relationship is likely to be misleading. The reason is that we use all public patents, but only institutional funding for Fraunhofer and Leibniz institutes as excluded instrument due to a lack of data. Further, patents are not produced in all science fields. Given these difficulties, we believe it is informative to think about a lower and an upper bound of the costs per patent. An upper bound is given by the simple average of R&D expenditures of the research institutes per patent, (excluding own income and expenditures for research in humanities) which is 5.3 million EURO (see Table 1). This would give us institutional costs per firm patent of 1.5 million EURO for the median county with non-zero public patents. A lower bound can be characterized by simply focusing on Fraunhofer institutes, which are mainly active in technology and application-oriented research. Using a fixed effect Poisson model with the number of Fraunhofer institutes' patent applications as dependent variable and the institutional funding for Fraunhofer institutes as explanatory variable (results are available upon request) we calculate the institutional costs per Fraunhofer EPO (or PCT) application to be around 2.7 million EURO, which is close to the simple average of expenditures per patent for the Fraunhofer institutes.[31] Thus, a lower bound of the institutional costs per patents in the median county with non-zero public patents is given by 0.8 million EURO. As a robustness check, we can also use the estimated costs per EPO patent for a UK firm of 4.6 million EURO (3.7

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[31] We estimate a semi-elasticity of 0.06. The mean number of Fraunhofer patent applications is 4.4. Thus, institutional funding has to increase by around 3.8 million EURO such that the number of patent applications increases by 23% which is one additional patent. However, this has to be scaled down, as we only consider institutional funding for institutes that existed between 1999 and 2007. These institutes account for roughly 70% of the overall expenditures.

million GBP) as reported in Dechezlepretre et al. (2016). This would suggest institutional costs per patent of 1.2 million EURO, which is within our estimated range. Since our costs per firm patent application assumes a similar impact of research institute' patents as for university' patents, we investigate this also empirically and did not find any evidence against this assumption (results are available upon request). Thus, we conclude that the institutional costs per firm patent application are between 0.8 and 1.5 million EURO.

To put these costs into perspective, we compare them to the public costs per firm patent application using another widely employed firm R&D support strategy, namely R&D tax credits. Two recent papers, one for the US and for the UK, estimate a ratio of value to money of 1.7 for R&D tax credits (see Rao (2016) and Dechezlepretre et al. (2016)). This means that for each GBP (or US Dollar) given as tax credit, a firm spends 1.7 GBP (US Dollar) in (qualifying) R&D expenses. Further, Dechezlepretre et al. (2016) quantify (qualifying) R&D expenses per firm patent to be around 1.5 million GBP for a national patent and 3.7 million GBP for a EPO patent. This implies public costs for one UK firm EPO patent application of 2.7 million EURO (using an exchange rate of 0.8). Under the assumption that UK and German firms are similar, this means that the public costs per firm patent application using R&D tax credits are roughly twice as large as the public costs using public R&D. In other words, it is less expensive to stimulate firm R&D by creating knowledge outside the firm than by providing financial incentives to the firm.

Intensive vs Extensive Margin: In the final part of the empirical analysis, we aim to investigate which firms are responding to an increase in public R&D. We start investigating the relevance of intensive and extensive margin. The results are reported in Table 5. In col. (1) and (2) we use the number of patenting firms, and in col. (3) and (4) the number of patents per firm, both on the county level. Col. (1) and (3) report the results of the log-linear model and col. (2) and (4) of the Poisson model. In all specifications, we include county-fixed effects and employ the IV strategy with lagged institutional funding for research institutes as excluded instrument. The point estimates of the linear and the Poisson model are very similar for each of the dependent variables, although as before less precisely estimated using the Poisson model. Since the point estimates are substantially larger and only significant for the number of patenting firms, our results suggests that the extensive margin is the more important adjustment margin. This contrasts with empirical evidence on the impact of R&D tax credits on firm patenting behavior, for which usually the intensive margin is the more important adjustment margin (e.g. Dechezlepretre et al. (2016)).

Next, we assess whether the extensive margin is driven by previously non-patenting firms or "occasionally" patenting firms. We do so by estimating the relationship of interest at the applicant-county level including applicant-county-fixed effects. The results are shown in Table 6. Col. (1) shows the results of the baseline and col. (2) of the IV Poisson model specification. The point estimates are literally zero in col. (1) and again larger

Table 5: Estimation Results for Intensive and Extensive Margin Response

Model	OLS	Poisson	OLS	Poisson
Dep. Var.	ln(.)		ln(.)	
	# patenting firm		# patent intensity	
IV implemented as	2SLS	CF	2SLS	CF
Excluded instrument: L4.(ln) Institutional funding for research institutes	x	x	x	x
	(1)	(2)	(3)	(4)
# Public patents	0.081**	0.075	0.015	0.018
	(0.035)	(0.055)	(0.021)	(0.060)
# Public patents, sqrd.	-0.002**	-0.002	-0.000	-0.000
	(0.001)	(0.002)	(0.000)	(0.002)
Observations	3,188	3,208	3,188	3,208
County-FE	x	x	x	x
Control variables	x	x	x	x
P-value Underidend.	0.027		0.027	
F-Stat. Weak ident.	13		13	
Shea R^2: I	0.010		0.010	
Shea R^2: II	0.013		0.013	

Notes: Table shows estimated coefficient for the impact of public patent applications on the number of patenting firms (col. (1) and (2)) and the patent intensity of firms (col. (3) and (4)). In col. (1) and (3) we use a log-linear model and in col. (2) and (4) a Poisson model. All regressions include county-fixed effects and are IV estimations using 4-year lagged (ln) institutional funding for Fraunhofer and Leibniz institutes, linear and squared, as excluded instruments. Robust standard errors (col. (1) and col. (3)) or bootstrapped standard errors (col. (2) and (4)) in parentheses. Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. *Source:* Author's calculation based on Statistik Loklal, INKAR and OECD RegPAT database 2003-2010.

in col. (2) and at least marginally significant. In col. (3) and (4) we split the sample into applicant-regions with and without patent applications filed between 1999 and 2002. The results show that pre-dominantly firms that have filed patents in a region between 1999 and 2002 respond to the number of public patent applications in that region. Thus, it is not previously non-patenting firms that respond, but occasionally patenting firms. A side benefit of this insight is that it rules out that the effect on firm R&D is driven by spin-offs from university or research institute R&D. In col. (5) we assess the extent of within-firm spillovers as potential negative non-local spillovers that could lead to an overestimation of the local knowledge spillovers. To do so, we include additional variables that measure the number of public patents, linear and squared, in all other regions in which the applicant has filed patents between 1999 and 2002 and instrument them using the lagged institutional funding in these regions. The results suggest negative spillovers and thus provide evidence for some relocation of activity in response to more public R&D in one location. Reassuring is that there is again evidence for a non-monotone relationship, as the negative effect is weaker the more public patents increase in other regions. Finally, we aim to shed some more light on the transmission channel. If personal interactions or workforce mobility are driving the results, we expect a stronger effect for firms that have closer links to the public R&D producers. Our results confirm this presumption. When splitting the sample into applicant-regions without jointly filed (col. (6)) and with jointly filed patent applications with a university or research institute between 1999 and 2002 (col. (7)), we find a very strong impact for the second group but an insignificant and substantially smaller estimates for the first group. Thus, while jointly filed applications are not driving the results, firms that have close links to institutes and universities benefit the most from public R&D.

5 Conclusion

In this paper, we assess the impact of public R&D by universities and research institutes on firm R&D in Germany. We proxy R&D activities using patent applications from the OECD RegPat database and address the potential endogeneity of public R&D by employing an instrumental variable strategy using lagged institutional funding for research institutes and central service staff of universities as excluded instruments. We find that an increase in the number of public patent applications by one increases the number of firm patent applications by 3.5 patent applications in the median county with non-zero public patent applications but also that the effects turns negative for high levels of public patent applications (above 21). We estimate that the costs of an additional public patent are between 2.7 and 5.3 million EURO, which suggests public costs per firm patent application between 0.8 and 1.5 million EURO. Further, we find that the overall effect is driven by an increase in the number of patenting firms in a region and that firms that have collaborated with institutes and universities in a region in the past benefit most from public R&D.

At least three conclusions can be drawn from our work. First, the German firm R&D support strategy, which relies dominantly on public R&D carried out by research institutes is a successful one. If German firms are similar to, for example, US or UK firms, our result suggests that public R&D leads to more firm patent applications at the same public costs than using R&D tax credits to stimulate firm R&D. Second, since public R&D seems to impact firms' R&D activities along the extensive margin, our findings suggest that an optimal R&D support strategy is likely to consists of public R&D as well as direct subsidies. Although the latter are less cost-efficient, they impact firm R&D along the intensive margin. Finally, our results highlight the potential crowding out effect of private R&D and identify a level of public R&D for which the effect turns negative.

Table 6: Main Results for Applicant Region Level Estimations

Model	Poisson						
Dep. Var.	# patents						
IV implemented as		CF	CF	CF	CF	CF	CF
Excluded instrument: L4.(ln) Institutional funding for research institutes		x	x	x	x	x	x
Applicant			without	with		without	with
			patents between 99-02			patents between 99-02	
						filed jointly w/ university or institute	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
# Public patents (PP)	0.005*	0.059*	0.001	0.088**	0.072*	0.025	2.589**
	(0.003)	(0.035)	(0.101)	(0.041)	(0.037)	(0.041)	(1.134)
# Public patents, sqrd.	-0.000	-0.002	0.000	-0.002	-0.002	-0.002	-0.0415**
	(0.000)	(0.001)	(0.003)	(0.001)	(0.001)	(0.002)	(0.018)
# PP other regions					-0.006***		
					(0.001)		
# PP other regions, sqrd.					0.000***		
					(0.000)		
Observations	800,624	800,624	264,016	536,608	800,624	796,008	4,616
Control Variables	x	x	x	x	x	x	x
Appl.-County-FE	x	x	x	x	x	x	x

Notes: Table shows estimated coefficient for the impact of the number of public patent applications within a county on firm patent applications with applicant-county-fixed effects on the applicant region level. All columns show Poisson estimates. The excluded instrument in col. (2) to (7) is the 4-year lagged (ln) institutional funding for Fraunhofer and Leibniz institutes, linear and squared. In col. (1), (2) and (5) all firm applicants are used. In col. (3) we include only firm applicants with no patent applications between 1999 and 2002. In col. (4) we include firm applicants with patent applications between 1999 and 2002. In col. (5) we test for within-firm spillovers by including the number of public patent applications in regions in which the applicant filed a patent between 1999 and 2002. In col. (6) we include only applicant-regions without patent applications filed jointly with a university or research institute between 1999 and 2002 and in col. (7) only applicant-regions with patent applications filed jointly with a university or a research institute between 1999 and 2002. County-Main Patent Class-Block-Bootstrapped standard in parentheses. Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. *Source:* Author's calculation based on Statistik Lokal, INKAR and OECD RegPAT database, 2003-2010.

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A Additional Regression Results

Table A.1: Results for the Impact of Institutional Funding on the Number of Public Patent Applications and First Stage Results

Model	OLS			
Dep. Var.	(# public patents)			
		First Stage Tab 3, col. (6)		First Stage Tab 4, col. (6))
	(1)	(2)	(3)	(4)
L4.ln(Institutional funding institutes)	0.314***	-4.461***	2.416***	-29.364**
	(0.030)	(0.704)	(0.527)	(13.119)
L4.ln(Institutional funding institutes), sqrd.		0.297***		1.090**
		(0.045)		(0.450)
L4.ln(Institutional funding universities)	0.069***	-1.218***	0.096	3.324
	(0.014)	(0.178)	(0.467)	(6.516)
L4.ln(Institutional funding universities), sqrd.		0.082***		-0.106
		(0.011)		(0.209)
R^2	0.447	0.546	0.155	0.169
Observations	3,208	3,208	3,208	3,208
Control Variables	x	x	x	x
County-FE			x	x

Notes: Table shows estimated coefficients for the impact of 4-year lagged (ln) institutional funding of research institutes and 4-year lagged (ln) institutional funding of central service staff of universities on the number of public patents. All regressions are OLS estimates. Col. (1) and (2) show the results without county-fixed effects and col. (3) and (4) the results with county-fixed effects. Col. (2) and (4) show the first stage results for the linear number of public patents as used in col. (6) in Table 3 and col. (6) in Table 4. In col. (1) and (3) we only include linear institutional funding to illustrate the positive impact of institutional funding on the number of public patent applications. Robust standard errors in parentheses. Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. *Source:* Author's calculation based on Statistik Lokal, INKAR and OECD RegPAT database, 2003-2010.

Table A.2: Results for Control Variables

Model	OLS	Poisson	OLS	Poisson
Dep. Var.	ln(# firm patents)	# firm patents	ln(# firm patents)	# firm patents
	Tab. 3		Tab. 4	
	col. (3)	col. (6)	col. (3)	col. (6)
	(1)	(2)	(3)	(4)
Close to LUX.	0.157**	-0.008		
	(0.064)	(0.124)		
Close to BEL or NLD	-0.316***	-0.150		
	(0.071)	(0.109)		
Close to Lux * D(>2006)	-0.144**	-0.106***	-0.096***	-0.061*
	(0.072)	(0.041)	(0.033)	(0.034)
Close to Lux * D(>2007)	-0.065	-0.023	-0.050	-0.032
	(0.066)	(0.041)	(0.031)	(0.042)
Population	0.009***	0.006***	-0.010	-0.006
	(0.000)	(0.002)	(0.007)	(0.011)
Population, sqrd.	-0.000***	-0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Population density	0.001***	0.001***	0.003	-0.003
	(0.000)	(0.000)	(0.003)	(0.003)
Population density, sqrd.	-0.000***	-0.000***	-0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Property tax multiplier	-0.001***	-0.002**	-0.001*	0.000
	(0.000)	(0.001)	(0.001)	(0.001)
Business tax multiplier	-0.003***	-0.001	0.003**	0.001
	(0.001)	(0.001)	(0.001)	(0.001)
Physicians per 100.000 capita	-0.005***	-0.003**	0.005***	0.006**
	(0.001)	(0.001)	(0.002)	(0.002)
Students per 1.000 capita	-0.000	0.001	0.001	-0.000
	(0.001)	(0.001)	(0.001)	(0.001)
Share SPD	-0.580***	-0.993**	0.383	0.183
	(0.195)	(0.393)	(0.395)	(0.374)
Share Union	0.477***	-0.246	-0.298	-0.257
	(0.165)	(0.371)	(0.238)	(0.284)
Share Greens	3.057***	1.069	-2.914***	-2.095
	(0.516)	(1.457)	(0.871)	(1.320)
Share Liberals	1.399**	3.102**	1.249*	0.297
	(0.711)	(1.335)	(0.744)	(0.697)
Observations	3,188	3,208	3,188	3,208
State-FE	x	x		
Year-FE	x	x	x	x
County-FE			x	x

Notes: Table shows estimated coefficients for the control variables in col. (3) and (6) of Table 3 and Table Table 4. Robust (col. (1) and (3)) and block-bootstrapped (col. (2) and (4)) standard errors in parentheses. Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. *Source:* Author's calculation based on Statistik Lokal, INKAR and OECD RegPAT database, 2003-2010.

Table A.3: Sensitivity Analysis for County Level Estimations

Model			IV			
Dep. Var.	ln(# patents)		ln(.)	ln(# patents)		
	Inventor weighted	w/o joint ventures	R&D employees			
	(1)	(2)	(3)	(4)	(5)	(6)
# Public patents	0.096**	0.093**	0.155**		0.096**	0.083**
	(0.044)	(0.045)	(0.075)		(0.046)	(0.040)
# Public patents, sqrd.	-0.002**	-0.002**	-0.003**		-0.002**	-0.002**
	(0.001)	(0.001)	(0.002)		(0.001)	(0.001)
# Public patents,				0.097**		
w/o medical patents				(0.046)		
# Public patents, sqrd.				-0.002**		
w/o medical patents				(0.001)		
Observations	3,188	3,188	1,556	3,188	3,114	3,188
Control Variables	x	x	x	x	x	x
County-FE	x	x	x	x	x	x
GDP and GVA					x	
# Patents 91-00-Year-FE						x
P-value Underidend.	0.024	0.027	0.122	0.030	0.030	0.025
F-Stat. Weak Ident.	15	18	31	14	19	21
Shea R^2: I	0.011	0.011	0.021	0.011	0.011	0.012
Shea R^2: II	0.014	0.015	0.029	0.013	0.015	0.016

Notes: Table shows estimated coefficients for the sensitivity analysis of the impact of the number of public patent applications on the number of firm patent applications with county-fixed effects. In all columns IV estimations are shown using 4-year lagged (ln) institutional spending for Fraunhofer and Leibniz institutes, linear and squared, as excluded instruments. In col. (1) we only use inventor and not applicant weighted number of patent applications. In col. (2) we exclude firm patent applications that are filed jointly with a university or a research institute. In col. (3) we use (ln) firm R&D employees on the county level as dependent variable. In col. (4) we exclude medical patents filed by universities from the number of public patent applications. In col. (5) we control in addition for (ln) local gross-domestic product and (ln) local gross-value added. In col. (6) we additionally control for (ln) number of firm patents filed between 1991 and 2000 interacted with year dummies. Robust standard errors in parentheses. Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. *Source:* Author's calculation based on Statistik Lokal, INKAR and OECD RegPAT database, 2003-2010.

Table A.4: Sensitivity Analysis with Respect to Patent Quality

Model	IV			
Dep. Var.	log(# EPO patents)			
		absolute quality weighted	relative quality weighted	family size weighted
	(1)	(2)	(3)	(4)
# Public patents	0.076*	0.076*	0.071*	0.071*
	(0.039)	(0.043)	(0.042)	(0.040)
# Public patents, sqrd.	-0.001*	-0.002*	-0.001	-0.001
	(0.001)	(0.001)	(0.001)	(0.001)
Observations	3,182	3,182	3,182	3,182
Control Variables	x	x	x	x
County-FE	x	x	x	x
P-value Underidend.	0.007	0.007	0.007	0.007
F-Stat. Weak Ident.	11	11	11	11
Shea R^2: I	0.034	0.034	0.034	0.034
Shea R^2: II	0.043	0.043	0.043	0.043

Notes: Table shows estimated coefficients for the sensitivity analysis with respect to firm patent application quality. In all columns IV estimations are shown using 4-year lagged (ln) institutional spending for Fraunhofer and Leibniz institutes, linear and squared, separately as excluded instrument. We use them separately here as the instrument quality is better in this case (and thus standard errors are lower). We construct a quality adjusted number of patent applications following the procedure outlined in Ernst et al. (2014). Due to data availability we can only implement the quality adjustment for the EPO sample. Thus, col. (1) shows our baseline specification using only EPO patents. In col. (2) we use the absolute quality indicator weighted number of firm patent applications. In col. (3) we use the relative quality indicator weighted number of firm patent applications and and in col. (4) we use a family size weighted number of firm patent applications. Robust standard errors in parentheses. Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. *Source:* Author's calculation based on Statistik Lokal, INKAR and OECD RegPAT database, 2003-2010.

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