Research Evaluation, 2023, **32**, 566–576
https://doi.org/10.1093/reseval/rvad028
Advance access publication 13 October 2023
Article

OXFORD

The effect of applied research institutes on invention: Evidence from the Fraunhofer centres in Europe

Pedro Llanos-Paredes *

Department of Geography and Environment, London School of Economics and Political Science (LSE), Houghton Street, London, WC2A 2AE, UK

*Corresponding author. Email: p.m.llanos-paredes@lse.ac.uk.

This study examines the impact of the Fraunhofer Society, Europe's largest network of applied research institutes, on patent applications. A difference-in-differences strategy was employed exploiting the establishment of five new Fraunhofer centres in the 2000s. The panel includes 65,963 European applicants (both firms and independent inventors) between 1980 and 2019. The results show that establishing a centre increases patent output by at least 13%, robust to using applicants of cities that established a centre by the end of the 2010s as an alternative control group. The effect is driven by an increase in applicants' productivity and not by agglomeration dynamics.

Keywords: innovation and invention; research and development; research institutions; intellectual property and intellectual capital; Europe.

1. Introduction

Innovation plays a key role in fostering economic growth (Romer 1994). This is why policy-makers have been increasingly interested in designing policies that can boost the innovation environments of their respective countries and regions (Edler and Fagerberg 2017). A specific way of deploying these innovation policies is through intermediary organizations that can direct and channel resources into promising but risky innovations. Perhaps one of the most successful instances of this kind of interventions would be the German Fraunhofer Society.

With 72 centres and an annual budget of ~2.3 billion Euros (~0.07% of Germany's GDP), the *Fraunhofer Society for the Advancement of Applied Research* is the largest organization of applied research in Europe (Haldane 2018). They have been promoting innovation and technology transfer by building bridges between firms, universities, and researchers since the aftermath of the Second World War (Rombach 2000). The areas in which they specialize are diverse: from materials and machinery to communication technology and clean energy. Their contribution to the German economy is so considerable that policymakers have tried to replicate their most important aspects through initiatives like the *Catapult Network* in the UK and the *Hollings Manufacturing Extension Partnership* (MEP) in the USA (Wessner 2013).

Although the theoretical literature on growth and innovation would suggest that applied research institutes such as the Fraunhofer are likely to promote regional patenting by bringing in high-skilled labour to the places in which they are embedded, there also seems to be an scarcity of empirical papers that isolate the effect of these interventions on individual inventor of firm-level productivity. For example, both Pfister et al. (2021) and Lehnert et al. (2022) find a modest effect of the Universities of Applied Sciences (UASs) on the total patenting output of Swiss and German regions. Similarly, Andrews (2022) finds a large effect of the establishment of colleges on the patenting of US counties. Nonetheless, in all these cases the authors are unable to disentangle whether these universities are actually increasing the productivity of firms and inventors, or if instead they are merely contributing to existing agglomeration dynamics at a regional level. Likewise, none of these studies look at the impact of a research institute that does not provide any type of educational services and that is solely focused on promoting applied research.

Thus, this is the first paper to provide an estimate of the effect of an applied research organization on the inventiveness of individual firms and inventors while ruling-out the effect of agglomeration dynamics. This is achieved by using rich applicant-level data derived from the text of individual patent filings. Such level of granularity allows me to isolate the effect of the intervention on the productivity of *individual* patenting entities, eliminating the possibility of confounding the effect of the centres with the clustering of innovative activities (Moretti 2021) or the crowding-in of high-skilled labour (Pfister et al. 2021; Andrews 2022). In this way, it contributes to the wider discussion on the effects of policies aimed at boosting science and invention (Schweiger, Stepanov and Zacchia 2022), and to the specific debates on the mechanisms and channels through which applied science can support innovation systems at different geographical levels (Wessner 2013).

Given that most German Fraunhofer institutes were established in the mid-twentieth century or on the basis of various pre-existing research organizations, I focus on the European centres established *outside* of Germany between 2001 and 2009. These are not all the international operations of the Fraunhofer Society, but the more recent timing of their foundation is what enables me to measure their impact over time. The analysis of the non-German centres also helps me isolate the effect of the 'Fraunhofer model' *outside* of its native institutional environment.

I rely on the OECD REGPAT database in its July 2021 version to retrieve longitudinal data of 65,963 patent applicants—both firms and individuals—between 1980 and 2019. The intervention and control groups are defined on the basis of 5,580 cities from four countries: Sweden, Austria, Italy and Portugal. The treatment variable is equal to one (1) for applicants that were in a city with an active Fraunhofer centre after said centre was established, and zero (0) otherwise. The control group includes all other firms and inventors from cities of the listed countries. There is balance and parallel trends on pre-treatment characteristics between the two groups.

With the resulting panel I then go on to implement a canonical two-way fixed effects (TWFE) estimator and an event study. The baseline estimates show a large and statistically significant effect on both the probability of filing a patent in a given year, and the log-transformed patent output per applicant. Instead of waning over time, the impact also seems to increase steadily for 5 years after treatment, only to then plateau ∼20%.

The fact that the Fraunhofer Society decides where to establish a centre might generate a concerns over the non-random allocation of the intervention: what if they have excellent information on the innovative potential of cities, and therefore they actively seek to open new institutes in the most dynamic environments? Also, what if particularly talented inventors and firms decide to locate themselves in cities with a Fraunhofer centre? Both problems of (*endogenous location choice* and *endogenous quality of labour*) could certainly diminish the reliability of the initial estimates.

Since these are valid concerns, I use an alternative control group comprised of cities that later established a Fraunhofer centres (between 2018 and 2021). I argue that they have some of the same characteristics that made the initial cities attractive to the Fraunhofer Society in the past. The coefficients of this second estimation are non-significant for the effect on the probability of patenting, but are similar in sign and magnitude for the overall patent output. Taken together, the results from both estimations suggest that establishing a Fraunhofer centre can increase the number of patents filed per applicant in at least 13%.

Regarding the endogenous quality of labour, I also provide a comparison of the applicant fixed effects of both estimations in order to show that the firms and inventors from the intervention group had similar levels of individual productivity to begin with. Since the effect of the institutes may also vary geographically, I carry out independent estimations for each country with a centre. I find that the effect is only positive on total patent output in places with high starting levels of patenting and public support for R&D. Inversely, in places that historically have not innovated much and do not invest as much in R&D, the intervention increases the likelihood of firms and inventors to at least file a patent in a given year.

The mechanisms through which the centres boost invention are well established in the theoretical literature: they can mobilize capital and labour into applied research (Charlot, Crescenzi and Musolesi 2015), they could strengthen university-industry linkages (D'Este and Patel 2007), and they are able to share knowledge both locally and across borders (Bathelt, Malmberg and Maskell 2004). I do find evidence that they promote collaboration between patent applicants, and that they can help to increase the number of university-owned patents in countries that allow for them.

The rest of the paper is organized as follows. Section 2 discusses the specifics of the so-called 'Fraunhofer model' and frames it within wider debates on the effects of applied research institutes and similar policies aimed at boosting innovation. Section 3 gives a detailed account of the data on applicants, patents and research centres used for the empirical analysis. Section 4 organizes the results of both the baseline estimation and the one using the alternative control group. Section 5 provides additional robustness checks and discusses in greater detail the cross-country differences in the effects, and the potential mechanisms through which the Fraunhofer centres could be affecting innovation. Finally, Section 6 provides a brief summary of the main findings and their significance.

2. The Fraunhofer Society in perspective

To better understand why one could expect the Fraunhofer Society to have an effect on invention, one must understand the business model that has guided their activities since the aftermath of the Second World War. As detailed in more qualitative accounts, they have always had the explicit goal of bridging the gap between industry and basic research on a wide variety of fields (Rombach 2000). This 'bridging' role is also clearly reflected on the Fraunhofer funding scheme: since they can rely on public monies for a third of their budget, they can allocate massive amounts of resources to the testing of concepts and technologies that do not yet possess an immediate application. The technical solutions developed this way can then be offered to industry—either to improve their existing processes or to feed into the research that firms have been carrying out by themselves (Allan, Figus and Schubert 2022).

Far from being over-reliant on public funding, the fact that the other *two thirds* of the Fraunhofer budget have to come from commercial projects and competitive funds is what really spurs the leaders of the Society to actively seek grants and partners in industry. They do not only offer the technological solutions they have developed through licensing (Wessner 2013), but also share the risks and rewards of the implementation of such innovations. In fact, according to Klingner (2010), it is precisely this responsiveness to the needs of industry and policymakers what led them to internationalize in the 1990s: they were trying to keep up with the new international operations of their main German and European customers.

The presence of an university has always been an essential prerequisite for establishing a new Fraunhofer centre (Klingner 2010). This is especially important for their activities, since they provide a significant part of the scientific staff that leads the development and concept testing of new technologies. Some of the lead Fraunhofer researchers hold a dual affiliation with the local universities. Their research teams also integrate particularly talented MSc and PhD students, who are trained by the more senior Fraunhofer staff in an apprenticeship-like scheme. The resulting theses and working papers also help to explore newer and riskier concepts that industry partners might be hesitant to test. If they show to be promising enough, they can then be further developed into a full product that might attract the interest of local firms and their own research divisions (Comin et al. 2019). If this does not happen, the Fraunhofer Society can also provide advice and financial support for spin-off businesses via its venture capital division, *Fraunhofer Ventures* (Wessner 2013).

The mere promotion of collaboration between academia and industry could in fact be one of the channels through which the Fraunhofer Society boosts industry innovation.

Evidence for this can be found in the classic paper by Jaffe (1989), who finds that university research can increase industry patents in almost 10%. Similarly, Lööf and Broström (2008) found a positive impact of university-industry linkages on the propensity of firms to apply for a patent—especially within the manufacturing sector. Cowan and Zinovyeva (2013) also estimated the positive effect of an overall expansion of the higher education system on patenting in Italian regions. Pfister et al. (2021) and Andrews (2022) use a difference in differences approach to find that establishing universities in new cities can give regional patenting a boost—both Switzerland and in the US.

Another channel through which the Fraunhofer Society could boost invention is by increasing the intensity and frequency of knowledge flows locally and across large distances (Bathelt, Malmberg and Maskell 2004). It is known that the centres usually seek dynamic environments that do not only have universities, but also competitive manufacturing firms and an organized business community (Rombach 2000). These actors are usually gathered by initiative of the Fraunhofer centres in workshops in which they discuss new potential projects. If the local expertise is not enough to devise a solution, the centres can also mobilize an international network of experts and researchers (Wessner 2013). These 'long-distance knowledge flows' could be what ultimately gives the Fraunhofer Society its edge over other similar interventions (Haldane 2018).

Thus, the main contribution of this paper will be to provide an estimation of the degree in which applied research organizations like the Fraunhofer Centres can 'catalyse' invention within cities by mobilizing capital into R&D, strengthening university-industry linkages, sharing knowledge across borders, and promoting spinoff businesses. In order to explore this question, I will exploit the establishment of new Fraunhofer centres in the 2000s to estimate their effects on (1) the likelihood of firms and independent inventors to seek any kind of intellectual property protection in a given year (also known as the extensive margin), and (2) the total amount of patent applications that inventors and firms file to a patent office (the intensive margin).

3. Fraunhofer centres and patent data

Most German Fraunhofer centres were established in the mid-twentieth century after a lengthy process of consolidating various (and often competing) research organizations. Since they might have had an independent and persistent effect on the inventiveness of local firms and inventors (Wessner 2013), I focus on the centres that were established *outside of Germany* at a later period—between 2001 and 2009 (see Table 1). The main advantage of restricting the analysis to this subset of centres is that, unlike their German counterparts, they were created over shorter time spans, solidly under the leadership of the Fraunhofer headquarters, and in places where there were potential partners in government, academia, and the business community (Klingner 2010).

It must be noted that these are not the only international operations of the Fraunhofer Society in Europe. Since 2016 there has been a second wave of centres opening in cities of Central and Eastern European countries. Nonetheless, I do not include firms and inventors of these places as part of the intervention group since these centres have not had enough time to mature and effectively change the innovation environments in which they are embedded. This is especially relevant if we consider that testing and developing new inventions is a time-consuming endeavour. Likewise, the agglomeration and scale economies discussed in the literature might make the centres' effect to compound over time.

As shown in Table 1, the oldest centre I analyse is the *Fraunhofer-Chalmers Research Centre for Industrial Mathematics* based in the Swedish city of Gothenburg. With an operating budget of ∼5.7 million Euros, they are known for offering contract research and Modeling, Simulation and Optimisation (MSO) services to firms seeking to slash production costs and improve the efficiency of production processes (Carlson and Torstensson 2018). Similarly, since 2009 the *Fraunhofer Innovation Engineering Center* in the Italian city of Bolzano has been focused on helping firms reap efficiency gains by supporting automation and robot customization (Benedicti 2019).

Although it might seem that the Austrian Fraunhofer is the largest of the analysed centres—both in terms of staff and operating budget—the aggregate statistics derived from the Annual Report are a reflection of the management of *two* different institutes: the *Fraunhofer Austria Center for Sustainable Production and Logistics* in Vienna, and the *Fraunhofer Austria Center for Data Driven Design* in Graz (Guggenberger and Tasch 2021). The approach to innovation of these institutes is similar to the one found in the Portuguese Fraunhofer, that offers the service of rapid prototyping through 3D printing and advanced networks while keeping a branch specialized in automating agriculture and water management (Fraunhofer 2020).

3.1 Patents, applicants and their location

I retrieve patent application data from the OECD REGPAT database, July 2021 (OECD 2021). This rich dataset of ∼4 million patents covers both filings to the European Patent Office (EPO) and to the World Intellectual Property Organization (WIPO) via the Patent Cooperation Treaty (PCT). It geolocalizes and disambiguates the addresses of applicants from 45 countries between 1977 and 2021 as they appear in EPO's *Worldwide Statistical Patent Database* (PATSTAT). In the case of patents that were submitted by more than one applicant, the dataset assigns to each applicant a fractional count of their contribution: for example if two applicants collaborated in filing a patent, each will be assigned 0.5 in the fractional count indicator (Maraut et al. 2008).

The patent-level data retrieved this way is then restricted to the filings between 1980 and 2019 from countries that established a Fraunhofer centre in the 2000s: Sweden, Austria, Italy and Portugal. I focus on patent applicants in general, instead of only looking into individual inventors. This is important since patenting is an increasingly collaborative enterprise that relies on the strength of the teams in charge of R&D activities, and the resources that firms and other large organizations can mobilize (Singh and Fleming 2010; Wu, Wang and Evans 2019). Thus, I aggregate the fractional count of the patents to an applicant-year level and generate an indicator of each applicant's total output in a given year[1] (i.e. the intensive margin of invention). By assuming the applicant existed for all the years between 1980 and 2019, I also create a variable that reflects the probability of patenting in a given year (i.e. the extensive margin of invention).[2]

Even though I am interested in the impact of the Fraunhofer centre on the patenting output of both firms and

Table 1. European Fraunhofer centres established in the 2000s

	FH-Chalmers	FH Austria	FH Italia	FH Portugal
Country	Sweden	Austria	Italy	Portugal
Established	2001	2008	2009	2009
Budget	€ 5.7 million	€ 8.3 million	€ 3.7 million	€ 3.8 million
Employees	67	116	57	96
Locations	Gothenburg	Vienna, Graz	Bolzano	Porto
Source	Carlson and Torstensson (2018)	Guggenberger and Tasch (2021)	Benedicti (2019)	Fraunhofer (2020)

individual inventors, the basic geographical unit I use to assign applicants to the treated or control group is the 'city' as defined by the REGPAT database.[3] I prefer this spatial unit for treatment assignment since 'provinces' are known to have different definitions across countries; and 'regions', even when standardized by the European Union under the *Nomenclature des unités territoriales statistiques* (NUTS), could also include satellite towns and rural areas in which very little invention takes place.

Although firms are not as mobile as individual inventors, some applicants do file patents in different cities. Since I am interested in capturing the applicant-level exposure to the Fraunhofer Society, I assume that (1) each applicant has stayed in the last city it filed an application, and (2) all applicants that were in a city when a Fraunhofer centre was established were exposed to the intervention. This means that applicants can only be considered 'movers' if in another patent application they report a being based in a different city, and that treatment assignment depends solely on being in a Fraunhofer city after the centre was established. For example, if an applicant from Gothenburg went on to patent in another city after 2001, I will still consider her as treated. Similarly, if an applicant previously patented in a control city but then moved to a place that already had a Fraunhofer centre, she will only be considered treated from that year onward.

The resulting sample is composed of 65,963 applicants of 5,580 European cities between 1980 and 2019, leading to 2,638,345 applicant-year observations. The overwhelming majority of the applicants are firms and other institutions, with <1% of the sample being composed of individual inventors. The combined patent output of the full sample is of 272,122 patents filed either to the EPO or to the WIPO under the PCT. Table 2 summarizes the data for both the pre- and post-intervention periods, showcasing the similarity between applicants before the first Fraunhofer centre was established in 2001.

Table 2. Patenting per applicant (1980–2019)

	Mean	SD	Min	Max	*N*
Before intervention (1980–2000)					
Control					
Probability of patenting	0.03	0.17	0.00	1.00	1,290,681
Patent output	1.79	6.04	0.11	373.00	39,356
Fraunhofer					
Probability of patenting	0.03	0.18	0.00	1.00	94,416
Patent output	1.91	3.20	0.17	49.00	2,992
After intervention (2001–19)					
Control					
Probability of patenting	0.07	0.25	0.00	1.00	1,167,790
Patent output	2.28	14.44	0.00	1,126.50	77,123
Fraunhofer					
Probability of patenting	0.07	0.26	0.00	1.00	85,435
Patent output	3.21	11.12	0.17	245.00	6,151

3.2 Data limitations

Given that the Fraunhofer institutes usually partner with universities and business organizations, one could be inclined to think that the centres are merely following the broader agglomeration dynamic of innovation (i.e. the centres are being located in places that already had more inventors and firms engaged in R&D activities) (Feldman 1999). Nonetheless, there are no Fraunhofer centres in the great patenting hubs of London or Paris. On the contrary, their placement suggests an strategic deployment from the German State (Wessner 2013) and a bias towards places with a historical connection with the German-speaking world (Klingner 2010). The Italian Fraunhofer, for example, is placed in one of the few German-speaking cities of Italy—Bolzano. Similarly, the Portuguese Fraunhofer centre was established in 2009 in the city of Porto, where the *Portuguese-German Chamber of Commerce and Industry* has one of its main offices.

Since the descriptive statistics reported in Table 2 suggest that there are striking similarities between applicants form control and Fraunhofer cities before 2001 (i.e. before the first centre was even established), in Section 4 I will follow a difference-in-differences strategy to retrieve a causal estimate of the effect of the centres on invention.[4] As a way of addressing any concerns regarding the endogeneity of the location, in Section 5 I will also provide an estimate that uses an alternative control group comprised of applicants from cities that established a Fraunhofer centre around the end of the 2010s. One can assume that this 'late-treated' group has some similarities to the cities initially selected by the Fraunhofer Society for hosting a centre. I will also check for sorting of firms and inventors into the Fraunhofer cities by comparing the applicant fixed effects retrieved from both estimations.

4. Effect of the Fraunhofer centres on invention

In order to retrieve a baseline estimation of the causal effect of establishing a Fraunhofer centre, I will first implement a two-way fixed effects (TWFE) estimator. For this approach, I regress outcome Y_{it} to a time-variant treatment indicator D_{it}, plus applicant-, year- and cohort fixed effects (α_i, λ_t, and γ_c respectively):

$$Y_{it} = \alpha_i + \lambda_t + \delta D_{it} + \gamma_c + \varepsilon_{it} \quad (1)$$

The treatment indicator D_{it} is equal to one only for applicants that were in a city when or after a Fraunhofer centre was established. Its value is zero (0) if otherwise. The applicant fixed effects α_i control for time-invariant differences in productivity and inventiveness among firms and independent inventors that are in the panel. The year fixed effects λ_t control for the trend in patenting output that is common to all cities and applicants. Finally, the cohort fixed effects γ_c is included to account for the fact that not all Fraunhofer centres were established in the same year. As shown in Table 1, there were three treatment waves: 2001 (Sweden), 2008 (Austria), and 2009 (Portugal and Italy).

It must be highlighted, however, that by estimating the effect of the Fraunhofer centre for the whole post-intervention period, the δ coefficient yielded by Equation (1) could be masking changes in the impact of the intervention over time. This is especially relevant if one takes into account that establishing partnerships and testing and developing new technologies tends to be a time-consuming endeavour. Thus, I implement a second and more complete specification that allows me to capture the effect of the Fraunhofer centres over time:

$$Y_{it} = \alpha_i + \lambda_t + \sum_{\tau=-q}^{-1} \delta_\tau D_{i\tau} \; + \sum_{\tau=1}^{m} \delta_\tau D_{i\tau} \; + \gamma_c + \varepsilon_{it} \qquad (2)$$

Here I regress outcome Y_{it} to τ periods of relative time to the establishment of a centre in a given city ($\tau = 0$). This way I can retrieve a δ for the years leading to the establishment of a centre (i.e. for periods $-q < \tau < -1$) and the effect for the years since the Fraunhofer was actually established (δ_τ for periods $1 < \tau < m$). While the pre-intervention δ coefficients will indicate if there were pre-trends or significant time-variant differences between Fraunhofer and non-Fraunhofer applicants; the post-treatment δ coefficients will provide an estimate of the effect on patenting over time.[5]

This identification strategy relies on the parallel trends assumption. This requires for both the treatment and control groups to exhibit a common trajectory up to the moment in which the intervention happened. Evidence of this is presented in Table 2, where one can appreciate that between years 1980 and 2000, applicants from both the Fraunhofer and Control cities exhibited a similar propensity to patent (i.e. the extensive margin) and a similar patent output conditional on them filing a patent (i.e. the intensive margin). Yet, since the first Fraunhofer centre was established in 2001, one can see a clear divergence in the average number of patents filed by firms and inventors operating in Fraunhofer cities.

If instead one looks at the average patent output *over time* (see Figure 1), it becomes even clearer that the divergence in trends starts when the first Fraunhofer centre is established in Gothenburg (the first red line), and it intensifies once the centres in Austria, Portugal and Italy are opened between 2008 and 2009. The correspondence of this second wave of institute openings with a widening of the gap between control and Fraunhofer cities is then what motivates the use of the TWFE estimator specified in Equation (1).

4.1 Baseline estimation

Table 3 organizes six different specifications of Equation (1). Columns 1 to 3 report the coefficients of three logarithmic regressions on the probability of patenting in a given year (i.e. the extensive margin). Columns 4 to 6 report the coefficients of a linear regression on the natural logarithm of patent output per applicant (i.e. the intensive margin). In order to cluster standard errors by city, applicants were assigned to the city in which they spent more years.

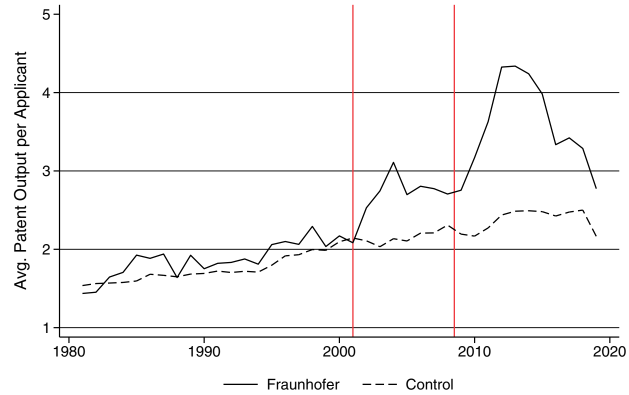

Figure 1. Patent output per applicant in Fraunhofer and control cities.

The most salient result is that, even when controlling for year, treatment cohort and applicant fixed effects, the establishment of a Fraunhofer centre in a given city has a positive effect on both the extensive and intensive margins. In the case of the probability of patenting, the coefficient confidently sits between 0.10 and 0.13, while in the case of the patent output it goes all the way from 0.12 to 0.26. Despite these differences, I consider Columns 3 and 6 to be my preferred specifications. They have the advantage of including applicant fixed effects that might account for time-invariant differences between cities, firms, and individual inventors.

While interesting, these results are reporting the average effect of establishing a Fraunhofer institute for the whole post-intervention period. This means they could be masking heterogeneous effects over time. By implementing the canonical event-study design defined by Equation (2), I can simultaneously test for differences before the establishment of a centre (i.e. test for pre-trends), and retrieve effects for all the years after the intervention happened. The results of this estimation are reported in Figure 2.

The results of the event study show that before the intervention (i.e. between t-6 and t-1) there were no significant differences between the treatment and control group. This placebo test provides additional support to the parallel trends assumption on which the identification strategy is grounded. Inversely, for all the years after treatment ($t1$ to $t9$) Figure 2 reports a positive effect that increases continuously up to three years after the establishment of a centre ($t2$), and then plateaus ~0.20. If we consider all the post-treatment periods from $t1$ to $t10$, the average effect is of 0.17.

5 Robustness, heterogeneity, and mechanisms

5.1 Late-treated as control group

Despite the unconditional parallel trends and the overall balance of the treatment and control groups of the baseline estimation, one could be concerned about the fact that the Fraunhofer Society selects the cities in which they establish a centre. This means that the placement of the institutes could be seeking environments particularly favourable to patenting, that have inventors and firms with a higher-than-average productivity, or that simply have some other idiosyncratic traits that make them appealing for opening a centre. This

Table 3. Effect of the Fraunhofer centres on patent applications

	Probability			Log-transformed		
	(1)	(2)	(3)	(4)	(5)	(6)
Fraunhofer centre	0.132***	0.098***	0.133***	0.127*	0.082	0.254*
	(0.023)	(0.023)	(0.024)	(0.055)	(0.046)	(0.103)
Year effects	Yes	Yes	Yes	Yes	Yes	Yes
Cohort effects	No	Yes	Yes	No	Yes	Yes
Applicant effects	No	No	Yes	No	No	Yes
Observations	2,638,345	2,638,345	2,638,345	125,623	125,623	125,623
Clusters				5,580	5,580	5,580

Standard errors clustered by city in parenthesis.
* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

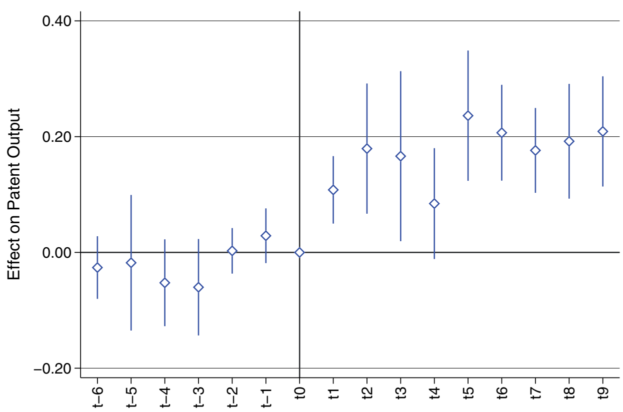

Figure 2. Effect of the Fraunhofer centres over time.

endogenous location choice is partially addressed in the main specification through the inclusion of applicant fixed effects: they absorb any time-invariant country- or city-level characteristics that might have influenced the decision of placing a Fraunhofer institute.

A very basic robustness check that deals with this potential endogeneity in location choice is included in Supplementary Appendix C, where I report event study estimates of Equation (2) including a time-variant indicator of city size. This control variable is built by adding up the total number of applicants in each city for each analysed year, and accounts for changes in the agglomeration and attractiveness of the cities included in the sample. As shown in Supplementary Figure A3, the results are almost identical to the ones reported in Figure 2.

Nonetheless, an alternative way of dealing with this concern is to compare the intervention cities with cities that were *later* selected by the Fraunhofer Society to also host a centre. As shown in Table 4, this alternative control group would include firms and inventors from places that also had a historical connection with the German-speaking world. The Polish city of Opole, for example, used to be called *Oppeln* and was part of Germany until 1945. It now hosts the Fraunhofer *Centre for Advanced Lightweight Technologies*. The Czech city of Ostrava is also known as *Ostrau* in German, and used to be part of the Austrian empire. Now it is also the home of the Fraunhofer *Innovation Platform for Applied Artificial Intelligence*. The Dutch city of Enschede sits right next to the Germany–Netherlands border, with parts of its urban area reaching the edges of the German city of Gronau. This is also where the *Engineering for Complex High-Tech Systems*

Table 4. Fraunhofer centres established between 2018 and 2021

Name	Year	Country	City
Advanced lightweight technologies	2018	Poland	Opole
Engineering for complex high-tech systems	2018	Netherlands	Enschede
Innovation platform for smart shipping	2021	Finland	Turku
Innovation platform for applied artificial intelligence	2021	Czechia	Ostrava

Table 5. Balance of pre-treatment characteristics (1980–2000)

	Treatment	Control	(C-T)	SE
Baseline estimation				
Patents per applicant	1.907	1.793	−0.114	0.112
Probability of patenting	0.032	0.030	−0.001**	0.001
Late-treated as control group				
Patents per applicant	1.907	1.412	−0.495***	0.171
Probability of patenting	0.032	0.025	−0.007***	0.002

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

centre was established. Finally, the city of Turku used to be Finland's capital and has one of the largest ports that connects the country with the rest of Europe. Thus, it should not come as a surprise that it also hosts the new Fraunhofer *Innovation Platform for Smart Shipping*.

Even though using these cities can then control for the unobservable characteristics that might have led to the Fraunhofer centres to be established in certain places, it might also make the identification lose some of the balance between the intervention and control groups. Evidence of this is presented in Table 5, from where one can conclude that the balance on pre-treatment characteristics is not as good as the one reported when using the broader control group that includes all non-Fraunhofer cities of Austria, Italy, Portugal and Sweden. Thankfully, these pre-treatment differences in the probability of patenting and the total patent output should not present a problem for the estimation strategy if the parallel trends assumption holds.

As shown in Figure 3, by implementing the same event-study design defined by Equation (2) one can retrieve non-statistically significant coefficients for the whole pre-intervention period. This means that the patenting activity of applicants from both the Fraunhofer cities and this alternative control group followed similar trajectories up to the moment in which the Fraunhofer centres were established.

Moreover, Figure 3 also reports a large and significant take-off of patenting in the Fraunhofer cities when compared with applicants from the late-treated group. In fact, instead of plateauing ∼0.20, the graph shows the coefficients almost reach 0.40. This only provides additional support to the initial baseline estimation.

Finally, Table 6 includes all the pre- and post-treatment periods and shows six different specifications of Equation (1). Contrary to the baseline estimation reported in Table 3, it is noticeable the lack of an effect on the probability of patenting. Despite this, Columns 4 to 6 also report a large and statistically significant effect on the log-transformed number of patent applications. This would suggest that the effect of the Fraunhofer centres is mainly through the intensive margin (i.e. making firms and inventors patent more inventions) and not through the extensive margin (i.e. increasing their likelihood of developing an invention in a given year).

Taken as a whole, the results of both the baseline estimation and the one based on this alternative control group suggest that the opening of a Fraunhofer institute in a given city generates an increase of *at least* 13% in the number of patents filed by local firms and inventors. This effect on the intensive margin also seems to be heterogeneous over time, requiring at least five years in order to plateau. In Section 5 I will delve deeper into the geographical heterogeneity of the effects, showing that they seem to interact with some country-level characteristics, and the mechanisms with which one could explain the positive impact on invention.

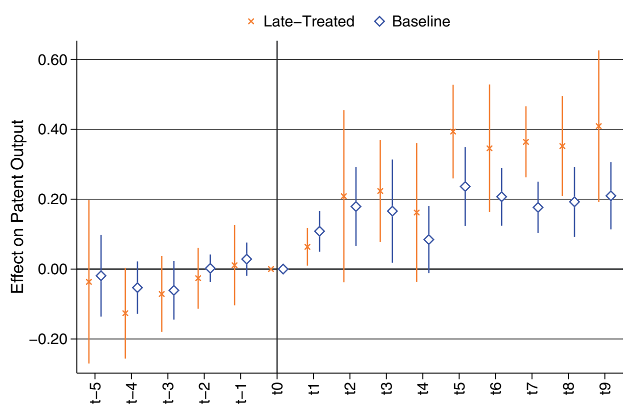

Figure 3. Effect of the Fraunhofer centres using different control groups.

5.2 Sorting

While the alternative control group based on late-treated cities dealt with the issue of endogenous location choice of centres, the estimation might still be biased by the fact that particularly productive firms and inventors can choose to locate themselves in environments that increase their chances of filing a patent application (i.e. endogenous quality of labour). This concern has been partially addressed by the main specification through the inclusion of applicant fixed effects: they account for differences unobserved ability, productivity or skill at an applicant level. An additional robustness check that deals with this particular issue is included in Supplementary Appendix B, where I report the event study estimates after excluding all movers (i.e. applicants that changed addresses) from the baseline sample. The results have similar signs and magnitudes to the ones reported in Figure 3.

Nevertheless, in order to dispel any remaining concerns about differences in the 'average skills' of applicants on both the treatment and control group, Figure 4 plots the distribution of fixed effects for both estimations on total patent output. They suggest that there are no major differences in the inherent productivity or inventiveness of firms and inventors from the treatment and control groups as previously defined. However, in the case of the baseline estimation (see Figure 4a), there seems to be a larger dispersion of fixed effects for the control group. This could be still pointing out to a bias in the initial estimation due to the heterogeneity in applicants' inventiveness.

In order to test for this bias, Table 7 goes on to report a comparison of means of the fixed effects of both estimation strategies. For the case of the baseline estimates, there is a significant difference in the applicant fixed effect between the treatment and control group. Given the fact that they are *higher* for the control group than for the intervention group, one might be inclined to assume that the most productive firms and inventors are sorting themselves into cities that *do not* have a Fraunhofer centre. This would mean that, if anything, the baseline estimation is negatively biased (i.e. it underestimates the real effect of the intervention). If instead one turns one's attention to the alternative estimation strategy, one can see that the difference in fixed effects is negligible, supporting the idea that the coefficients derived from the second comparison against the late-treated group is just as reliable.

5.3 Heterogeneity

The estimates derived from Equation (2) showed that the intervention had heterogeneous effects over time, but it did not

Table 6. Effect on patent applications: late-treated as control group

	Probability			Log-transformed		
	(1)	(2)	(3)	(4)	(5)	(6)
Fraunhofer centre	0.062	0.022	0.049	0.208***	0.095**	0.121*
	(0.043)	(0.045)	(0.046)	(0.052)	(0.029)	(0.059)
Year effects	Yes	Yes	Yes	Yes	Yes	Yes
Cohort effects	No	Yes	Yes	No	Yes	Yes
Applicant effects	No	No	Yes	No	No	Yes
Observations	207,996	207,996	207,990	10,440	10,440	10,440
Clusters				53	53	53

Standard errors clustered by city in parenthesis.
* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

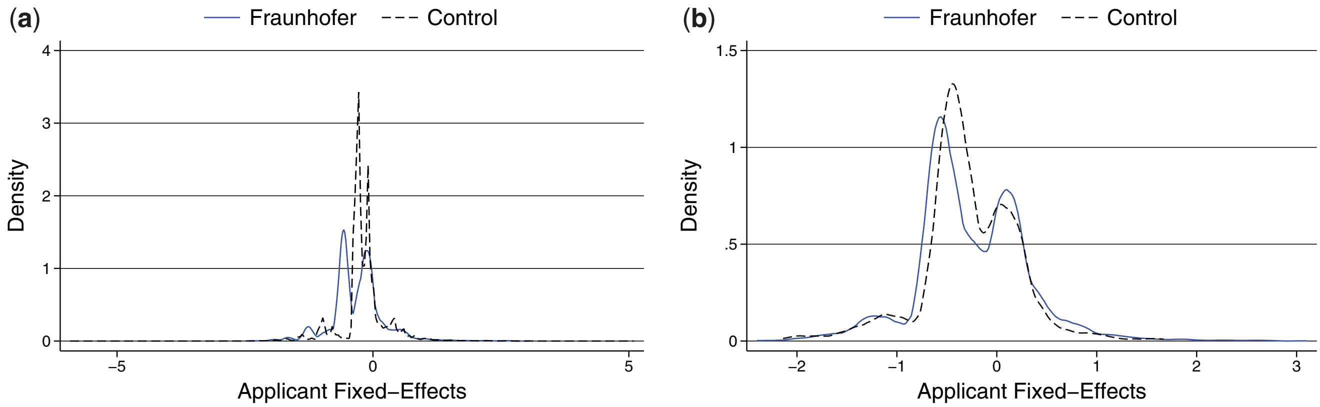

Figure 4. Distribution of fixed effects. (a) Baseline Control Group. (b) Late-Treated as Control Group.

Table 7. T-test of applicant fixed effects

	Treatment	Control	(C-T)	SE
Baseline estimation	−0.307	−0.198	0.109***	0.007
Late-treated as control	−0.256	−0.279	−0.023	0.022

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

account for any other kind of heterogeneity in the impact of the Fraunhofer institutes. In this case, the most obvious potential source of heterogeneity would be the existence of national-level differences in the innovation environments in which the centres try to embed themselves. Thus, Table 8 organizes TWFE estimators of Equation (1) for the four countries considered in the baseline analysis. Columns 1 to 4 report the effects on the probability of patenting, while 5 to 8 on the total number of patents filed.

The reported coefficients suggest that in the case of Austria (Cols. 1 and 5) the Fraunhofer centres did not influence the likelihood of firms and inventors to file a patent, but they helped them to file more applications if they decided to patent at all. Sweden (Cols. 4 and 8) also shows a similar pattern, with an even larger effect on the intensive margin. On the other hand, the centres of Italy and Portugal do not seem to have a positive effect on the total number of patents per applicant, but they increased the probability of the inventors to file a patent.

These two very different ways in which the Fraunhofer centres impact invention are related to the different patenting practices across countries. The literature has long established that innovation patterns depend on the relationships that firms establish with the educational and financial systems (Hall and Soskice 2001). It is entirely possible that in some places companies engaged in R&D do not mind leaving some inventions unpatented, while in other environments it can be standard practice to seek intellectual property protection as soon as a marginal improvement on a product is developed (Cohen, Nelson and Walsh 2000).

This latter instance could very well be the case for Austria and Sweden, that for decades have been among the top patenting nations of Europe (Crintea-Rotaru et al. 2013). In such an environment, it should not come as a surprise that an applied research institute only increases the yearly patent output of applicants (i.e. their productivity), but not their likelihood to engage in the development of new products and technologies in a given year. Inversely, if the Fraunhofer centre is established in countries like Portugal and Italy where filing patents is not that common, we could then expect a larger effect via the extensive margin (i.e. incentivizing firms and researchers to seek intellectual property protection for their inventions).

It must also be mentioned that Sweden and Austria also report larger public support to R&D in the form of subsidies and government aid (Crintea-Rotaru et al. 2013). As discussed by Wessner (2013), there are many instances in which the contract research carried out by the Fraunhofer centres on behalf of the private sector is funded by these government grants. This would only reinforce the idea that applied research institutes do not operate in the void. On the contrary: their effectiveness is highly dependent on the institutional environment in which they are embedded, and they interact with other policies aimed at boosting innovation.

In Supplementary Appendix D I also explore another source of potential heterogeneity. Applicants is a broad category that includes mainly firms, but also independent inventors and other research institutions. Thus, in Supplementary Figure A4 I report a specification that only takes into account institutional applicants (companies and other organizations). The results show coefficients that are almost identical in sign and in magnitude to the ones reported in the baseline event study specification, suggesting that the main results are not being driven by this subset of applicants.

5.4 Mechanisms

As discussed in Section 2, one can expect the Fraunhofer centres to have an effect on invention through the mobilization of capital and labour into R&D (Charlot, Crescenzi and Musolesi 2015), by strengthening collaboration and university-industry linkages (Lööf and Broström 2008), and by creating ‘global pipelines’ through which researchers can exchange knowledge across borders (Bathelt, Malmberg and Maskell 2004). More specifically, it has been documented that Fraunhofer centres hire academics and postgraduate students from local universities in order to incorporate them into a broader network of Fraunhofer experts (Rombach 2000). Similarly, they engage the private sector via workshops from which firms can decide to licence existing technologies, hire Fraunhofer staff to carry out contract research, or collaborate in the testing of new products and manufacturing lines (Wessner 2013).

Although it would be ideal to observe *all* types of collaboration and engagement between inventors and firms, I will

Table 8. Heterogeneity in effects on patenting by country

	Probability				Log-transformed			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Austria	0.007				0.201*			
	(0.005)				(0.096)			
Italy		0.017***				−0.049		
		(0.003)				(0.032)		
Portugal			0.077***				−0.266***	
			(0.003)				(0.048)	
Sweden				0.005				0.453***
				(0.003)				(0.051)
Year effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Applicant effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2,615,385	2,579,583	2,578,958	2,597,276	123,799	121,137	121,143	122,517
Clusters	5,580	5,578	5,578	5,578	5,580	5,578	5,578	5,578

Standard errors clustered by city in parenthesis.
* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

Table 9. Effects on collaboration

	(1) Collaboration	(2) Across Regions	(3) With Universities
Fraunhofer centre	0.020**	0.000	0.002
	(0.007)	(0.000)	(0.001)
Year effects	Yes	Yes	Yes
Cohort effects	Yes	Yes	Yes
Applicant effects	Yes	Yes	Yes
Observations	2,638,345	2,638,345	2,638,345
Clusters	5,580	5,580	5,580

Standard errors clustered by city in parentheses.
* $P < 0.05$,
** $P < 0.01$,
*** $P < 0.001$.

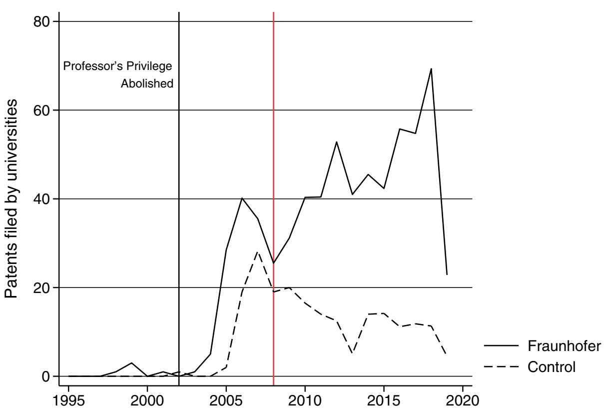

Figure 5. University patents in Austria, 1995–2019.

assume that the most meaningful cases of institutional collaboration will have an expression in a tangible output of invention: the patent applications themselves. Table 9 includes TWFE estimators of Equation (1) on the probability of applicants to start patenting with others (Col. 1), on the probability of patenting with applicants from different regions (Col. 2), and on the probability of patenting with universities.

Since only the first coefficient is significant, it seems that the effect on local collaboration is the most meaningful in terms of mechanisms. Nonetheless, this does not mean that the Fraunhofer society does not impact patenting through the other channels; it just means that this cannot be observed on the patent data used for this analysis.

Another way to look into the possible avenues through which the Fraunhofer centres impact invention is to see its interaction with other policies and institutional reforms that happened around the same time the centres were established. In the case of Austria, the main policy that changed the way innovation is done was the abolition of the Professor's Privilege in 2002 (Martínez and Sterzi 2020). Up to that point, if a university lab carried out any kind of research, the professor leading the research team would retain the intellectual property of any invention derived out of that collective effort. After the reform, universities could instead keep the ownership of the patent and licence it if necessary.

As shown in Figure 5, the total number of university patents was almost null before the abolition of the professor's privilege. After the reform, the number of university patents rose for inventors and firms in both the control cities and the cities that would eventually host a Fraunhofer centre. Finally, after the establishment of the centres of Vienna and Graz, one can see that the total number of university patents diverges, reaching a large gap in the years leading to the end of the analysed period. This only contributes to the previously stated notion that the effect of applied research institutes interacts with domestic policies and institutions.

6. Conclusions

The Fraunhofer Society is Europe's largest research organization. The centres it opened outside of Germany in the 2000s had a large and positive impact on innovation, with an effect of at least 13% on the total patent filings of firms and inventors from cities in which they are located. By looking specifically at the effects by country, it seems that in places that provide public support to R&D the effect is mainly via the intensive margin, while in countries that do not invest that much in supporting R&D the effect is via the extensive margin (i.e. the probability to patent at all in a given year).

In terms of maturation of the intervention, both the baseline estimation and the one based on the alternative control group show that it takes very few years for a Fraunhofer centre to consistently increase the productivity of local firms and inventors (see Figures 2 and 3). Such an immediate effect is consistent with previous studies on the effects of research facilities and other applied research interventions (Helmers and Overman 2017; Pfister et al. 2021).

Regarding the mechanisms, Section 2 detailed the incentives the Fraunhofer centres have to engage with the private sector and the local business community. This in turn can mobilize four of the mechanisms through which, according to Bercovitz and Feldman (2005), research divisions can affect local invention: sponsored research, licensed testing, the hiring of students and researchers that would have otherwise worked in other activities, and the spin-off firms that might emerge from the newly developed technologies.

In fact, there is evidence that institutions with emphasis on applied research are more likely to collaborate with firms than those that are focused only on *basic* research (Arvanitis, Kubli and Woerter 2008). Likewise, technical degrees that provide close collaboration with the private sector—like the ones Fraunhofer centres tend to sponsor—have a positive effect on patent applications (Toivanen and Väänänen 2016). The provision of both infrastructure and research facilities can also increase the interest of local firms in investing on R&D and filing patent applications themselves (Glaeser 2010; Helmers and Overman 2017; Lehnert, Pfister and Backes-Gellner 2020).

Finally, the fact that the Fraunhofer society can harness the expertise of an international and established network of experts might help to explain why it is much more impactful than other similar interventions: they do not only bridge the gap between industry and academia, but also between countries and regions. Overall, the impact of the intervention is large enough to be considered a major catalyst of invention.

Supplementary data

Supplementary data are available at *Research Evaluation Journal* online.

Acknowledgements

I thank Andres Rodriguez-Pose, Henry Overman, Neil Lee, Nancy Holman, Beatriz Jambrina-Canseco, Antonio Avila-Uribe and seminar participants at LSE for their suggestions and comments.

Funding

This work was supported by the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 860887.

Conflict of interest statement. None declared.

Notes

1. By *year* I refer to the year in which the application was filed to the competent authority but *not* the year in which the patent was granted.
2. This approach is similar to the one used by Moretti (2021), who relies on US patent data to construct a panel of inventors between 1971 and 2007.
3. This variable was extracted by the OECD from the applicant's address and edited to avoid problems with the geolocation. I also carried out some additional checks to standardize the language in which the some cities were written: for example I had to replace *Bozen* (German) for *Bolzano* (Italian) and *Wien* (German) for *Vienna* (English) in order to keep the uniformity of city names across the panel.
4. Although I use a two-way fixed effects (TWFE) estimator to retrieve such estimate, note that even under the assumptions of a classic 2×2 difference-in-differences the descriptives reported in Table 2 imply a 41% increase in the patent output of treated applicants. Of course, such a simple calculation with only two periods overestimates the average treatment effect on the treated (ATT), but it motivates the use of more refined techniques to estimate the dynamic effects of the intervention.
5. There is a burgeoning literature on the bias that TWFE estimators may face in difference-in-differences designs where the treatment roll-out is staggered. The problem would be especially acute in instances where all units are eventually treated. In this particular case the bias is expected to be minimal, since the never-treated group is large for the whole analysed period (93.1% of all applicants in 2019, the last year included in the sample). Nonetheless, in order to address any concerns regarding an overestimation of the effects of the Fraunhofer centres, in Supplementary Appendix A I show that the results of the baseline event study are indistinguishable from the coefficients retrieved from the Interaction Weighted (IW) estimator. This estimator developed by Sun and Abraham (2021) is specifically designed to restrict the comparisons of the treatment cohorts with the never-treated group.

References

Allan, G., Figus, G., and Schubert, T. (2022) *Understanding the Macroeconomic Effects of Public Research: An Application of a Regression Microfounded CGE-Model to the Case of the Fraunhofer-Gesellschaft in Germany*, Discussion Papers No. 72. Fraunhofer ISI.

Andrews, M. J. (2022) 'How Do Institutions of Higher Education Affect Local Invention? evidence from the Establishment of U.S. colleges', *American Economic Journal: Economic Policy*, 15: 1.

Arvanitis, S., Kubli, U., and Woerter, M. (2008) 'University-Industry Knowledge and Technology Transfer in Switzerland: What University Scientists Think About Co-Operation With Private Enterprises', *Research Policy*, 37: 1865–83.

Bathelt, H., Malmberg, A., and Maskell, P. (2004) 'Clusters and Knowledge: Local Buzz, Global Pipelines and the Process of Knowledge Creation', *Progress in Human Geography*, 28: 31–56.

Benedicti, S. (2019) *Relazione Annuale 2019*. Fraunhofer Italia.

Bercovitz, J., and Feldman, M. (2005) 'Entpreprenerial Universities and Technology Transfer: A Conceptual Framework for Understanding Knowledge-Based Economic Development', *The Journal of Technology Transfer*, 31: 175–88.

Carlson, J. S., and Torstensson, L. (2018) *Annual Report 2018: Fraunhofer-Chalmers Research Centre for Industrial Mathematics*. FCC.

Charlot, S., Crescenzi, R., and Musolesi, A. (2015) 'Econometric Modelling of the Regional Knowledge Production Function in Europe', *Journal of Economic Geography*, 15: 1227–59.

Cohen, W. M., Nelson, R. R., and Walsh, J. P. (2000) 'Protecting Their Intellectual Assets: Appropriability Conditions and Why U.S. manufacturing Firms Patent (or Not)'. NBER Working Paper 7552, National Bureau of Economic Research.

Comin, D., Licht, G., Pellens, M., and Schubert, T. (2019) 'Do Companies Benefit from Public Research Organizations? The Impact of the

Fraunhofer Society in Germany', ZEW Discussion Papers, No. 19-006, ZEW Leibniz-Zentrum für Europäische Wirtschaftsforschung.

Cowan, R., and Zinovyeva, N. (2013) 'University Effects on Regional Innovation', *Research Policy*, 42: 788–800.

Crintea-Rotaru, S., Félix, B., López, A. H., Petkova, R., Ritola, V., and Villette, G. (2013) *Science, Technology and Innovation in Europe*, 2013 edn. Eurostat pocketbooks.

D'Este, P., and Patel, P. (2007) 'University–Industry Linkages in the UK: What Are the Factors Underlying the Variety of Interactions with Industry?', *Research Policy*, 36: 1295–313.

Edler, J., and Fagerberg, J. (2017) 'Innovation Policy: What, Why, and How', *Oxford Review of Economic Policy*, 33: 2–23.

Feldman, M. P. (1999) 'The New Economics of Innovation, Spillovers and Agglomeration: A Review of Empirical Studies', *Economics of Innovation and New Technology*, 8: 5–25.

Fraunhofer, A. (2020) *Annual Report 2020*. Fraunhofer Portugal.

Glaeser, E. L. E. L. (2010) *Agglomeration Economics*. University of Chicago Press

Guggenberger, E., and Tasch, M. (2021) *Jahresbericht 2021*. Fraunhofer Austria Research GmbH.

Haldane, A. G. (2018) *The UK's Productivity Problem: Hub No Spokes*, pp. 1–40. Bank of England.

Hall, P. A., and Soskice, D. (2001) *Varieties of Capitalism: The Institutional Foundations of Comparative Advantage*, Oxford University Press.

Helmers, C., and Overman, H. G. (2017) 'My Precious! The Location and Diffusion of Scientific Research: Evidence From the Synchrotron Diamond Light Source', *Economic Journal*, 127: 2006–40.

Jaffe, A. B. (1989) 'Real Effects of Academic Research', *The American Economic Review*, 79: 957–70.

Klingner, R. (2010) *Written Evidence Submitted by Fraunhofer-Gesellschaft (TIC 71)*. House of Commons Science and Technology Committee.

Lehnert, P., Pfister, C., and Backes-Gellner, U. (2020) 'Employment of RD Personnel After an Educational Supply Shock: Effects of the Introduction of Universities of Applied Sciences in Switzerland', *Labour Economics*, 66: 101883.

Lehnert, P., Pfister, C., Harhoff, D., and Backes-Gellner, U. (2022) *Innovation Effects and Knowledge Complementarities in a Diverse Research Landscape*. Swiss Leading House "Economics of Education" Working Paper No. 164.

Lööf, H., and Broström, A. (2008) 'Does Knowledge Diffusion between University and Industry Increase Innovativeness?', *Journal of Technology Transfer*, 33: 73–90.

Maraut, S., Dernis, H., Webb, C., Spiezia, V., and Guellec, D. (2008) 'The OECD REGPAT Database: A Presentation'. STI Working Paper 2008/2. OECD Science, Technology and Industry.

Martínez, C., and Sterzi, V. (2020) 'The Impact of the Abolishment of the Professor's Privilege on European University-Owned Patents', *Industry and Innovation*, 28: 247–82.

Moretti, E. (2021) 'The Effect of High-Tech Clusters on the Productivity of Top Inventors', *American Economic Review*, 111: 3328–75.

OECD (2021) 'OECD REGPAT Database July 2021' <https://www.oecd.org/sti/inno/intellectual-property-statistics-and-analysis.htm> accessed 23 Sep 2021.

Pfister, C., Koomen, M., Harhoff, D., and Backes-Gellner, U. (2021) 'Regional Innovation Effects of Applied Research Institutions', *Research Policy*, 50: 104197.

Rombach, D. (2000) 'Fraunhofer: The German Model for Applied Research and Technology Transfer', *Proceedings—International Conference on Software Engineering*, 531–7. ICSE 2000.

Romer, P. M. (1994) 'The Origins of Endogenous Growth', *Journal of Economic Perspectives*, 8: 3–22.

Schweiger, H., Stepanov, A., and Zacchia, P. (2022) 'The Long-Run Effects of RD Place-Based Policies: Evidence from Russian Science Cities', *American Economic Journal: Economic Policy*, 14: 322–51.

Singh, J., and Fleming, L. (2010) 'Lone Inventors as Sources of Breakthroughs: Myth or Reality?', *Management Science*, 56: 41–56.

Sun, L., and Abraham, S. (2021) 'Estimating Dynamic Treatment Effects in Event Studies with Heterogeneous Treatment Effects', *Journal of Econometrics*, 225: 175–99.

Toivanen, O., and Väänänen, L. (2016) 'Education and Invention', *The Review of Economics and Statistics*, 98: 382–96.

Wessner, C. W. (2013) *21st Century Manufacturing: The Role of the Manufacturing Extension Partnership Program*, pp. 1–476. National Academies Press.

Wu, L., Wang, D., and Evans, J. A. (2019) 'Large Teams Develop and Small Teams Disrupt Science and Technology', *Nature*, 566: 378–82.