

BARRIERS TO KNOWLEDGE CREATION IN THE MULTINATIONAL FIRM*

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Abstract

This paper shows that knowledge creation, as measured by patents, is increasingly conducted in cross-border collaborative teams of inventors. It documents the importance of cross-border communication costs by showing that a higher overlap in business hours is associated with increased cross-border collaboration. This effect is distinct from the effect of physical distance, which matters as well. It is stronger for technology classes where lab experiments are involved and thus more frequent interactions may be required. The data further suggest that episodes of telecommunications liberalization (and the resulting decline in the cost of international calls) lead to an increase in cross-border collaboration, particularly when the business hour overlap between the headquarters and a subsidiary is larger. This effect is stronger for experiment-based technology classes. Less successful inventors respond more than their most successful peers.

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1 Introduction

Multinational enterprises (MNEs) play a central role in knowledge creation. According to conservative estimates, MNEs account for close to half of all global R&D expenditures and at least two-thirds of business R&D expenditures (UNCTAD, 2005).¹ Despite the importance of R&D efforts undertaken by MNEs, there is little micro evidence on factors driving where and how this knowledge is being produced.

In this paper, we document the changing patterns of knowledge production inside MNEs over the past four decades and explain the factors behind these patterns. Using a newly-assembled dataset of MNEs and their inventor teams, we show that knowledge is increasingly produced in teams that involve inventors located in multiple countries. We demonstrate that this trend has been stimulated by telecom liberalization and hampered by time zone differential, both of which are factors affecting communication costs.

We build a new comprehensive database of innovation activity within MNEs that tracks cross-border collaboration between inventors located in a MNE's home country and inventors located at its affiliates abroad. For each patent filing, we harmonize (i) shareholder information on the global ultimate owners of each assignee establishment, and (ii) geo-coded information on the location of each inventor. Our novel cross-country database of MNEs, inventor teams and their innovation activity encompasses around 83% of all triadic patents over the 1980-2014 period, e.i., those granted at three major patent offices: US Patent and Trademark Office (USPTO), European Patent Office (EPO) and Japanese Patent Office (JPO).

Several new stylized facts emerge from the data. First, knowledge creation is increasingly conducted in global collaborative teams of inventors working together within the same MNE. For US MNEs in our database, 23% of triadic patents involved at least one inventor located in the US and at least one inventor located abroad. For German and Dutch MNEs, the corresponding figures were 28% and almost 43%, respectively.² Second, a large share of patenting activity takes place outside of MNEs' home countries. Among US MNEs, 16% of patent filings involved inventor teams located solely in foreign affiliates. For German and Dutch MNEs, it was 13% and 49%, respectively. Third, the rise in cross-border collaboration has been stronger in experimental technology classes and in affiliates with a high overlap in business hours vis-à-vis the headquarters (HQ).

¹The European Commission estimates that, in 2007, foreign-owned firms accounted for 15% of all business R&D in the United States; 20-25% in France, Germany, and Spain; 30%-50% in Canada, Hungary, Portugal, the Slovak Republic, Sweden, and the United Kingdom (UK); and more than 50% in Austria, Belgium, the Czech Republic, Malta, and Ireland (Dachs et al., 2012).

²Cross-border patents tend to be high-quality innovations by most conventional measures (Kerr and Kerr, 2018) and are a key source of international transfers of technology (LaBelle et al., 2023).

In our analysis, we follow [Kerr and Kerr \(2018\)](#) in defining cross-border or “global collaborative patents” as innovations that involve at least one inventor located in the MNE home country and at least one inventor located in another country. We then examine three drivers behind the rise of global collaborative patents: (i) time zone differences that lead to heterogeneity in the business hour overlap, (ii) episodes of telecom sector liberalization, which in the 1990s and the early 2000s resulted in a sudden and substantial decline in the price of international calls, and (iii) the interaction between the two.

Why should time zones matter for repeated interaction beyond the role of physical distance? Although much of physical production can be fragmented into individual stages and carried out relatively independently, innovative activity involves exchange of knowledge that is both tacit and strategic to firms. Sociological studies suggest that work practices in multinational organisations that involve knowledge work have evolved to demand greater hours, commitment, and flexibility from their employees.³ In economics, [Chauvin et al. \(2020\)](#) show that temporal distance stemming from time zone differences reduce synchronous and impromptu communication from first-best levels within a multinational organisation, presenting costly frictions especially for the multinational’s knowledge-intensive work.

The last few decades have witnessed a dramatic decline in the price of international calls (see Figure C.2). This was largely driven by the liberalization of telecommunications markets, a process that started in 1984 in the US with the UK, Japan and New Zealand following suit shortly, and the reforms gaining speed in Europe in the 1990s. Lower prices of international calls were accompanied by an increase in the volume of international calls, which, as we argue, facilitated cross-border cooperation, including cooperation in R&D.

We hypothesize that a decline in communicating costs facilitated cross-border knowledge production between MNE establishments in home and host countries, particularly when the time zone differential was not too large. Moreover, we hypothesize that these factors were more important for experiment-based technology classes where more frequent communications between inventors may be required. Finally, we explore the heterogeneous impact on inventors with different patenting histories. On the one hand, inventors with lesser track records may stand to benefit more from international collaborations and thus may be willing to incur the high costs of international communication and the inconvenience of time zone differential. On the other hand, the presence of such costs, which must be partially born by their collaborators located in HQ, makes them less

³For instance, [Kvande \(2009\)](#) discusses evidence from multinational law and computing firms that require employees to adjust working hours to collaborate with international business partners.

attractive as team members. Thus, it is ambiguous *a priori* whether inventors with a lesser or with a stronger track records would be affected more by a decline in communication costs.

In our core analysis, the outcome of interest is the share of patents produced by inventors in a particular foreign affiliate of an MNE that involved cooperation with one or more inventors from HQ. Our explanatory variables of interest include bilateral telecom liberalization between the MNE home and the affiliate host country and the interaction of liberalization with the business hour overlap between the affiliate and the HQ. We define liberalization as both the home and the host country having liberalized their markets. By considering the share of global collaborative patents in all patents linked to a given foreign affiliate in a given time period, we are implicitly controlling for all factors that drive the volume of innovative activity in each location. By controlling for affiliate-HQ-technology fixed effects, we exploit the variation over time and thus abstract from the possibly endogenous decision of where to locate a foreign subsidiary. We also control for unobservable host-country-year heterogeneity, and hence take into account factors that may have driven liberalization as well as variation in the supply of potential inventors that can be hired by an MNE in a given host country in a given year. Inclusion of these fixed effects means that our identification comes from comparing the impact of liberalization on affiliates located in the same host country but differing in terms of business hours overlap vis-à-vis their parent firm's HQ. Finally, technology-specific shocks are accounted for by technology-year fixed effects.

We extend the baseline analysis in three dimensions: (i) an event study focusing on telecom liberalization episodes and comparing affiliates with high versus low time zone differential vis-à-vis HQ; (ii) an examination of whether telecom liberalization and time zone differential have affected the quality of patents and the size of inventor teams; and (iii) an inventor-level analysis allowing for heterogeneous effects on inventors with different patenting histories.

Our econometric analysis produces three main sets of findings. First, in a simple cross-sectional setting, we find that a greater overlap in business hours between MNE HQ and affiliates leads to a higher incidence of inventor collaboration. For instance, an increase in business hour overlap by eight hours is associated with a 6% point increase in the probability that a patent filed by inventors located in foreign affiliates involves HQ. In other words, an inventor working for a Polish subsidiary of a German MNE is 6% points more likely than an inventor located in its Japanese subsidiary to collaborate on a patent with colleagues at the firm's HQ. The business hour overlap matters beyond the effect of physical distance, which itself reduces the likelihood of cross-border collaboration (by 2%

points when comparing a Japanese and a Polish subsidiary of a German MNE). It is also stronger for experimental technology classes, where more frequent interactions are likely to be required.

Second, we show that episodes of telecom sector liberalization have led to an increase in cross-border collaboration, particularly when the business hour overlap between the HQ and a subsidiary was larger. The results are robust to using an indicator variable for liberalization episodes or the cost of international calls between the two countries. Again we show that the impact is stronger for experiment-based technology classes. These conclusions are confirmed by event studies following the methodology by [Borusyak et al. \(2021\)](#) and comparing the impact of telecom liberalization episodes on affiliate-HQ pairs with a large versus small business hour overlap. Sticking with our example of a German MNE with a Polish and a Japanese subsidiary, our results suggest that after telecom liberalization, the share of patents based on collaboration with HQ filed by inventors located in the Polish subsidiary will increase by 6.4% points (which is equivalent to a 22% rise). In contrast, collaborative patents in the Japanese subsidiary will go up by only 2.6% points (10%).

Third, we show that a decline in communications frictions has led to an increase in the number and in the share of patents citing science, breakthrough patents (defined following [Kelly et al. \(2021\)](#)), the number of inventors listed on a patent, particularly if the business hours overlap was substantial. When it comes to the increase in the inventor team size, the effect was driven by inventors from HQs and not by inventors located in affiliates.

Finally, our inventor-level analysis confirms the earlier conclusions. It also indicates that the impact of telecom liberalization in affiliates with high business hour overlap vis-à-vis HQ is larger for inventors with lesser track records than for their more successful colleagues. This is suggestive of high costs of working across time zones. It is consistent with the scenario where high monetary and inconvenience costs of working across time zones must be compensated by high expected benefits of collaboration and thus favor collaboration with inventor with a proven track record. Only when such costs decline, collaboration becomes worthwhile with inventors from foreign affiliates who have less of a track record.

We contribute to several strands of literature. First, we contribute evidence to the literature on where and how knowledge work is conducted within the multinational firm. Canonical models of foreign direct investment (FDI) posit a distance-concentration trade-off, which focus on trade in goods and do not take into account knowledge transfer ([Helpman et al., 2004](#)). Recent models focusing on FDI differ in how R&D and knowl-

edge production are incorporated. [Bilir and Morales \(2020\)](#) model knowledge creation as concentrated in the HQ country and exploited abroad. In [Keller and Yeaple \(2013\)](#), a distance-knowledge trade-off emerges because it is more costly to transfer knowledge by direct communication than by trading intermediates. Similarly, [Gumpert \(2018\)](#) models how communication costs limit the ability of a firm's establishments to access knowledge at the headquarters.

Our findings support the existence of substantial knowledge transfer costs, both due to time zone differences and physical distance. They also show that multinationals increasingly conduct their R&D operations outside their home countries and in collaborative teams of inventors located in multiple countries. As such, the evidence is reminiscent of a vertical model of FDI as in [Antràs et al. \(2006\)](#), who study the formation of cross-country teams in production. It is also in line with a theory of the multinational firm as an organization that specializes in the creation and transfer of knowledge across borders ([Kogut and Zander, 1993](#)).

Second, we contribute to the body of evidence documenting the importance of communication costs and time zone differences on multinational firm organization. [Stein and Daude \(2007\)](#) find that differences in time zones negatively affect FDI, while [Oldenski \(2012\)](#) finds that activities requiring complex within firm communication are more likely to occur at MNE HQ. Closest to our study is [Bahar \(2020\)](#), who presents evidence of a trade-off between distance to the HQ and knowledge intensity of the affiliates' industry. We extend this literature by explicitly showing that a decline in international communication costs has differential effects depending on the business hour overlap between the HQ and a foreign affiliate.⁴

Third, we add to the literature on cross-border collaboration in knowledge work. [Kerr and Kerr \(2018\)](#) find, in a sample of publicly listed companies from the United States, that global collaborative patents are frequently observed when a firm enters a new foreign region for innovative work, especially where intellectual property protection is weak. They also find that collaborative patents are higher quality than patents produced by inventor teams located only in the US, and employment of ethnic inventors at home is related to cross-border collaboration.⁵ [Catalini et al. \(2020\)](#) show that travel costs constitute an im-

⁴One proposed reason for the negative relationship between distance (both physical and cultural) and FDI is the difficulty of a parent firm to monitor the activities of its affiliates abroad ([Blonigen et al., 2020](#)). Monitoring costs can be especially high in the context of innovative activity, where parent firms have an incentive to protect the leakage of proprietary technology. Our results suggest that business hour overlap may contribute to the difficulty of monitoring.

⁵Related, [Foley and Kerr \(2013\)](#) find that increases in the share of a US multinational's innovation performed by inventors of a particular ethnicity at home are associated with increases in the share of that firm's affiliate activity in countries related to that ethnicity.

portant friction to collaboration between inventors, especially for high-quality scientists that are otherwise embedded in worse local environments. Similarly, using the introduction of the jet engine to civil aviation in the 1950s as an exogenous reduction in travel time, [Pauly and Stipanovic \(2021\)](#) find that a decrease in travel time between two cities lead to an increase in patent citations between them. Our inventor-level analysis extends this literature by pointing out how the interaction between a drop in communication costs and the time zone differential affect collaborations of inventors with different track records. We show that a decline in communication frictions tends to benefit inventors with lesser track records more.

Recent research suggests that ideas are getting harder to find ([Bloom et al., 2020](#)). Patents increasingly involve large research teams and evidence shows that interactions with better inventors are strongly correlated with subsequent productivity ([Akcigit et al., 2018](#)).⁶ This increases the importance of collaboration across borders and ability of large teams of inventors to work together, often facilitated by within-firm mobility. Our work sheds new light on the barriers to cross-border collaboration.

Recent work has also quantified the impact of globalization on the rise of cross-border patenting, which in turn plays a crucial role in fostering development by facilitating exchange of knowledge and technology across countries. For instance, [LaBelle et al. \(2023\)](#) estimate that cross-border patenting would have been 43% lower in 2018 absence the effects of globalization and this would have results in a larger real income gap between the poor and rich countries of the world. By shedding light on the role of time zone differentials and telecom costs, our work contributes to a better understanding of factors inhibiting cross-border innovation and hence international knowledge transfer.

The remainder of this paper is structured as follows. We describe our data in Section 2 and present stylised facts in Section 3. Section 4 contains our results on the determinants of global collaborative patenting activity. Section 5 focuses on the telecom liberalization episodes at the level of the establishment, while in Section 6 we disaggregate the analysis further down to the inventor level. Concluding remarks appear in Section 7.

⁶[Akcigit et al. \(2018\)](#) introduce an endogenous growth model with knowledge diffusion in which inventors learn from each other via collaboration. They quantify the importance of interactions for growth by studying the effects of reducing interaction costs, such as IT or infrastructure, on inventors' learning and knowledge accumulation.

2 Data

2.1 Patents

The main patent dataset underlying our analysis comes from USPTO's (United States Patent and Trademark Office) PatentsView project. PatentsView covers the universe of US patents. Crucially, it contains inventor identifiers resulting from a disambiguation exercise and information on inventor location (at the city level). Inventor location allows us to pinpoint where knowledge creation takes place, while the inclusion of identifiers allows us to track inventors across time and space.

We combine the USPTO data with EPO's PATSTAT (Spring 2021 edition) using publication numbers. PATSTAT is an effort to collect data on patent filings from all over the world. Importantly, this provides us with patent filings at EPO and JPO, two important patent offices other than the USPTO.

We focus on patent families, where a patent family is defined as a collection of patents concerning the same invention in multiple patent offices around the world. In this way, we count a single invention only once and consider the date of its first filing as the relevant date. Our analysis focuses on triadic patent families, which include patents granted at all three of the patent offices mentioned earlier (USPTO, EPO, JPO).⁷ These patent families capture the most important inventions relevant at a global level.⁸

2.2 Building our data set

The purpose of our analysis is to understand drivers of cross-border collaboration in innovation within a multinational firm. This requires several ingredients.

First, we need to be able to match patents to a firm. A firm can register legal ownership of a patent in a subsidiary that is located in a country different from the firm's HQ, different from the location where the underlying technology was created (i.e. where inventors reside), and different from the location where the intellectual property will be applied (Griffith et al., 2014). Therefore, it is crucial that we accurately identify the firm that is the ultimate owner of a patent and understand where exactly the invention was created. This requires assigning patents to firms. To do so, we use the Orbis Intellectual Property

⁷Note that triadic patents are sometimes defined as patent families granted in the US and filed, but not necessarily published, at the EPO and the JPO. We instead require the patent family to include a publication in all three offices.

⁸Note that the EPO uses two different definitions of patent families: the simple (DOCDB) and the extended (INPADOC) definition. We use the extended definition here which groups together all applications that have at least one priority in common. In what follows, we use the terms "patent" and "invention" interchangeably, both of which refer to the relevant patent family.

(IP) database, provided by Bureau van Dijk. Orbis IP sources its patents data from Lexis Nexis and maps the assignee (or patent owner) names indicated on the patent to Orbis firm identifiers based on a textual matching algorithm and extensive manual checks (see appendix A).

We then use Orbis's data on ownership links to identify the global ultimate owner (GUO) of the assignee. In the analysis below, a GUO is our definition of a firm. The ownership links were extracted in September 2020, and they reflect the state of the world at that point in time. As we combine the data on ownership links with historical patent data, we may attribute some patents and inventors to a firm to whom they did not belong at the time of the patent filing, but which the firm subsequently acquired. We would then be confounding an effect that operates through acquisition with an effect operating in a fixed network of establishments. Our robustness check focusing only on foreign affiliates that already existed in the 1980s alleviates this concern.

Second, we need to know where the innovative activity actually took place. We obtain this information from the patent data, which give us the location of each inventor who contributed to the patent.

Third, we need to define what we mean by cross-border collaboration within an MNE. We focus on collaboration between inventors located in the MNE HQ country and those located in its foreign affiliates. While we could potentially consider collaboration between all pairs of entities within an MNE, this would result in a very large and sparse matrix. In addition, innovation is likely to follow a hub-and-spoke model, i.e., most collaboration takes place between an R&D hub in the home country and individual subsidiaries. We thus restrict our analysis to HQ-subsidiary collaboration.⁹

Fourth, we need to decide which MNE establishments to consider. Given the nature of the research question, we want to consider only establishments engaged in R&D, which in our case means establishments where at least one inventor listed on a patent belonging to an MNE was located. We define establishments based on patent data, using the information on the inventors' location of residence to identify the country and time zone where they are located.¹⁰ Our definition of establishment comprises all inventors working for a given firm while located in a particular country and time zone. This implies that countries with a single time zone will have at most one establishment of a given firm,

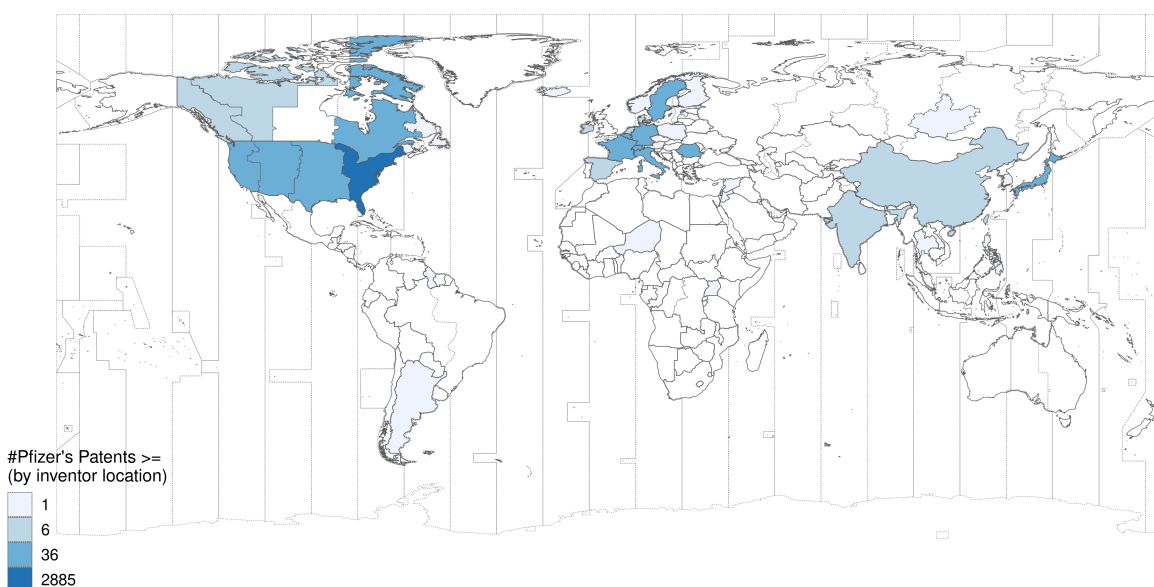
⁹In our estimation sample of patents with at least one inventor based at a foreign affiliate, around 7.7% of patents are affiliate-affiliate collaborations without HQ-involvement. 29.8% of patents are in collaboration with HQ inventors (40.9% weighted by citations). Thus, collaboration indeed seems to follow a hub-and-spoke model, especially for the patents of highest quality. Nevertheless, affiliate-affiliate collaborations are also present in the data and should be studied further in future work.

¹⁰We use the R package *lutz* to infer the time zone from inventor locations.

while countries with multiple time zones can have multiple establishments belonging to the same MNE. In other words, our approach amounts to pooling together patents for multiple establishments belonging to a single MNE and located in the same time zone of a single country. But it also implies that an MNE may have more than one establishment in its HQ country if the country has multiple time zones.

Figure 1 below illustrates our approach in the context of Pfizer. Pfizer's R&D HQ country is the United States, where the company has establishments in each of the four time zones. Thus when we consider cross-border collaboration between the US and Canada within Pfizer, we will consider 12 cases of possible cooperation (4 Pfizer locations in the US x 3 Pfizer locations in Canada). We further consider collaborations between each of the 4 Pfizer locations in the US and all other countries where Pfizer has foreign affiliates.

Figure 1: Pfizer's establishments



Our final dataset includes 509,884 patent families that are matched to a firm. It accounts for 83% of all granted triadic patents over the period 1980-2014 (or 84% when weighting by citations). For more details, see Appendix [Sample Coverage](#).

2.3 Variable Definitions

The following variables are used in our analysis.

- Collaboration: this is our outcome variable of interest. It captures the share of

patents obtained by inventors located in a given establishment that involve at least one inventor based in the HQ country of the firm.

- **Business Hour Overlap:** We take the the difference in time zone between the HQ location and the foreign establishment location. The maximum difference is 12 hours. Then we define business hour overlap as 8 hours minus the time zone difference, setting negative values to 0, so that our overlap variable ranges from 0 to 8 hours. In our regression analysis we transform the resulting variable by adding 1 and taking logs. Alternatively, we divide the business hour overlap into two-hour bins.
- **Distance:** The establishment location is defined as the centroid of the country-time zone pair. The distance is the geodesic (or straight-line) distance between the two establishment locations.
- **Technology:** Our definition of a technology corresponds to a 4-digit IPC class. There are around 650 such classes.
- The year of liberalization of the market for international calls in a given country comes from Table 1 in [Boylaoud and Nicoletti \(2000\)](#).
- Bilateral data on prices of international calls were collected from OECD reports for the years 1990, 1998 and 2003 (see [OECD \(1994\)](#), [OECD \(1999\)](#) and [OECD \(2003\)](#)). These contain bilateral rates for international phone calls from country A to country B at the peak hour. We convert these rates to a per-minute rate in 1990 US dollars. The rates pertaining to calls from A to B and from B to A are typically not the same, we consider the average or the minimum of the two in our analysis.
- **Breakthrough patents:** We use the definition of breakthrough patents provided by [Kelly et al. \(2021\)](#). They compute a measure of patent importance that is based on the patent text. This measure is high when a patent text is both dissimilar to prior patent filings and similar to subsequent patent filings, as this is indicative of the patent causing a shift in the patent literature. We rely on the version of their measure that considers patents filed up to five years after the focal patent. After purging out filing year fixed effects, [Kelly et al. \(2021\)](#) define a patent as a breakthrough if it is in the top 10% of this measure.
- **Patents citing science:** We use data by [Marx and Fuegi \(2020\)](#) who collect citations to scientific articles from the front page of patent filings since 1800. Citing science has been found to be an important indicator of the quality of innovation ([Ahmadpoor and Jones, 2017](#)).

- Star inventors: We measure inventors’ initial productivity by computing the number of all patents they filed prior to 1990, regardless of the firm filing the patent.¹¹ We then define as stars the top 25% of all inventors working in foreign establishments of a given firm. In a robustness exercise, we also use the top 10% or the (log) number of patents filed by an individual inventor before 1990. In yet another definition, we weight the number of patents by citations received before 1990 and recompute the top 25%.

2.4 Experiment-Intensive Technologies

In order to identify technologies that rely on high-intensity communication, we perform analysis on patent texts. We focus on the brief summary text provided by *PatentsView* for all patent applications filed at the USPTO in the year 2000 and search for the words “experiment” and “trial”. We compute the share of patents containing at least one of these terms within each technology class and define a technology as experiment-intensive if this share is higher than 35.7% (the median share in the regression sample). For around 5% of observations, we are not able to classify the technology class using the procedure outlined above, as these technologies are not present in the sample of US patents we use for classification.

To get a sense of the broad fields in which our experiment-intensive technologies are concentrated, Table D.1 shows the share of experiment-intensive technologies (4-digit) within each more aggregate technology grouping (1-digit). Among these technology groupings, chemistry patents involve the most experimentation and electricity and fixed constructions patents the least. Table D.2 displays the 15 most common 4-digit technology classes in our sample and how they are classified. Again we see chemistry-related technology classes having the largest share of experimental patents.

In Figure C.1, we correlate the share of experimental patents by technology with other patent classifications. We show that experimental technologies tend to be more process-intensive (based on data from Ganglmair et al. (2022)) and more scientific (based on data from Marx and Fuegi (2020)). We will show below that experimental technologies nevertheless capture something distinct that matters for communication frictions.

¹¹We capture any patent that appears in the USPTO’s PatentsView data. This dataset contains patents granted from 1976 onwards.

3 Stylized Facts

This section contains a few stylized facts to motivate our analysis.

A large share of patenting activity takes place outside of MNE HQ countries and is driven by inventors located in foreign affiliates. Table 1 lists the top 10 HQ countries in our sample in terms of the number of patent families attributed to MNEs. The most innovative country in the sample, Japan, is the least collaborative: only around 11% of patents filed by Japanese MNEs involved also inventors located outside of Japan. In contrast, around 39% of all inventions filed by US MNEs involved at least one inventor from a foreign affiliate. European MNEs stand out when it comes to patenting innovations created outside HQ countries and the incidence of HQ-affiliate collaboration. In German MNEs, 28% of patents involved global collaboration. MNEs from the Netherlands and Switzerland have notably high levels of innovative activities abroad. In fact, less than 10% of patents in Dutch and Swiss MNEs were created solely by inventors based in those countries.

Table 1: Patent Families and Collaboration Patterns by Country

HQ Country	Number of patent families	Only HQ inventors (in %)	Only foreign affiliate inventors (in %)	HQ-affiliate collaboration (in %)
JP	110277	88.71	5.82	5.47
US	76772	60.60	16.33	23.06
DE	34078	58.62	12.93	28.45
FR	17353	50.81	24.91	24.28
KR	13555	77.29	6.54	16.17
GB	7031	34.79	32.20	33.01
SE	6384	48.29	26.10	25.61
IT	5311	55.71	13.22	31.07
NL	4796	8.42	48.81	42.76
CH	4571	5.73	55.83	38.44

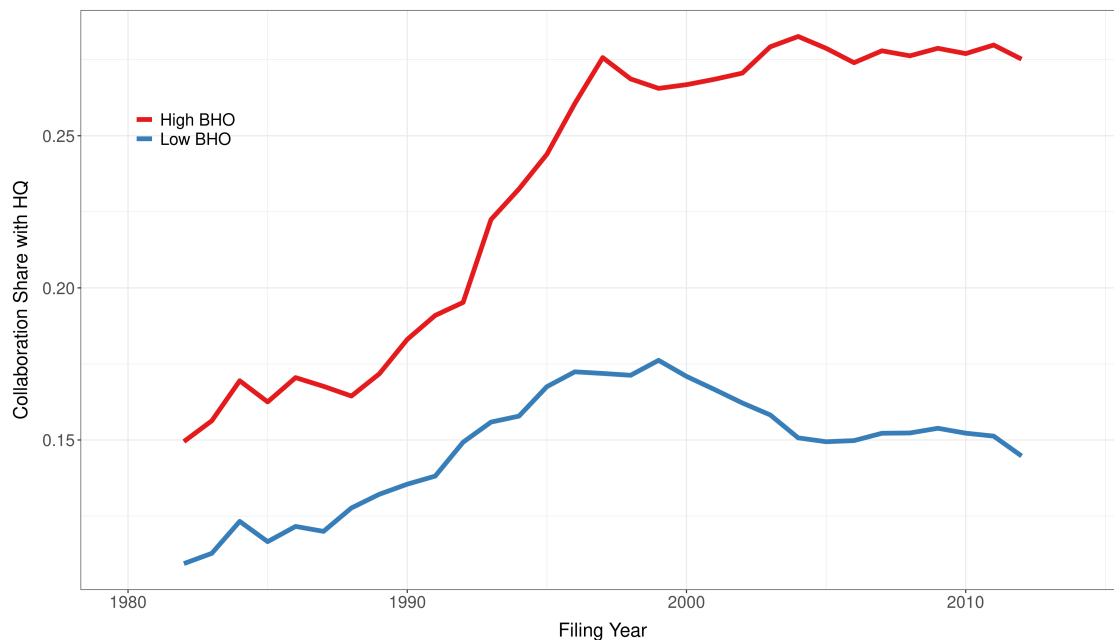
Liberalization of the telecom sector has led to a rapid decline in the cost of international calls and an exponential increase in the call volume. Table D.3 presents the results of regressing call prices between country pairs on a binary variable that equals 1 if telecom sectors in both countries are liberalized. We find that telecom prices declined between 30% and 40% after liberalization.¹² Figure C.3 shows the sharply increasing call volumes

¹²In figure C.2 we plot a histogram of bilateral price changes between 1990 to 2003.

during the liberalization period.¹³

Collaboration of affiliate-based inventors with HQ has been on the rise, especially in affiliates with a high overlap in business hours vis a vis the HQ. The share of cross-border collaboration in patenting has doubled from 13.5% in 1980 to around 27.3% in 2014 for establishment pairs with a high overlap in business hours (see Figure 2). For affiliates located further away in terms of time zones, the increase in collaborations has been less impressive, as such collaborations went from 8.7% in 1980 to 13.4% in 2014. Thus the temporal distance is alive and well, with the importance of time zone differences being exacerbated by improved communication technology.

Figure 2: Cross-border Collaboration over Time



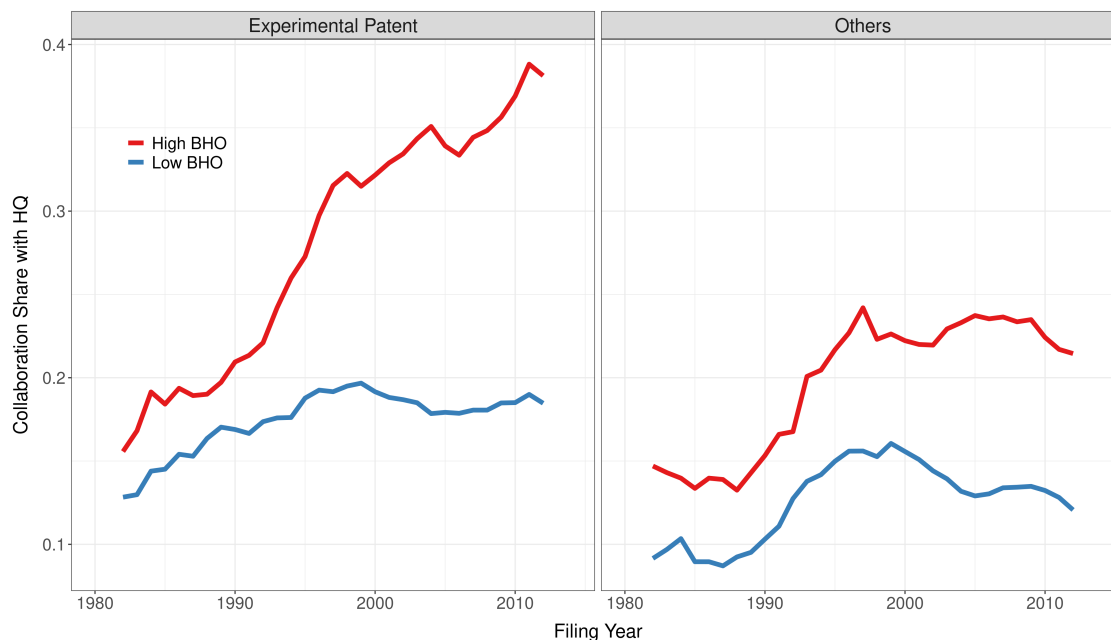
Notes: This figure shows the five-year moving average share of patents filed by affiliate inventors that involve at least one HQ inventor. High overlap contains affiliates having more than 4 business hours overlap with HQ.

The rise in cross-border collaboration has been particular strong in experimental technology classes when business hours overlap was high. Inventors, located in affiliates with a high business hours overlap vis a vis MNE HQ, increased collaboration with HQ-based inventors, particularly in experimental technology classes. Their share of collaborative patents has tripled, increasing from 11.4% in 1980 to 36.4% in 2014. A much less

¹³We do not have data on the bilateral volume of calls and can thus not rerun the price regression with call volumes.

pronounced rise has been registered in non-experimental technology classes or in affiliates with a greater temporal distance to HQ (see Figure 3).

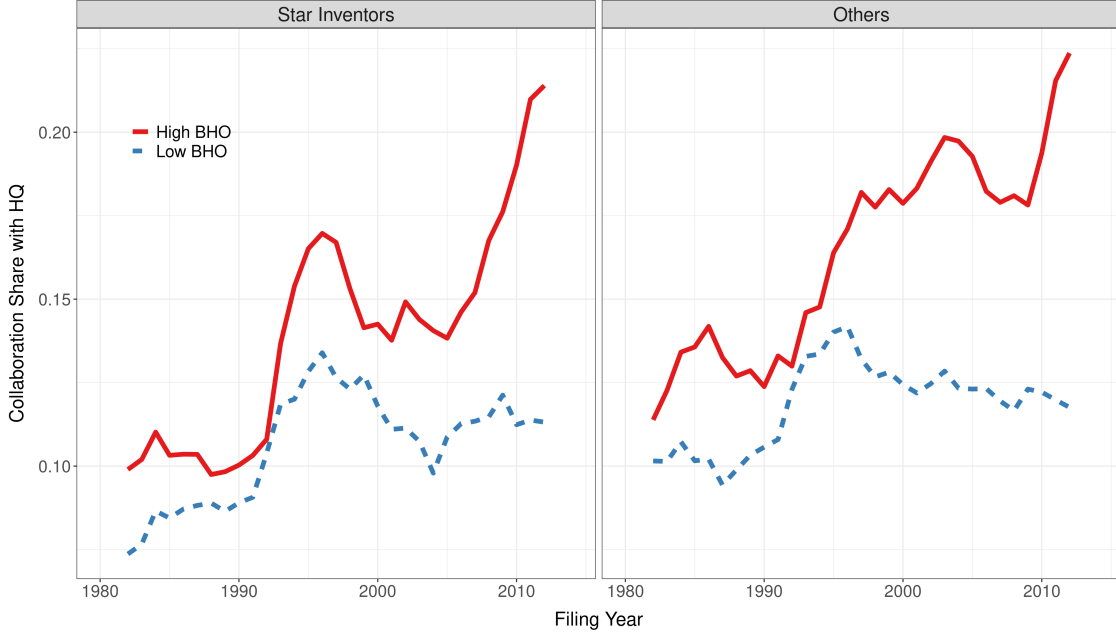
Figure 3: Cross-border Collaboration over Time by Technology



Notes: This figure shows the five-year moving average share of patents filed by affiliate inventors that involve at least one HQ inventor. High overlap contains affiliates having more than 4 business hours overlap with HQ. Experimental technology classes are defined as in section 2.4.

The rise in cross-border collaborations has been driven by less experienced inventors in affiliates with greater business hour overlap with the HQ. Figure 4 shows a growing share of collaborative patents involving affiliate inventors with lesser temporal distance to HQs. This rise is particularly pronounced for non-star inventors, i.e., inventors with a lesser track record.

Figure 4: Cross-border Collaboration over Time by Inventor Type



Notes: This figure shows the share of patents filed by affiliate inventors that involve at least one HQ inventor. High overlap contains affiliates having more than 4 business hours overlap with HQ. Star inventors are the top 25% inventors that had filed the most patents in USPTO data up to the year 1989 (see section 2 for details).

4 Cross-border Collaboration and Time Zones

In the first pass at the data, we abstract from the telecom liberalization and examine the drivers of cross-border collaboration in a cross-sectional setting. We estimate the following equation:

$$\text{Collaboration}_{aht} = \alpha_1 \text{Overlap}_{ah} + \alpha_2 \text{Overlap}_{ah} \times \text{Experimental}_t + \text{FE}_{c(a)t} + \text{FE}_{f(a)} + \epsilon_{aht} \quad (1)$$

where $\text{Collaboration}_{aht}$ is the share of patents filed by inventors in foreign affiliate a in technology t that are in collaboration with inventors located in HQ establishment h of the same MNE.¹⁴ Focusing on the share of patents as our outcome variable implicitly controls for all factors that may determine the scale of R&D activity in affiliate a or the likelihood of R&D outputs being converted into patents.

The explanatory variables of interest are Overlap_{ah} , the overlap in business hours between the time zone in which affiliate a is located and the time zone of the MNE's HQ establishment h , and its interaction with an indicator for experimental technology classes

¹⁴In the case of countries spanning multiple time zones, establishments located in different time zones will enter the sample as separate observations.

(Experimental_{*t*}). The affiliate country-technology fixed effect captures unobservable heterogeneity related to innovative prowess of the host country. Thus our identification relies on variation in business hour overlap between foreign affiliates operating in country *c* and technology *t* and their parent companies in various home countries. The fixed effect for MNE *f* (to whom affiliate *a* belongs) captures the possibility of different firms having different willingness to engage in cross-border collaboration in innovative activity. Standard errors are clustered at the location pair-technology level.¹⁵

We hypothesize that a high overlap in business hours reduces communication frictions and thus increases collaboration ($\alpha_1 > 1$). In addition, we expect technology classes that require a high frequency of interactions to be more sensitive to time zone differences. Hence, we anticipate that a greater overlap will matter more for them and expect a positive coefficient on the interaction term ($\alpha_2 > 0$).

The estimation results, presented in Table 2, confirm our hypothesis that business hour overlap facilitates cross-border collaboration. In all specifications, the coefficient on the business hour overlap is positive and statistically significant at the 1 percent level. Inventors in experimental technology classes benefit more from higher overlap in business hours, with the effect statistically significant at the 1 and the 5 percent level in columns 2 and 4, respectively.

The magnitude of the estimated effects is economically meaningful. Column 1 implies that an increase in business hour overlap by eight hours is associated with a 14% point (or 39%) increase in the probability of a patent involving HQ for inventors located at foreign affiliates. In other words, an inventor working for a Polish subsidiary of a German multinational is 14% points more likely than an inventor located in its Japanese subsidiary to collaborate on a patent with colleagues at the firm's HQ.

There are several threats to our interpretation of the results. First, there may be other variables correlated with business hour overlap. In particular, geographical distance may be both correlated with temporal distance and important for collaboration patterns, for instance because of increased travel time. In columns 3 and 4, we show that controlling for geographical distance barely changes our estimated coefficients. As in previous studies, we find a negative effect of geographical distance on collaboration. Although physical distance is an important determinant of collaboration, we find that it matters less than temporal distance. Inventors based in Tokyo are 2% points less likely to collaborate with their Berlin HQ than their colleagues in Warsaw.¹⁶ Finally, we find no evidence that the

¹⁵The results are robust to clustering at the firm level.

¹⁶The distance between Berlin and Tokyo is around 8918km, while the distance between Berlin and Warsaw is around 516km. Then, we compute $(\log(8918) - \log(516)) \times (-0.0081)$

effect of physical distance matters more for experimental technologies, suggesting that the business hours overlap captures a distinct friction to communication especially relevant for projects with a high frequency of interactions.

A second concern is that experimental technologies might feature other characteristics that make collaboration difficult when temporal distance is high. In a robustness check (not shown to save space), we classify technology classes by how much they rely on scientific articles and by how process- rather than product-intensive they are. Controlling for the interaction of these technology characteristics and business hour overlap barely affects the baseline results. In addition, using a continuous measure of the share of experimental patents by technology class (instead of an indicator) yields a highly significant effect.

Table 2: Collaboration, Business Hour Overlap and Distance

	Share Collaboration			
	(1)	(2)	(3)	(4)
Overlap	0.0646*** (0.0019)	0.0593*** (0.0020)	0.0597*** (0.0032)	0.0537*** (0.0033)
Experimental \times Overlap		0.0111*** (0.0028)		0.0129** (0.0058)
log(distance)			-0.0081** (0.0034)	-0.0089** (0.0035)
Experimental \times log(distance)				0.0024 (0.0050)
Observations	316,877	316,877	316,877	316,877
R ²	0.47	0.47	0.47	0.47
Dependent variable mean	0.36	0.36	0.36	0.36
<i>Fixed Effects</i>				
GUO	✓	✓	✓	✓
Host Country-Technology	✓	✓	✓	✓

Notes: This table reports the results of estimating equation 1. The sample contains all patents filed by inventors located in a foreign affiliate. The dependent variable is the share of these patents that is produced in collaboration with a HQ-based inventor. Overlap captures the log-transformed number of overlapping business hours between affiliate and HQ. Distance is the geographical distance between affiliate and HQ. Experimental is 1 for experimental technology classes, 0 otherwise. Standard errors are clustered at the location pair-technology level. ***, **, * denote statistical significance at the 1%, 5% and 10% levels, respectively.

The cross-sectional analysis presented thus far provides suggestive evidence of a substantial effect of business hour overlap on collaboration patterns. Nonetheless, a causal interpretation of the results remains difficult. Firms may anticipate the difficulty caused

by temporal distance and adapt the nature of investments they make. For example, a German MNC may strategically locate tasks or personnel in Japan requiring little collaboration whereas placing those with a high need for interaction in its Polish subsidiary. The following section addresses this concern by exploiting exogenous variation in communication costs stemming from the liberalization of telecommunication sectors. By relying on temporal variation with affiliate-HQ-technology cell, it abstracts from concerns about location of new subsidiaries responding to telecom liberalization.

5 Liberalization of Telecommunication Markets

The next step in our analysis takes advantage of the temporal variation in the timing of telecom liberalization episodes across countries. The underlying intuition is that liberalization of a telecom market brings competition and leads to a decline in the price of international calls, which in turn boosts communications between affiliates and HQ and facilitates cross-border cooperation. We hypothesize that the impact of liberalization will be increasing in the business hour overlap between the affiliate and HQ. Put differently, we conjecture that if a large time difference makes communications very inconvenient, a drop in the price of international calls is not going to compensate fully for this inconvenience.

Table D.5 lists the year of telecom liberalization for OECD countries. Among them, only the US, UK and Japan liberalized in the 1980s, followed by other Commonwealth countries and Sweden in the early 1990s and Western Europe in 1998. Our empirical approach exploits this staggered pattern of liberalization.

5.1 Baseline

To test our hypothesis we estimate the following equation:

$$\begin{aligned} \text{Collaboration}_{ahty} = & \beta_1 \times \text{Liberalization}_{c(a)c(h)y} + \beta_2 \times \text{Liberalization}_{c(a)c(h)y} \times \text{Overlap}_{ah} \\ & + \text{FE}_{aht} + \text{FE}_{c(a)y} + \text{FE}_{ty} + \epsilon_{ahty} \end{aligned} \quad (2)$$

where $\text{Collaboration}_{ahty}$ is the share of patents filed by inventors in foreign affiliate a in technology t in year y that are in collaboration with inventors located in HQ establishment h of the same MNE. $\text{Liberalization}_{c(a)c(h)y}$ measures whether markets for international calls have been liberalized in both the affiliate country $c(a)$ and the HQ country $c(h)$ in year y . Because of the so called termination fees, the liberalization status of both

markets matters. To study whether the impact of liberalization varies with the type of communication required, we estimate equation 2 for the full sample, and separately for experimental and other technology classes.

We include several sets of fixed effects. First, all our specifications include establishment-pair-technology fixed effects (aht), meaning a fixed effect for firm f 's affiliates in a particular time zone of host country $c(a)$ and a particular time zone of home country $c(h)$. This implicitly requires firm f 's presence in a particular time zone of country c both before and after the two-sided liberalization of the telecom markets, thus eliminating the possibility that our results are driven purely by entry of MNEs into a new location. This also eliminates any other time-invariant factors that may drive research collaboration between two establishments, such as a common language or historical ties.

Second, we control for affiliate-country-time ($c(a)y$) or alternatively HQ-country-time ($c(h)y$) fixed effects. The former allow us to take into account unobservable affiliate-country-time heterogeneity (that may be driving affiliate country liberalization) and use variation in geographic location of HQ to identify the effects of interest. Thus differences in timing of liberalization across pairs of countries and differences in time zones across host countries are the source of identifying variation. Alternatively, we account for unobservable HQ-country-time heterogeneity and use variation across affiliate countries of MNEs.

Third, we include technology-time fixed effects (ty), capturing any technology-specific changes in collaboration patterns. For example, as industries mature and products become more complex, innovation may require increasingly larger teams.

The results, presented in Table 3, provide support for our hypothesis. The impact of telecom liberalization on cross-border R&D collaboration increases in the business hour overlap between the affiliate and the HQ.¹⁷ In the first three specifications, no statistically significant impact is present if there is no overlap in business hours. In addition to the continuous variable capturing overlap in business hours, we estimate a variation of equation 2, dividing the liberalization variable into two-hour intervals of business hour overlap (columns 4 to 6). We find that in the full sample and in the experimental technology classes telecom liberalization has its biggest impact when temporal distance is lowest, i.e. a business hour overlap of at least 6 hours, followed by the temporal distance of 4-6 hours.

¹⁷Note that these indicators are exhaustive, hence no need for inclusion of a self-standing overlap measure.

Table 3: Telecom Liberalization and Collaboration

	Share Collaboration					
	Full Sample (1)	Experimental (2)	Non-experimental (3)	Full Sample (4)	Experimental (5)	Non-experimental (6)
Liberalization	0.0154 (0.0143)	0.0234 (0.0167)	0.0050 (0.0209)			
× Overlap	0.0208*** (0.0059)	0.0258*** (0.0081)	0.0124** (0.0052)			
× 0-2 hours				0.0260* (0.0141)	0.0384** (0.0149)	0.0081 (0.0212)
× 2-4 hours				0.0422 (0.0345)	0.0372 (0.0474)	0.0548** (0.0213)
× 4-6 hours				0.0446** (0.0201)	0.0452* (0.0251)	0.0561** (0.0236)
× 6-8 hours				0.0639*** (0.0140)	0.0858*** (0.0176)	0.0306* (0.0182)
Observations	575,782	293,242	282,540	575,782	293,242	282,540
R ²	0.84	0.81	0.87	0.84	0.81	0.87
Dependent variable mean	0.27	0.28	0.26	0.27	0.28	0.26
<i>Fixed Effects</i>						
Establishment Pair-Technology	✓	✓	✓	✓	✓	✓
Year-Host Country	✓	✓	✓	✓	✓	✓
Year-Technology	✓	✓	✓	✓	✓	✓

Notes: This table reports the results of estimating equation 2. The sample contains all patents filed by inventors located in a foreign affiliate. The dependent variable is the share of these patents that is produced in collaboration with a HQ-based inventor. Liberalization equals 1 if source and affiliate countries have liberalized their markets for telecommunication, 0 otherwise. Overlap captures the log-transformed number of overlapping business hours between affiliate and HQ. Standard errors are clustered at the country-pair level. ***, **, * denote statistical significance at the 1%, 5% and 10% levels, respectively.

The liberalization impact is generally larger and varies more with business hour overlap for experimental technology classes, confirming our earlier results that communication frictions are more relevant in technology classes that plausibly require more exchange between inventors. In non-experimental technology classes, this pattern is less pronounced.

To better understand the magnitude of the result, take the estimates in column 4 of table 3 and consider a German MNE with a Polish and a Japanese subsidiary with 8 and 0 hour business hour overlap, respectively. After telecom liberalization, the share of patents in collaboration with HQ filed by inventors located in the Polish subsidiary will increase by 6.4% points (which is equivalent to a 22% increase). In contrast, collaborative patents in the Japanese subsidiary will increase by 2.6% points (equivalent to a 10% increase).¹⁸ Thus, the effect of telecom liberalization on collaboration is more than twice as large for the Polish affiliate, both in absolute and relative terms.

¹⁸The relative effect is computed using the pre-treatment mean for each interval of business hour overlap.

We conduct a series of robustness check, which we present in the Appendix. Table D.6 shows that the results are robust to focusing on affiliates that already existed in the 1980s. This further alleviates concerns about telecom liberalization triggering FDI, thereby leading to creation of new establishments. Table D.7 in the appendix shows that results are robust to using the variation coming from affiliate-country liberalization by including HQ-country-year fixed effects. In Table D.8, instead of splitting the sample, we interact our liberalization and overlap variables with the indicator capturing experimental technologies. The triple interaction term yields a statistically significant coefficient, again supporting our hypothesis that experimental technologies are affected more. Moreover, this result is robust to including location-pair-year fixed effects and to controlling for a triple interaction with physical distance.

Finally, in Table D.9, we interact liberalization with the North-South distance and the East-West distance. Only the East-West interaction is statistically significant and its negative sign suggests that a greater East-West distance limits the benefits of liberalization. This is intuitive as the East-West distance is associated with a change in time zones. As one may expect, this interaction ceases to be significant once we include the interaction term with the business hour overlap.

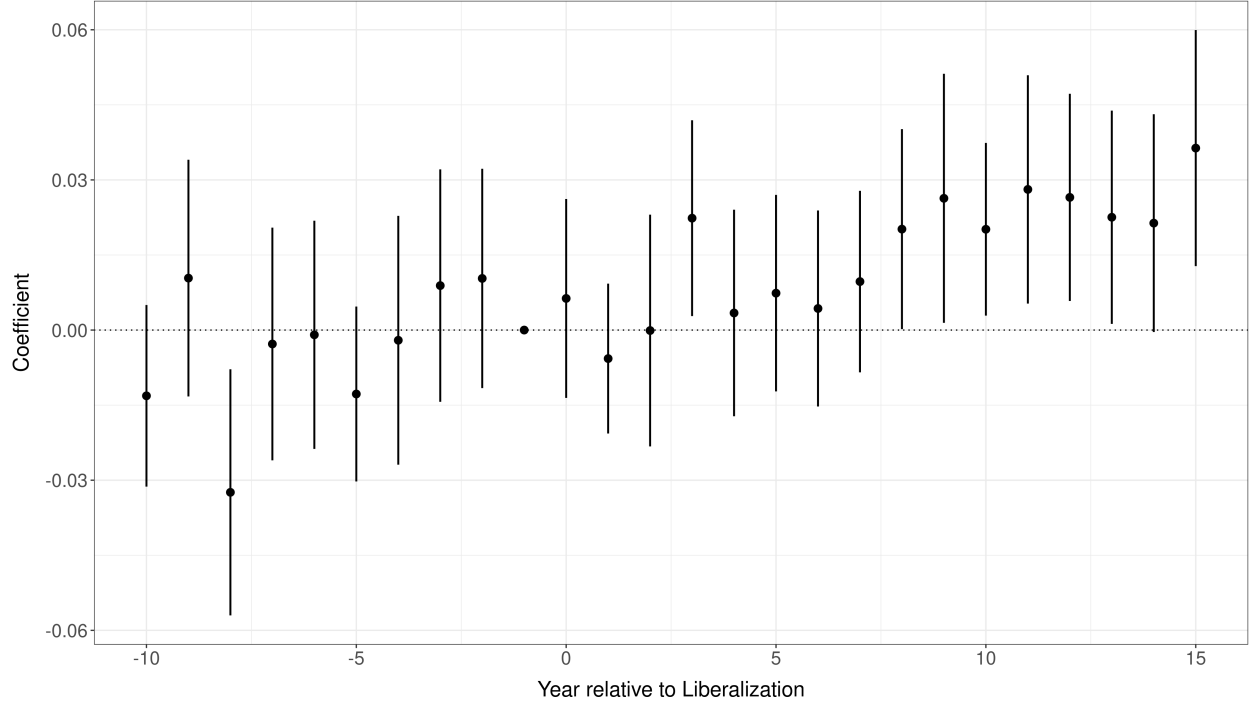
5.2 Event Study

The panel nature of our data allow us to conduct event studies. Specifically, we test whether collaboration patterns were already on the rise prior to telecom liberalization in country pairs with high business hour overlap relative to those with low business hour overlap. This test also allows us to document how telecom liberalization affects collaboration over time. We estimate the following model:

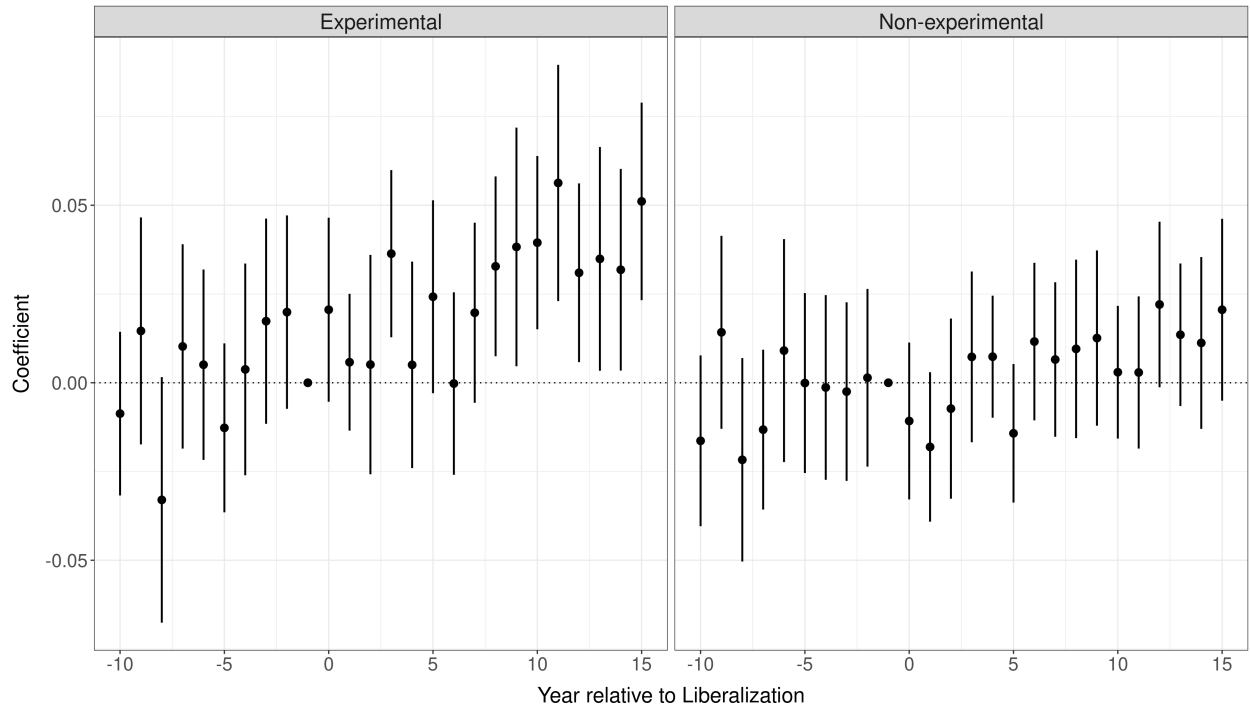
$$\begin{aligned} \text{Collaboration}_{ahty} = & \sum_{\substack{k=-10 \\ k \neq -1}}^K \beta_{1,k} \text{Liberalization}_{c(a)c(h),y+k} + \\ & + \sum_{\substack{k=-10 \\ k \neq -1}}^K \beta_{2,h} \text{Liberalization}_{c(a)c(h),y+k} \times \text{Overlap}_{ah} + \text{FE}_{aht} + \text{FE}_{c(a)y} + \text{FE}_{ty} + \epsilon_{ahty} \quad (3) \end{aligned}$$

This specification resembles equation 2, but we allow for a time-varying impact of liberalization rather than relying on a simple pre- versus post-liberalization comparison. Again, we estimate this model on the full sample and the two subsamples of technology types separately.

Figure 5: Event Study of the Impact of Telecom Liberalization on Collaboration



(a) Full Sample



(b) Split by Technology

Notes: This figure reports the results of estimating equation (3). The sample contains all patents filed by inventors located in a foreign affiliate. The dependent variable is the share of these patents that is produced in collaboration with a HQ-based inventor. Liberalization is defined as the liberalization of telecommunication markets in both source and host country. The corresponding dummy variable is interacted with the log-transformed number of overlapping business hours between affiliate and HQ. Standard errors are clustered at the country-pair level. 90% confidence intervals are shown.

Figure 5 depicts our estimates for β_2 , the coefficient on the interaction term between liberalization and business hour overlap. We do not detect business hour overlap affecting collaboration patterns prior to telecom liberalization. This lends support to the assumption that, in the absence of telecom liberalization, cross-border collaboration would have followed similar patterns in all country pairs regardless of business hour overlap. The figure further indicates that telecom liberalization mattered and that this effect was magnified by the business hour overlap, though the impact did not materialize immediately. The results are much more clear cut when we disaggregate them into experimental and non-experimental technology classes in Panel b. As visible in the figure, the effect for experimental technologies is much more pronounced. It takes around five years for the effect to kick in, which is to be expected as it takes time to start new collaborations and develop new patentable ideas.

A recent set of methodological papers on difference-in-differences shows that traditional two-way fixed effects may produce misleading estimates when the treatment effect is heterogeneous between groups or over time.¹⁹ Although these studies propose alternative estimators that are robust to such heterogeneity, they do not deal with cases as in our baseline equation (2), where the treatment variable, $Liberalization_{c(a)c(h)y}$, is interacted with a continuous term, $Overlap_{ah}$.

We therefore modify our event study specification in equation (3) to present results from one of these alternative estimators. Specifically, we redefine our treatment variable to equal 1 for affiliate and HQ country pairs that both liberalize their telecom markets *and* that have a business hour overlap greater than four hours. We then employ the imputation estimator of Borusyak et al. (2021) to estimate the treatment effect in the ten years before and fifteen years after the liberalization episode.²⁰ Figure C.4 in the Appendix confirms the lack of pre-trend effects prior to liberalization and corroborates the finding that cross-border collaboration has increased by around 5 percentage points in the decade following it (panel a).²¹ As in our baseline estimates, these effects are stronger for experimental technology classes (panel b) and statistically indistinguishable from zero for non-experimental technologies (panel c).

¹⁹See Roth et al. (2022) for an overview of this literature.

²⁰To achieve the imputation estimates, we can only include unit (affiliate-HQ-country-pair) and time fixed effects in this revised specification.

²¹Note that the Borusyak et al. (2021) estimator does not use $t - 1$ as a baseline period. The pre-trend coefficients up to $t - 1$ are estimated in regression which is entirely separate from the estimation of the coefficients from $t = 0$ onwards.

5.3 International Call Prices

An alternative (and a more direct) way of capturing telecom price liberalization is to focus on the actual price of international calls. Figure C.2 shows a histogram of call rate changes from 1990 to 2003. As visible in the figure, prices of international calls declined over this period for essentially all country pairs, though with substantial heterogeneity. The average rate declined by around 160%. Whereas the US generally saw a low decline in international call rates over this period, the European liberalization of telecommunication markets in the late 1990s resulted in a large drop in rates for those countries.

Thus next, we exploit heterogeneity in changes of international call prices across country pairs and estimate the following equation:

$$\begin{aligned} \text{Collaboration}_{ahty} = & \beta_1 \times \log(\text{Call Price}_{c(a)c(h)y}) + \beta_2 \times \log(\text{Call Price}_{c(a)c(h)y}) \times \text{Overlap}_{ah} \\ & + \text{FE}_{aht} + \text{FE}_{c(a)y} + \text{FE}_{ty} + \epsilon_{ahty} \end{aligned} \quad (4)$$

This equation is very similar to our previous specification in equation 2, but there are two differences. First, the indicator variable for the liberalization episodes has been replaced with $\text{Call Price}_{c(a)c(h)y}$. This variable is defined as the per-minute price for an international phone call between the affiliate and the MNE's HQ country.²² Second, because the data on call prices are available only for 1990, 1998 and 2003, y now represents 5-year periods (1990-1994, 1998-2002 and 2003-2007) instead of annual observations.

The results, presented in Table 4 below, provide further support for our hypothesis. A decline in call prices, i.e. communications costs, boosts the share of cross-border collaborative patents only in the presence of some overlap in the business hours between HQ and affiliates. The mean reduction in minimum call prices between 1990 and 2003 in the regression sample is around 2.19 log points. This translates into an increase in collaboration of around 7.8 percentage points for the German-owned Polish subsidiary and no statistically significant effect for the Japanese affiliate of the same firm.

²²As call prices are not necessarily symmetric, i.e. calling from country A to B can be less/more expensive than vice versa, we take the minimum of both prices.

Table 4: International Call Prices and Collaboration

	Share Collaboration					
	Full Sample (1)	Experimental (2)	Non-experimental (3)	Full Sample (4)	Experimental (5)	Non-experimental (6)
log(Call Price)	0.0008 (0.0124)	-0.0055 (0.0149)	0.0101 (0.0120)			
× Overlap	-0.0131*** (0.0027)	-0.0136*** (0.0037)	-0.0127*** (0.0037)			
× 0-2 hours				-0.0079 (0.0127)	-0.0152 (0.0149)	0.0022 (0.0119)
× 2-4 hours				-0.0268* (0.0154)	-0.0118 (0.0181)	-0.0549*** (0.0192)
× 4-6 hours				-0.0306 (0.0198)	-0.0448 (0.0436)	-0.0153 (0.0318)
× 6-8 hours				-0.0355*** (0.0131)	-0.0430** (0.0167)	-0.0255** (0.0117)
Observations	232,577	114,138	118,439	232,577	114,138	118,439
R ²	0.95	0.94	0.96	0.95	0.94	0.96
Dependent variable mean	0.31	0.33	0.30	0.31	0.33	0.30
<i>Fixed Effects</i>						
Establishment Pair-Technology	✓	✓	✓	✓	✓	✓
Period-Host Country	✓	✓	✓	✓	✓	✓
Period-Technology	✓	✓	✓	✓	✓	✓

Notes: This table reports the results of estimating equation 4. The sample contains all patents filed by inventors located in a foreign affiliate. The dependent variable is the share of these patents that is produced in collaboration with HQ-based inventors. The call price captures the minimum bilateral call price between the affiliate and HQ. Overlap captures the log-transformed number of overlapping business hours between affiliate and HQ. Standard errors are clustered at the country-pair level. ***, **, * denote statistical significance at the 1%, 5% and 10% levels, respectively.

5.4 Has Telecom Liberalization Boosted Patent Quality and Volume?

Our analysis so far has produced evidence of telecom liberalization boosting the share of cross-border patents, but has it also affected the quality of innovative activity? To answer this question we focus on the impact of liberalization on the share of patents citing science and the share of breakthrough patents, following the approach outlined in Section 2.

As visible in Table 5, telecom liberalization was followed by an increase in the share of patents citing science as well as breakthrough patents, both increasing in the business hour overlap. The estimates show a positive and statistically significant coefficient on the interaction term between the liberalization indicator and the business hours overlap variable. Coming back to our earlier example of a German MNE with subsidiaries in Poland and in Japan, telecom liberalization would have increased the share of patents citing science by around 2% points in the former, while there would have been no statistically significant change in the latter subsidiary. For breakthrough patents, the Polish subsidiary

would have seen an increase of around 2% points. Replacing the continuous measure of business hours overlap with bin-specific indicators leads to similar conclusions, though the coefficients are less precisely estimated.

In Appendix Table D.10, which also shows the corresponding baseline results for comparison, we focus on both the extensive and the intensive margin. We first show in panel A that, conditional on filing any patent, subsidiaries with a high overlap in business hours are more likely to collaborate with HQ post-liberalization and produce at least one patent that cites science or that is considered a breakthrough. Similarly, the results in panel B indicate that the total number of collaborations and breakthrough patents also increases.²³

Table 5: Liberalization and Patent Characteristics

	Citing Science (1)	Breakthrough (2)	Citing Science (3)	Breakthrough (4)
Liberalization	-0.0011 (0.0103)	-0.0188 (0.0117)		
× Overlap	0.0111** (0.0044)	0.0163*** (0.0036)		
× 0-2 hours			0.0029 (0.0104)	-0.0078 (0.0101)
× 2-4 hours			0.0062 (0.0155)	-0.0271 (0.0223)
× 4-6 hours			0.0347* (0.0188)	0.0506*** (0.0172)
× 6-8 hours			0.0306** (0.0148)	0.0157 (0.0122)
Observations	575,782	534,948	575,782	534,948
R ²	0.79	0.85	0.79	0.85
Dependent variable mean	0.63	0.22	0.63	0.22
<i>Fixed Effects</i>				
Establishment Pair-Technology	✓	✓	✓	✓
Year-Host Country	✓	✓	✓	✓
Year-Technology	✓	✓	✓	✓

Notes: This table reports the results of estimating equation 2. The sample contains all patents filed by inventors located in a foreign affiliate. The dependent variable is the share of these patents that cites science (columns 1 and 3) and the share of breakthrough patents (columns 2 and 4), respectively. Refer to section 2 for a description of these variables. Liberalization equals 1 if source and affiliate countries have liberalized their markets for telecommunication, 0 otherwise. Overlap captures the log-transformed number of overlapping business hours between affiliate and HQ. Standard errors are clustered at the country-pair level. ***, **, * denote statistical significance at the 1%, 5% and 10% levels, respectively.

²³As the dependent variable contains zeros, we transform the dependent variable using the inverse hyperbolic sine.

5.5 Team Size

A decline in communication costs may be expected to lead to an increase in the size of inventor teams. This is the question we turn to in this subsection and estimate the following specification:

$$\begin{aligned} \log(\text{Team Size})_{ahty} = & \beta_1 \times \text{Liberalization}_{c(a)c(h)y} + \beta_2 \times \text{Liberalization}_{c(a)c(h)y} \times \text{Overlap}_{ah} \\ & + \text{FE}_{aht} + \text{FE}_{c(a)y} + \text{FE}_{ty} + \epsilon_{ahty} \end{aligned} \quad (5)$$

where the dependent variable now captures the average number of inventors listed on all collaborative patents involving foreign affiliate a and HQ establishment h in technology class t in year y . The right-hand-side of the equation remains as before. We take logs of the dependent variable, since the size of inventor teams is right-skewed.²⁴

Table 6: Telecom Liberalization and Team Size

Inventors located in	log(Team Size)		
	HQ or establishment (1)	Establishment only (2)	HQ only (3)
Liberalization	-0.0216 (0.0212)	-0.0271 (0.0229)	0.0056 (0.0257)
× Overlap	0.0226** (0.0091)	-0.0039 (0.0099)	0.0358*** (0.0082)
Observations	575,782	575,782	575,782
R ²	0.79	0.73	0.88
Dependent variable mean	0.94	0.62	0.40
<i>Fixed Effects</i>			
Establishment Pair-Technology	✓	✓	✓
Year-Host Country	✓	✓	✓
Year-Technology	✓	✓	✓

Notes: This table reports the results of estimating equation 5. The sample contains all patents filed by inventors located in a foreign affiliate. The dependent variable is the average size of the inventor teams filing patents. Liberalization equals 1 if source and affiliate countries have liberalized their markets for telecommunication, 0 otherwise. Overlap captures the log-transformed number of overlapping business hours between affiliate and HQ. Standard errors are clustered at the country-pair level. ***, **, * denote statistical significance at the 1%, 5% and 10% levels, respectively.

²⁴When we focus on HQ inventors only, we use a $\log(1 + x)$ transformation instead, since the HQ team size can be zero.

The results, presented in column 1 of table 6 mirror our earlier findings and confirm our priors. As anticipated, telecom liberalization leads to an increase in the size of inventor teams but only when there is a substantial business hour overlap between a foreign affiliate and HQ. To unpack these results, we disaggregate the dependent variable to measure the number of inventors involved who are based in a foreign affiliate (column 2) and in HQ (column 3). A greater response of HQ-based inventors seems to be driving the results.

6 Inventor-level Analysis

So far, the focal point of our analysis has been a foreign affiliate of an MNE. In a final step of our study, we further exploit the granularity of patent data by conducting an inventor-level analysis. This allows us to study whether the effects of communication frictions vary with inventor characteristics. In particular, guided by the existing literature, we distinguish between established or star inventors and their peers with a lesser track record.

6.1 Baseline

We start by estimating the following equation:

$$\begin{aligned} \text{Collaboration}_{iahy} = & \beta_1 \times \text{Liberalization}_{c(a)c(h)y} + \beta_2 \times \text{Liberalization}_{c(a)c(h)y} \times \text{Overlap}_{ah} \\ & + \text{FE}_{ah} + \text{FE}_{c(a)y} + \text{FE}_i + \epsilon_{iahy} \end{aligned} \quad (6)$$

where $\text{Collaboration}_{iahy}$ is the share of patents involving inventor i working in a MNE's foreign affiliate a that are filed in collaboration with inventors located in the MNE's HQ h in year y . This equation is similar to our baseline establishment-level specification (equation 2) but to simplify the analysis we drop the technology dimension. This leaves us with an establishment-pair fixed effect (ah) and an affiliate-country-time fixed effect ($c(a)y$). In some specifications, we also include an inventor fixed effect (i) to control for any time-invariant inventor characteristics.

The inventor-level analysis confirms the findings of the affiliate-level analysis. The estimates in Table 7 show that liberalization matters for cross-border collaboration when the overlap in business hours is high. This result holds when we use a continuous measure of business hour overlap as well as when we use indicators for overlap intervals. Importantly, the results remain similar after including inventor fixed effects, though the estimated magnitudes decrease slightly. The magnitudes are also similar to those found

earlier. For instance, the estimates from column 4 imply that liberalization increased the likelihood of an investor being involved in cross-border collaboration by 3.4% points when the affiliate-HQ business hour overlap was between 6 and 8 hours. Robustness of the results to inclusion of inventor fixed effects implies that our earlier findings were not driven by a change in the composition of employees at the establishment level around liberalization episodes, but rather that individual inventors started collaborating more with HQ after liberalization.

Table 7: Telecom Liberalization and Collaboration - Inventor Level

	Share Collaboration			
	(1)	(2)	(3)	(4)
Liberalization	0.0030 (0.0195)	-0.0202 (0.0147)		
× Overlap	0.0242*** (0.0041)	0.0220*** (0.0034)		
× 0-2 hours			0.0182 (0.0217)	-0.0101 (0.0156)
× 2-4 hours			0.0340 (0.0298)	0.0205 (0.0326)
× 4-6 hours			0.0255 (0.0254)	0.0007 (0.0246)
× 6-8 hours			0.0514** (0.0199)	0.0338** (0.0165)
Observations	526,809	526,809	526,809	526,809
R ²	0.54	0.77	0.54	0.77
Dependent variable mean	0.16	0.16	0.16	0.16
<i>Fixed Effects</i>				
Establishment Pair	✓	✓	✓	✓
Year-Host Country	✓	✓	✓	✓
Inventor		✓		✓

Notes: This table reports the results of estimating equation 6. The sample contains all patents filed by inventors located in a foreign affiliate. The dependent variable is the share of these patents that is produced in collaboration with a HQ-based inventor. Liberalization equals 1 if source and affiliate countries have liberalized their markets for telecommunication, 0 otherwise. Overlap captures the log-transformed number of overlapping business hours between affiliate and HQ. Standard errors are clustered at the country pair level. ***, **, * denote statistical significance at the 1%, 5% and 10% levels, respectively.

6.2 Star Inventors

In the final part of our study, we explore heterogeneous impacts on inventors with different patenting histories. As discussed in the introduction, a priori the effects of a decline in

communication barriers on the likelihood of cross-border collaboration by star inventors versus their less successful peers are ambiguous. On the one hand, inventors with lesser track records may stand to benefit more from international collaborations and thus may be willing to incur the high costs of international communication and the inconvenience of time zone differential. On the other hand, the presence of such costs, which must be partially born by their collaborators located in HQ, makes them less attractive as team members.

To examine these differential impacts we estimate the following equation:

$$\begin{aligned}
\text{Collaboration}_{iahy} = & \beta_1 \times \text{Liberalization}_{c(a)c(h)y} + \beta_2 \times \text{Liberalization}_{c(a)c(h)y} \times \text{Overlap}_{ah} \\
& + \beta_3 \times \text{Liberalization}_{c(a)c(h)y} \times \text{Star}_i \\
& + \beta_4 \times \text{Liberalization}_{c(a)c(h)y} \times \text{Overlap}_{ah} \times \text{Star}_i \\
& + \beta_5 \times \text{Star}_i + \beta_6 \times \text{Overlap}_{ah} \times \text{Star}_i + \text{FE}_{ah} + \text{FE}_{c(a)y} + \epsilon_{iahy}
\end{aligned} \tag{7}$$

This equation is a modified version of equation 6. We introduce an inventor-level indicator for being highly productive (Star_i) and all its interaction terms that are not captured by fixed effects (see Section 2.3 for a definition of star inventors). This specification is estimated on a reduced sample, since our definition of Star_i requires us to observe an inventor's track record from the 1980s. The coefficient of interest, β_4 , captures whether the increase in collaboration for inventors in high-overlap affiliates differs according to their initial track record.

The estimation results are presented in Table 8. They confirm our earlier findings that telecomm liberalization boosts cross-border collaboration when the business hour overlap is higher. We also find that star inventors are in general more likely to collaborate across borders. Most importantly, we find that telecomm liberalization in the presence of a higher business hour overlap has a larger effect on cross-border collaboration by non-star inventors. The negative estimate for β_4 is significant at the 5 percent level in all specifications. This finding is independent of the way we define star inventors (whether they are among top 10% or top 25% in their affiliate, whether we use a continuous measure of their past track record, or whether we focus on citations to their patents). This finding is also robust to including inventor fixed effects. In sum, our results suggest that less experienced inventors are more sensitive to an exogenous change in communication frictions.

Table 8: Telecom Liberalization and Collaboration - Inventor Heterogeneity

Star Inventor Definition	Share Collaboration					
	(1)	Top 25% (2)	Top 25% (3)	Top 10% (4)	Continuous (5)	Top 25% Cited (6)
Liberalization	-0.0133 (0.0127)	-0.0139 (0.0125)	-0.0233 (0.0150)	-0.0129 (0.0129)	-0.0151 (0.0128)	-0.0132 (0.0128)
Liberalization \times Overlap	0.0168*** (0.0044)	0.0189*** (0.0050)	0.0204*** (0.0037)	0.0179*** (0.0042)	0.0205*** (0.0051)	0.0184*** (0.0047)
Star Inventor		0.0036* (0.0019)		0.0076*** (0.0018)	0.0009 (0.0012)	0.0050* (0.0026)
Overlap \times Star Inventor		0.0010 (0.0022)	0.0030 (0.0054)	0.0018 (0.0038)	0.0008 (0.0010)	0.0003 (0.0027)
Liberalization \times Star Inventor		0.0026 (0.0052)	0.0104 (0.0104)	-0.0024 (0.0042)	0.0015 (0.0018)	0.0005 (0.0042)
Liberalization \times Overlap \times Star Inventor		-0.0096** (0.0042)	-0.0146** (0.0064)	-0.0125** (0.0051)	-0.0033** (0.0015)	-0.0073** (0.0035)
Observations	149,609	149,609	149,609	149,609	149,609	149,609
R ²	0.58	0.58	0.78	0.58	0.58	0.58
Dependent variable mean	0.13	0.13	0.13	0.13	0.13	0.13
<i>Fixed Effects</i>						
Establishment Pair	✓	✓	✓	✓	✓	✓
Year-Host Country	✓	✓	✓	✓	✓	✓
Inventor			✓			

Notes: This table reports the results of estimating equation 6. The sample contains all patents filed by inventors located in a foreign affiliate that were active in the 1980s. The dependent variable is the share of these patents that is produced in collaboration with a HQ-based inventor. Liberalization equals 1 if source and affiliate countries have liberalized their markets for telecommunication, 0 otherwise. Overlap captures the log-transformed number of overlapping business hours between affiliate and HQ. An inventor is defined as a star if they belong to the top 25% in terms of 1980s patent filings among inventors in the same firm. Standard errors are clustered at the country pair level. ***, **, * denote statistical significance at the 1%, 5% and 10% levels, respectively.

7 Conclusions

Using a newly constructed dataset, this paper studies innovation inside multinational firms, which frequently involves inventors based outside the HQ country. We analyze communication frictions that affect cross-border inventor collaboration and thereby the production of knowledge inside the firm.

We first show that business hour overlap is crucial for collaboration between affiliate- and HQ-based inventors. This effect is distinct from the effect of a physical distance, which matters as well. Inventors in technology classes involving experimentation, potentially requiring a higher frequency of communication, are most sensitive to the business

hour overlap.

We also study the evolution of collaboration over time. We focus on the liberalization of the telecom sector during the 1980s and 1990s, which dramatically decreased the price of international phone calls, leading to an increase of cross-border communications. We find that telecom liberalization boosted cross-border collaboration between foreign affiliates and HQ, especially in experimental technologies at affiliates which were temporally close to HQ. This finding suggests that while cheap communication matters, it cannot fully overcome the underlying geographic features. More importantly, our results suggest that a decline in communications frictions led to an increase in the share of breakthrough patents and in the size of inventor teams.

Finally, we show that reducing frictions to cross-border knowledge creation inside multinationals is less important for star inventors than for others. This may indicate that reducing communication frictions benefits a broad set of less experienced inventors in FDI host countries, potentially reducing the knowledge gap between them and star inventors.

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On-line Appendix

A Details on Orbis IP (matching patents to firms)

This appendix section provides the details on the matching of patents to firms.

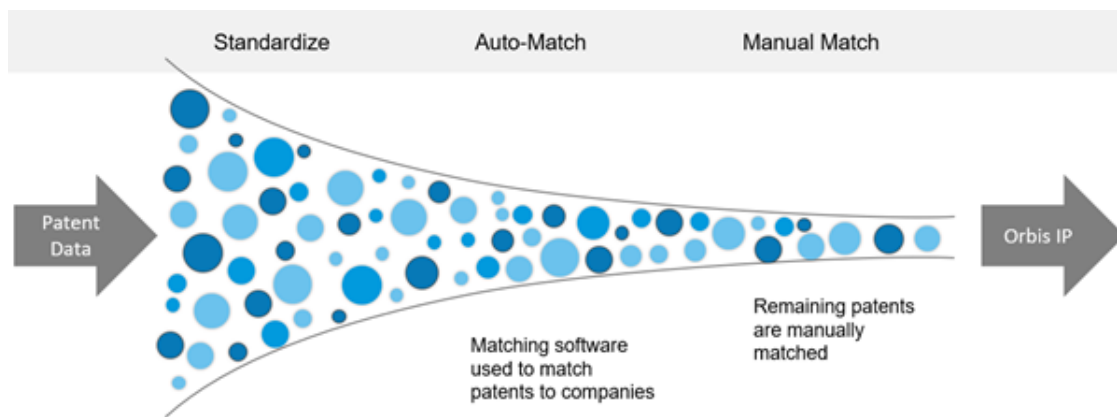
Orbis IP sources its patent information from LexisNexis. At the time of our access to Orbis IP in October-November 2020, the database had approximately 110 million patent documents, covering information from patent offices in 109 countries. Bureau van Dijk (BvD) describes their procedure of matching patents to firms as follows.

At BvD, the matching process begins with processing xml documents to extract the assignee details and company details from BvD's global company database to be matched to include the following fields:

- Company name
- Local name
- Street (not to match but to detect duplicates)
- Postal Code (not to match but to detect duplicates)
- City (important for the matching when given by the IP)
- Region in country (not to match but to detect duplicates)
- Country ISO Code
- Email/Website (as a confirmation)
- Category of company
- Listed/delisted
- Status (active/inactive)
- Company ID (for duplicates)
- Source
- BvD ID
- Activity description

The above data to be matched follows the below process first through automated fuzzy logic-based matching and then through manual matching:

Figure A.1: Orbis IP procedure for matching patents to firms



Source: Orbis IP / Bureau van Dijk.

A.1 Automated Matching Tool (Fuzzy Logic)

BvD's fuzzy matching takes place in three steps:

1. Normalisation: transforms the original query to match the database candidates as far as possible.
2. Candidate selection: retrieves the best potential candidates from the normalised query.
3. Candidate evaluation: evaluates the distance of each candidate from the normalised query, and filters the candidates to select the best matches.

These three steps are explained in more detail below.

1. Normalisation

The goal of the normalisation process is to reduce the differences between the original query and the database entities to a minimum. When entities are added to the database, they are normalised with the same process that is used to normalise the query, ensuring minimal differences.

Different normalisation processes take place (lowercase, remove diacritics, etc). Some are specific to the type of entity: for companies, the legal form will be normalised (i.e. Limited becomes ltd) and for individuals the first name will be normalised using hypocorism.

Note that the normalisation process for one entity can lead to multiple searches: consider a single query to retrieve Thierry Henry (French football player). Thierry and Henry are both French first names and last names, so as part of the normalisation process it performs two distinct searches: a) one for first name Thierry, last name Henry b) and one for first name Henry, last name Thierry.

2. Candidate selection

The goal of the selection step is to retrieve - as quickly as possible - all potential candidates in the database. When handling a large quantity of data it isn't possible to check every entity of the database in order to retrieve only the best candidates, therefore a fuzzy algorithm is used in order to locate within the database only those candidates that "should be" the best ones, and to evaluate only those candidates.

All such algorithms come at a cost: there is a trade-off to be made between the "recall" and the "precision". Globally, the recall will measure the fact that the selected candidates always contain the true match, while the precision will measure the fact that the proposed candidate are valid matches, and will limit false positives in the results. No algorithm will guarantee a 100% recall, except if you evaluate all the candidates present in the database one by one, which isn't possible when handling a large quantity of data.

The algorithm implemented for the candidate selection is based on the N-Gram algorithm, where a query is split into different blocks of letters (or grams) of a given size ($N=3$). The potential candidates are then those candidates that share as much N-Gram as possible with the normalised query. This algorithm is language agnostic. For example, if you misspell "Bureau van Dijk" and query the system for "Buro van Dijk", the decomposition in N-Gram of both names ($N=3$) would give:

BUR URO VAN DIJ IJK

BUR URE REA EAU VAN DIJ IJK

and would retrieve BUR, VAN, DIJ, IJK in common to both queries, leading to the selection of the candidate.

Note that the major flaw of the N-Gram algorithm is working with "small" words, indeed making a mistake in a three-letter word using 3 as the gram size would never select the correct three-letter candidate as no gram will be common (i.e. if one were to type BNW intending to retrieve BMW). Therefore, small words are handled differently and the applicable method uses an algorithm based on the edit distance.

3. Candidate evaluation

In the last step of the process, the goal is to sort and reduce the candidates to the distance threshold value specified by the user. The computed similarity is based on the edit distance.

A.2 Manual Matching Software

The BvD Matching Software application is designed to supplement the automatic matching functionality that is typically used to correlate records found in the patent databases to records in BvD's company database. Records that cannot be matched automatically are presented to BvD Matching Software users so that they can accept or reject possible matches manually. The likelihood of a match is declared for each record in the application's interface. The final purpose of the matching process is to link patent records to an appropriate BvD identification number.

BvD uses the following fields to calculate a matching score between patent and BvD company databases: Assignee name, Street, City, Postal code, Country (or ISO code). The registered/legal address of the companies is used. BvD takes into consideration the current name of the companies, alongside their previous names and 'also known as' names. There is no limit in the number of characters for a name (or any other field).

1. Normalisation To identify similarities and enable high scoring matches, the matching system uses n-gram indexes, normalisation rules, and data dictionaries. The system can handle spelling mistakes, typos, word orders, special characters, context of words as it relates to a specific field/country, etc.

Specific normalisation rules are defined for each possible matching data field, and for each country. The normalisation rules are applied on BvD records (in the Orbis database) and patent records, hence the normalised values are taken into account for comparison/matching. For example, punctuation marks are replaced by blanks, legal forms are standardized, non-relevant words are ignored, synonyms are converted to a simple form, accented characters are converted into non-accented characters.

BvD Matching Software is Unicode compliant. It supports local characters such as Chinese, Cyrillic, Hungarian, German, Polish, Arabic, etc., and for some specific languages BvD uses transliteration to transform local characters into common and comparable characters enabling cross-alphabet matching.

2. Calculation After the data have been normalised, the match score is calculated using an algorithm based on the following principle. For each field of a given record, calculate the % of accuracy of the match between the BvD and patent records by using proximity calculations. Then, take a weighted average of all the % of proximities. Weights are calculated automatically; they are not fixed. The weight of a criterion is based on the probability of finding a company in the BvD database corresponding to the criterion being searched. This means the weight of each criterion depends on the number of occurrences in the BvD database and therefore, may differ from one release to another. The more occurrences that are found, the less the field is significant.

The automated process produces a matching score for each record. A quality indicator uses the following scoring criteria:

Figure A.2: Orbis IP patent-to-firm matching score indicator

A	Excellent	total score ≥ 95 %
B	Good	total score between 85 and 94 %
C	Fair	total score between 75 and 84 %
D	Weak	total score between 60 and 74 %
E	Poor	total score < 60 %

Source: Orbis IP / Bureau van Dijk.

The higher the score, the better the data match. Candidates with a poor matching quality (E) may be irrelevant. Any match with less than a 70% score is pushed into the manual matching pipeline.

B Sample Coverage

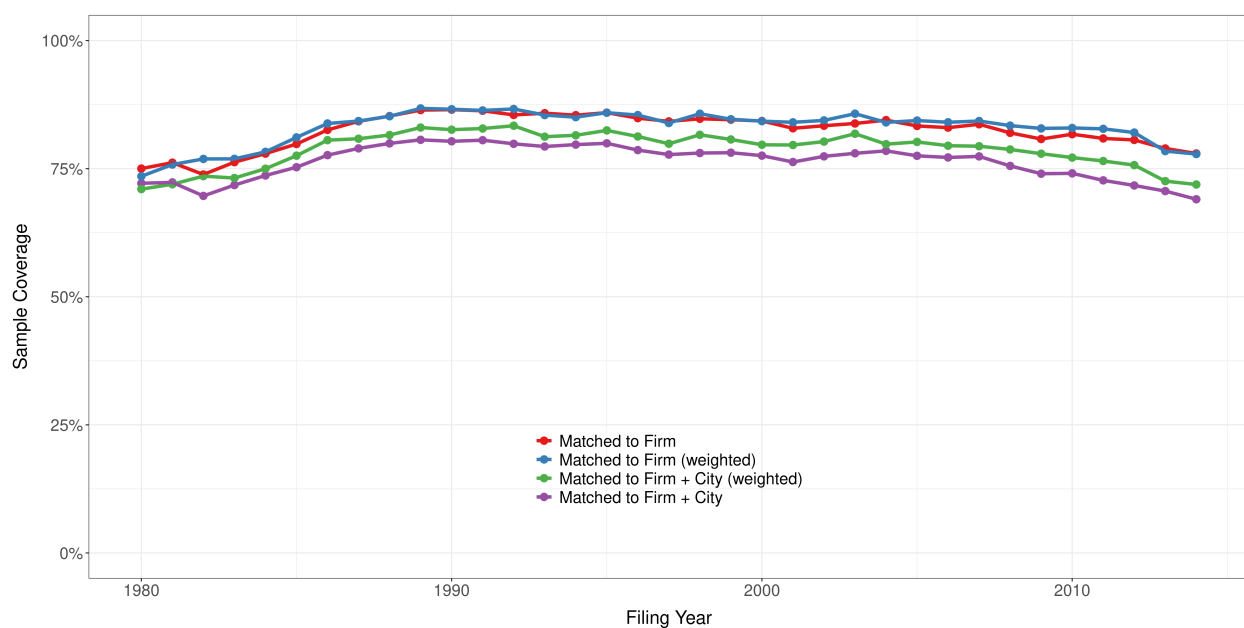
This section of the appendix provides details on the sample coverage of our dataset.

To determine the sample coverage, we first need to calculate the relevant total number of granted triadic patents. We focus on patents that are present in both PATSTAT and PatentsView. There are some differences in what these two datasets contain. Notably, PATSTAT includes design patents only after 2001. Since we cannot use PATSTAT to determine the members of the extended patent family for these early design patents, they are not considered in the relevant total number of patents we try to match.

The most relevant variables for our analysis are the Orbis firm identifier and the inventor location (at the city level) from PatentsView. We focus on inventor location rather than assignee location to capture where innovation takes place physically. Both the firm identifier and the inventor location can be missing.

One patent often lists multiple inventors and sometimes also multiple assignees. When we compute sample coverage at the patent level we flag a patent as covered if the patent is matched to at least one assignee and one inventor location. Based on this methodology we find a coverage of around 83% (or 84% when weighting by forward citations). The coverage is slightly lower with 79% when we look at patents that are granted in the US and filed but not necessarily granted at EPO and JPO. In figure B.1 we plot the sample coverage for granted triadic patents by year. It remains relatively stable between 75% and 85% with the lowest coverage at the beginning and the end of the sample.

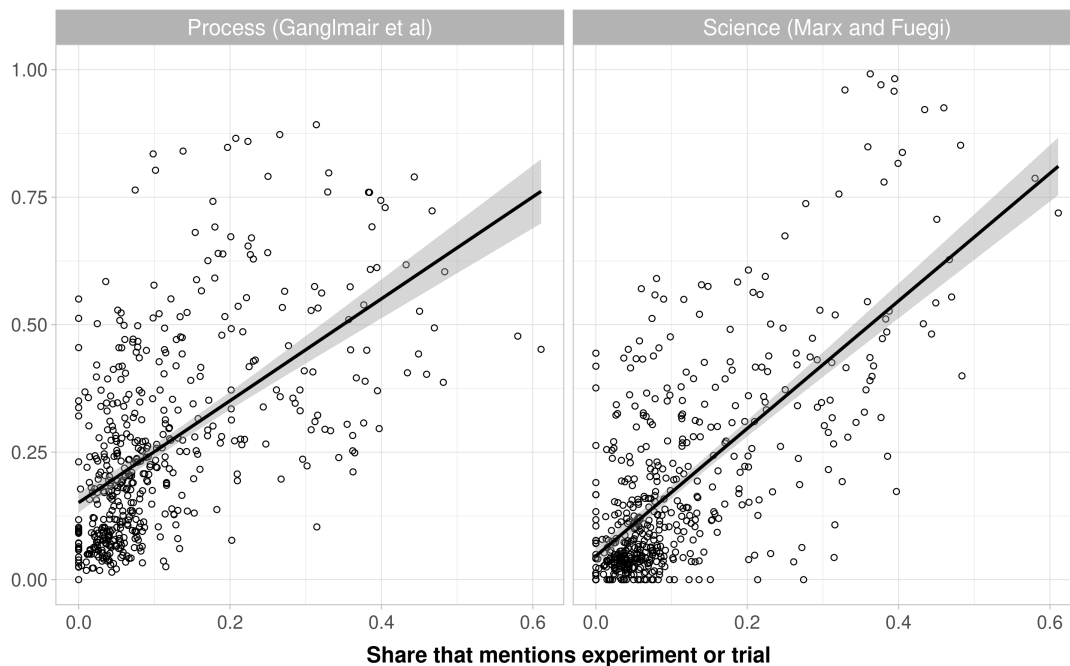
Figure B.1: Sample Coverage



Notes: This figure shows the yearly share of granted triadic patents that our sample covers.

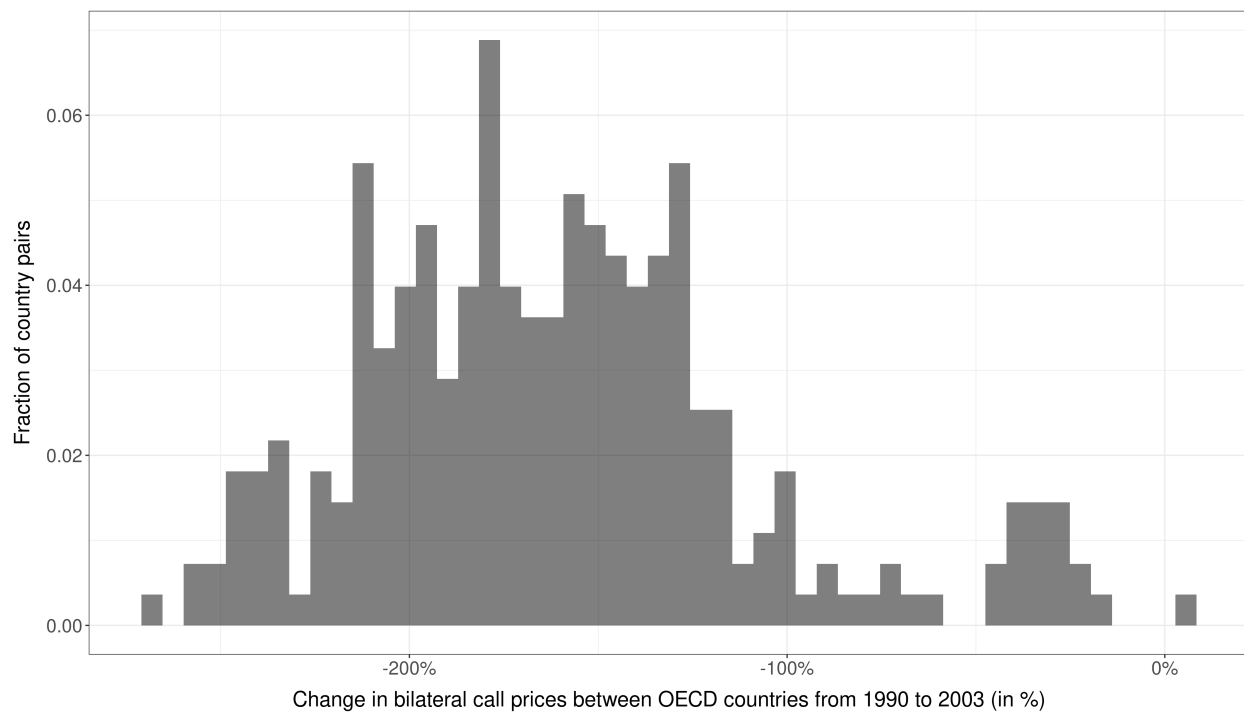
C Additional Figures

Figure C.1: Experimental Technology Classes vs other Classifications



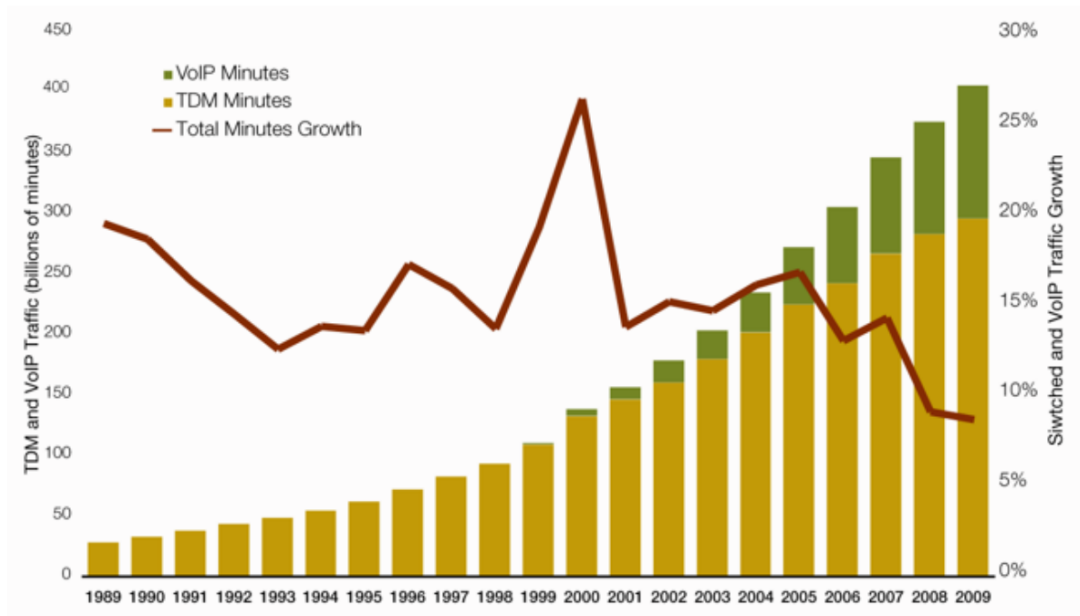
Notes: Each dot represents a technology class. The x-axis captures our measure of experimental technology class, i.e. the share mentioning experiments or trials. In panel A, the y-axis plots the share of patents containing a process claim (based on data from [Ganglmair et al. \(2022\)](#)) and in panel B the y-axis depicts the share of patents citing a scientific article (based on data from [Marx and Fuegi \(2020\)](#).)

Figure C.2: Change in International Call Prices from 1990 to 2003



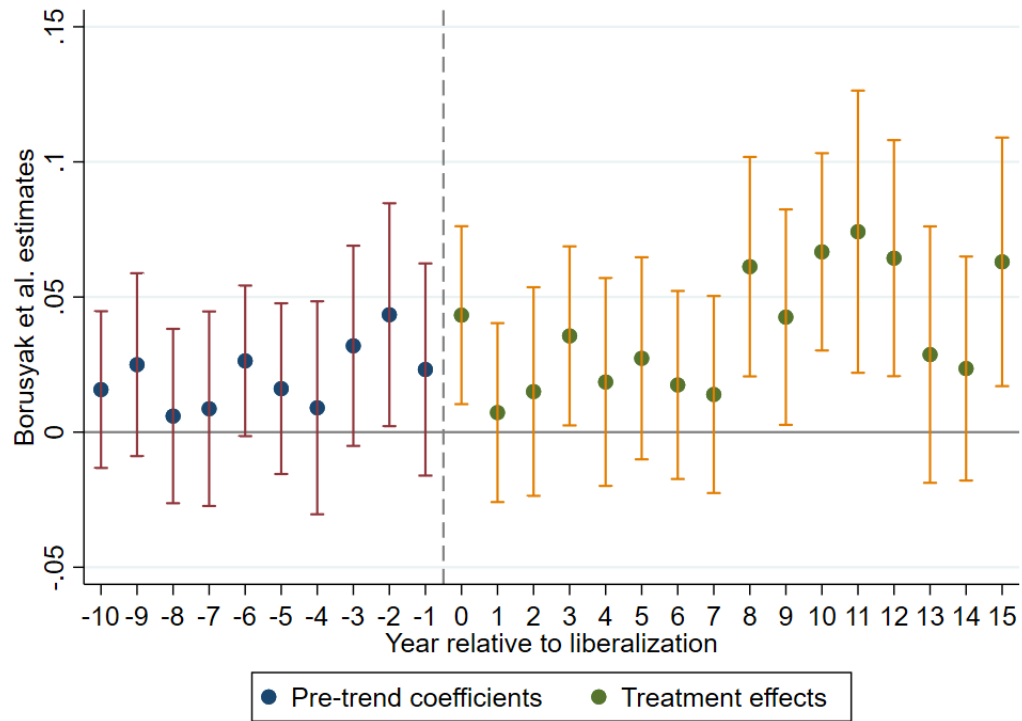
Notes: This figure plots a histogram of the change in bilateral, international call prices between OECD countries from 1990 to 2003. Source: OECD.

Figure C.3: Volume of international calls

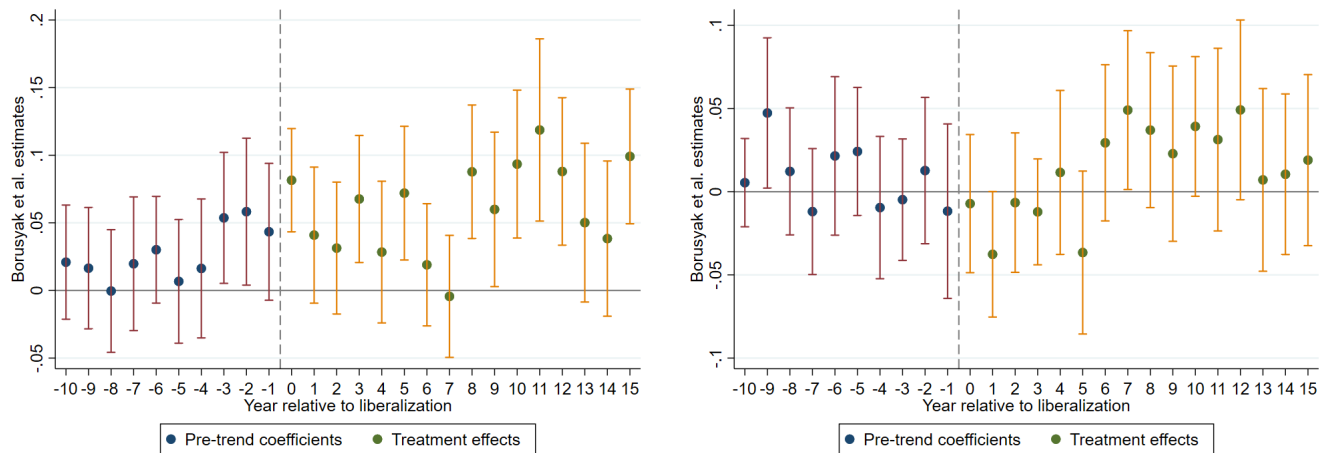


Notes: This figure is taken from a 2009 Telegeography report. The bar chart shows the total volume of international phone calls by year.

Figure C.4: Event Study of the Impact of Telecom Liberalization on Collaboration - Borusyak et al. (2021) estimates



(a) Full sample



(b) Split by technology

Notes: This figure reports the results of estimating equation (3), including unit and time fixed effects only. Standard errors are clustered at the country-pair level. 95% confidence intervals are shown.

D Additional Tables

Table D.1: Share of experiment-intensive Technologies

IPC Class	Share Experimental	Patent Count
Chemistry, Metallurgy	0.98	242455
Human Necessities	0.63	172939
Electricity	0.00	122026
Performing Operations, Trans- porting	0.34	120374
Physics	0.28	120272
Mechanical Engineering, Light- ing, Heating, Weapons, Blasting	0.12	42462
Textiles, Paper	0.76	13287
Fixed Constructions	0.00	6159

Notes: This table shows the share of experimental (4-digit) technology classes by the more aggregate 1-digit IPC classes. See section 2 for the definition of experimental technology classes.

Table D.2: Classification of Top-15 Technologies

Technology Code	Technology	Share Mentioning Experiment/Trial	Men- tioning Experi- mental	Classified as Experi- mental	Patent Count
C07D	heterocyclic compounds	0.48		Yes	28121
C07C	acyclic or carbocyclic compounds	0.47		Yes	14001
A61P	therapeutic activity of chemical compounds or medicinal preparations	0.43		Yes	37235
C12N	micro-organisms or enzymes; compositions thereof; propagating, preserving, or maintaining micro-organisms; mutation or genetic engineering; culture media	0.39		Yes	18183
C08G	macromolecular compounds obtained otherwise than by reactions only involving carbon-to-carbon unsaturated bonds	0.37		Yes	11627
A61K	preparations for medical, dental, or toilet purposes	0.36		Yes	49856
C08L	compositions of macromolecular compounds	0.36		Yes	16546
C07K	peptides	0.36		Yes	15852
G01N	investigating or analysing materials by determining their chemical or physical properties	0.22		Yes	21043
A61B	diagnosis; surgery; identification	0.11		No	15806
A61F	filters implantable into blood vessels; prostheses; devices providing patency to, or preventing collapsing of, tubular structures of the body, e.g. stents; orthopaedic, nursing or contraceptive devices; fomentation; treatment or protection of eyes or ears; bandages, dressings or absorbent pads; first-aid kits	0.09		No	10962
H04L	transmission of digital information, e.g. telegraphic communication	0.06		No	17932
G06F	electric digital data processing	0.05		No	17506
H01L	semiconductor devices; electric solid state devices not otherwise provided for	0.05		No	13193

Notes: This table shows our classification of experimental technology classes for the 15 most frequent. See section 2 for the definition of experimental technology classes.

Table D.3: Liberalization and Call Prices

Dependent Variables: Model:	log(Average Call Price) (1)	log(Minimum Call Price) (2)
Liberalization	-0.3090*** (0.0375)	-0.4097*** (0.0487)
<i>Fixed Effects</i>		
Country-Pair	✓	✓
Year	✓	✓
Observations	955	955
R ²	0.93	0.93

Notes: The sample contains OECD country pairs for the years 1990, 1998 and 2003. The dependent variable is either the average or minimum call price for a given country pair (they vary depending on direction). Liberalization equals 1 if source and affiliate countries have liberalized their markets for telecommunication, 0 otherwise. Standard errors are clustered at the country pair level. ***, **, * denote statistical significance at the 1%, 5% and 10% levels, respectively.

Table D.4: Collaboration and Business Hour Overlap - Cross Section

	Share Collaboration			
	(1)	(2)	(3)	(4)
Overlap	0.0646*** (0.0019)	0.0593*** (0.0020)	0.0557*** (0.0023)	0.0584*** (0.0021)
× Experimental		0.0111*** (0.0028)		0.0117*** (0.0032)
× Share Experimental			0.0446*** (0.0098)	
× Cites Science				-0.0042 (0.0034)
× Process				0.0053* (0.0029)
Observations	316,877	316,877	316,877	316,877
R ²	0.47	0.47	0.47	0.47
Dependent variable mean	0.36	0.36	0.36	0.36
<i>Fixed Effects</i>				
GUO	✓	✓	✓	✓
Host Country-Technology	✓	✓	✓	✓

Notes: This table reports the results of estimating equation 1. Standard errors are clustered at the location pair-technology level. ***, **, * denote statistical significance at the 1%, 5% and 10% levels, respectively.

Table D.5: Year of Liberalization of International Calls

Year of Liberalization	Country
1984	United States
1986	United Kingdom
1987	Japan
1990	New Zealand
1991	Australia
1992	Canada, Sweden
1993	Finland
1996	Denmark, Korea, Mexico
1997	Netherlands
1998	Austria, Belgium, France, Germany, Ireland Italy, Luxembourg, Norway, Spain, Switzerland
2000	Czech Republic, Portugal
2001	Greece
2002	Hungary
2006	Turkey

Notes: This table shows the year of liberalization of the telecommunication sector, as reported in [Boylaud and Nicoletti \(2000\)](#).

Table D.6: Liberalization - 1980s Establishments

	Share Collaboration					
	Full Sample (1)	Experimental (2)	Non-experimental (3)	Full Sample (4)	Experimental (5)	Non-experimental (6)
Liberalization	0.0112 (0.0167)	0.0166 (0.0191)	0.0046 (0.0220)			
× Overlap	0.0245*** (0.0069)	0.0316*** (0.0092)	0.0118** (0.0056)			
× 0-2 hours				0.0261 (0.0158)	0.0367** (0.0168)	0.0094 (0.0218)
× 2-4 hours				0.0417 (0.0340)	0.0359 (0.0468)	0.0562** (0.0221)
× 4-6 hours				0.0312 (0.0199)	0.0243 (0.0218)	0.0455* (0.0232)
× 6-8 hours				0.0623*** (0.0156)	0.0888*** (0.0187)	0.0180 (0.0190)
Observations	316,967	170,235	146,732	316,967	170,235	146,732
R ²	0.74	0.69	0.80	0.74	0.69	0.80
Dependent variable mean	0.19	0.20	0.16	0.19	0.20	0.16
<i>Fixed Effects</i>						
Establishment Pair-Technology	✓	✓	✓	✓	✓	✓
Year-Host Country	✓	✓	✓	✓	✓	✓
Year-Technology	✓	✓	✓	✓	✓	✓

Notes: This table reports the results of estimating equation 2. The sample contains all patents filed by inventors located in a foreign affiliate that already existed in the 1980s. The dependent variable is the share of these patents that is produced in collaboration with a HQ-based inventor. Liberalization equals 1 if source and affiliate countries have liberalized their markets for telecommunication, 0 otherwise. Overlap captures the log-transformed number of overlapping business hours between affiliate and HQ. Standard errors are clustered at the country pair level. ***, **, * denote statistical significance at the 1%, 5% and 10% levels, respectively.

Table D.7: Liberalization - Source Country-Time Fixed Effect

	Share Collaboration					
	Full Sample (1)	Experimental (2)	Non-experimental (3)	Full Sample (4)	Experimental (5)	Non-experimental (6)
Liberalization	-0.0072 (0.0072)	-0.0081 (0.0081)	-0.0049 (0.0121)			
× Overlap	0.0176*** (0.0055)	0.0263*** (0.0071)	0.0004 (0.0057)			
× 0-2 hours				-0.0015 (0.0064)	0.0013 (0.0070)	-0.0064 (0.0113)
× 2-4 hours				0.0261 (0.0308)	0.0356 (0.0406)	0.0135 (0.0167)
× 4-6 hours				0.0217 (0.0180)	0.0294 (0.0211)	0.0083 (0.0198)
× 6-8 hours				0.0380*** (0.0097)	0.0560*** (0.0125)	0.0007 (0.0147)
Observations	575,782	293,242	282,540	575,782	293,242	282,540
R ²	0.84	0.81	0.87	0.84	0.81	0.87
Dependent variable mean	0.27	0.28	0.26	0.27	0.28	0.26
<i>Fixed Effects</i>						
Establishment Pair-Technology	✓	✓	✓	✓	✓	✓
Year-Source Country	✓	✓	✓	✓	✓	✓
Year-Technology	✓	✓	✓	✓	✓	✓

Notes: This table reports the results of estimating equation 2. The sample contains all patents filed by inventors located in a foreign affiliate. The dependent variable is the share of these patents that is produced in collaboration with a HQ-based inventor. Liberalization equals 1 if source and affiliate countries have liberalized their markets for telecommunication, 0 otherwise. Overlap captures the log-transformed number of overlapping business hours between affiliate and HQ. Standard errors are clustered at the country pair level. ***, **, * denote statistical significance at the 1%, 5% and 10% levels, respectively.

Table D.8: Liberalization - Triple Interactions

	Share Collaboration		
	(1)	(2)	(3)
Liberalization	0.0099 (0.0175)		
× Experimental	0.0083 (0.0142)	0.0078 (0.0156)	0.0410 (0.1787)
× Overlap	0.0103* (0.0058)		
× Experimental × Overlap	0.0167** (0.0072)	0.0233*** (0.0070)	0.0213* (0.0111)
× Experimental × log(distance)			-0.0020 (0.0109)
Observations	575,782	575,782	575,782
R ²	0.84	0.86	0.86
Dependent variable mean	0.27	0.27	0.27
<i>Fixed Effects</i>			
Establishment Pair-Technology	✓	✓	✓
Year-Host Country	✓		
Year-Technology	✓	✓	✓
Year-Location Pair		✓	✓

Notes: This table reports the results of estimating equation 2. The sample contains all patents filed by inventors located in a foreign affiliate. The dependent variable is the share of these patents that is produced in collaboration with a HQ-based inventor. Liberalization equals 1 if source and affiliate countries have liberalized their markets for telecommunication, 0 otherwise. Overlap captures the log-transformed number of overlapping business hours between affiliate and HQ. Standard errors are clustered at the country pair level. ***, **, * denote statistical significance at the 1%, 5% and 10% levels, respectively.

Table D.9: Liberalization and Distance

	Share Collaboration		
	(1)	(2)	(3)
Liberalization	0.0154 (0.0143)	0.2017** (0.0921)	-0.0072 (0.1353)
× Overlap	0.0208*** (0.0059)		0.0242** (0.0116)
× log(distance)[East-West]		-0.0108** (0.0049)	0.0032 (0.0074)
× log(distance)[North-South]		-0.0002 (0.0092)	-0.0021 (0.0086)
Observations	575,782	575,782	575,782
R ²	0.84	0.84	0.84
Dependent variable mean	0.27	0.27	0.27
<i>Fixed Effects</i>			
Establishment Pair-Technology	✓	✓	✓
Year-Host Country	✓	✓	✓
Year-Technology	✓	✓	✓

Notes: This table reports the results of estimating equation 2. The sample contains all patents filed by inventors located in a foreign affiliate. The dependent variable is the share of these patents that is produced in collaboration with a HQ-based inventor. Liberalization equals 1 if source and affiliate countries have liberalized their markets for telecommunication, 0 otherwise. Overlap captures the log-transformed number of overlapping business hours between affiliate and HQ. The East-West distance fixes the latitude of the affiliate to that of the HQ. The North-South distance fixes the longitude of the affiliate to that of the HQ. Standard errors are clustered at the country pair level. ***, **, * denote statistical significance at the 1%, 5% and 10% levels, respectively.

Table D.10: Liberalization and Patent Characteristics - Extensive Margin*Panel A: Extensive Margin*

	# Collaboration > 0 (1)	# Citing Science > 0 (2)	# Breakthroughs > 0 (3)
Liberalization	0.0102 (0.0172)	0.0026 (0.0103)	-0.0103 (0.0126)
× Overlap	0.0308*** (0.0068)	0.0117*** (0.0039)	0.0241*** (0.0040)
Observations	575,782	575,782	575,782
R ²	0.80	0.77	0.79
Dep. variable mean	0.28	0.66	0.30

Panel B: Inverse Hyperbolic Sine

	IHS(Collaboration) (4)	IHS(Citing Science) (5)	IHS(Breakthroughs) (6)
Liberalization	0.0061 (0.0194)	0.0334* (0.0174)	0.0044 (0.0168)
× Overlap	0.0456*** (0.0085)	0.0076 (0.0077)	0.0192*** (0.0061)
Observations	575,782	575,782	575,782
R ²	0.76	0.71	0.76
Dep. variable mean	0.26	0.66	0.28
<i>Fixed Effects</i>			
Establishment	✓	✓	✓
Pair-Technology			
Year-Host Country	✓	✓	✓
Year-Technology	✓	✓	✓

Notes: This table reports the results of estimating equation 2. The sample contains all patents filed by inventors located in a foreign affiliate. The dependent variable captures patents in collaboration with HQ inventors (column 1), patents citing science (column 2), and breakthrough patents (column 3), respectively. Refer to section 2 for a description of these variables. Panel A estimates the extensive margin and panel B uses the inverse hyperbolic sine transformation. Liberalization equals 1 if source and affiliate countries have liberalized their markets for telecommunication, 0 otherwise. Overlap captures the log-transformed number of overlapping business hours between affiliate and HQ. Standard errors are clustered at the country-pair level. ***, **, * denote statistical significance at the 1%, 5% and 10% levels, respectively.