Time after Time: Communication Costs and Inventor Collaboration in the Multinational Firm[*]

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Abstract

We show that knowledge creation, as measured by patents, is increasingly conducted in cross-border collaborative teams of inventors. We document 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. 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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[*] The opinions expressed in this paper are those of the authors only and do not represent the views of EBRD.

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1 Introduction

Knowledge creation and diffusion are the pillars of modern growth theory. Multinational enterprises (MNEs) play a central role in both the creation and diffusion of knowledge across international borders. According to conservative estimates of UNCTAD (2005), MNEs account for close to half of all global R&D expenditures and at least two-thirds of business R&D expenditures.[1]

Despite the importance of R&D efforts undertaken by MNEs, there is little micro evidence on this subject. Where do MNEs create knowledge? Is knowledge creation within a multinational firm becoming more concentrated in a few geographic locations, or is there more collaboration taking place across borders? What are the impediments to knowledge creation inside the boundaries of the firm?

Due to its very nature, knowledge creation is difficult to measure. We use data on patents and cross-border collaboration in inventor teams to capture the incidence of knowledge creation. We follow Kerr and Kerr (2018) in defining "global collaborative patents". These are innovations that involve at least one inventor located in the MNE home country and at least one inventor located in another country. Our data cover the 1980-2014 period and include geographic location of individual inventors within a team that obtained a patent. Matching patent data with the Orbis database, we are able to observe links between various establishments within a multinational firm.

In our analysis, we focus on three drivers of knowledge creation within an MNE: (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.[2] In economics, Chauvin et al. (2020) show that temporal distance stemming from time zone differences reduce synchronous and

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[1] The 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).

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

impromptu communication from first-best levels within a multinational organisation, presenting costly frictions especially for the multinational's knowledge-intensive work. Time zones differences have been shown to be a barrier to women sharing in the benefits of activities by firms engaged in international trade (Bøler et al., 2018).

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 in turn facilitated cross-border cooperation, including cooperation in R&D.

In this study, 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 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 variables of interest include bilateral telecom liberalization between the MNE home and 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, or explicitly focus on the cost of international calls between the two countries. 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 hetorogeneity, 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 a 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 a vis HQ; (ii) an examination of whether the size of inventor teams was affected by telecom liberalization and time zone differential; 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 39% 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 33% 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 8% 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. Let's stick with our example of a German MNE with a Polish and a Japanese subsidiary to illustrate the magnitudes. 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 6.4pp (22%). In contrast, collaborative patents in the Japanese subsidiary will go up by only 2.6pp (10%).

Third, one may expect to observe an increase in the inventor team size as the communication frictions decline. This is indeed what we find. We show that the number of inventors listed on a patent increases after telecom liberalization, particularly in affiliates having a larger business hours overlap with HQ. The effect is 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 a vis HQ is larger for inventors with lesser track records than for their 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 studies differ on how R&D and knowledge production are incorporated into models of FDI. 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.[3]

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[3] One proposed reason for the negative relationship between distance (both physical and cultural) and

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 (US), 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.[4] Catalini et al. (2020) show that travel costs constitute an important friction to collaboration between inventors, especially for high-quality scientists. Similarly, using the introduction of the jet engine to civil aviation in the 1950s as an exogenous reduction in travel time, Pauly and Stipanicic (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).[5] 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 determinants of cross-border collaboration.

Fourth, our paper adds to the literature on FDI and the geographic diffusion of knowledge and technology (Keller, 2004). Keller (2002) finds that productivity effects of R&D are declining in distance, while Bilir and Morales (2020) show that parent and affiliate R&D activities are complementary. We contribute to this literature by documenting that a decline in communication frictions lead to more R&D collaboration between HQ and MNE affiliates, thus increasing their complementarity.

The remainder of this paper is structured as follows. We describe our data in Section

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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.

[4] Related, 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.

[5] 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. The subsequent section presents stylised facts. 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.

2 Data

2.1 Patents

The main patent dataset underlying our analysis comes from USPTO's (United States Patent and Trademark Office) PatentsView project. PatensView 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 potentially 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 earliers (USPTO, EPO, JPO).[6] These patent families capture the most important inventions relevant at a global level.[7]

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

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

[7] Note that 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.

of a patent in a subsidiary that is located in a country different to the firm's HQ, different to the location where the underlying technology was created (i.e. where inventors reside), and different to 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 (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 that at the time of the patent filing were not part of it, but that 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.[8]

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

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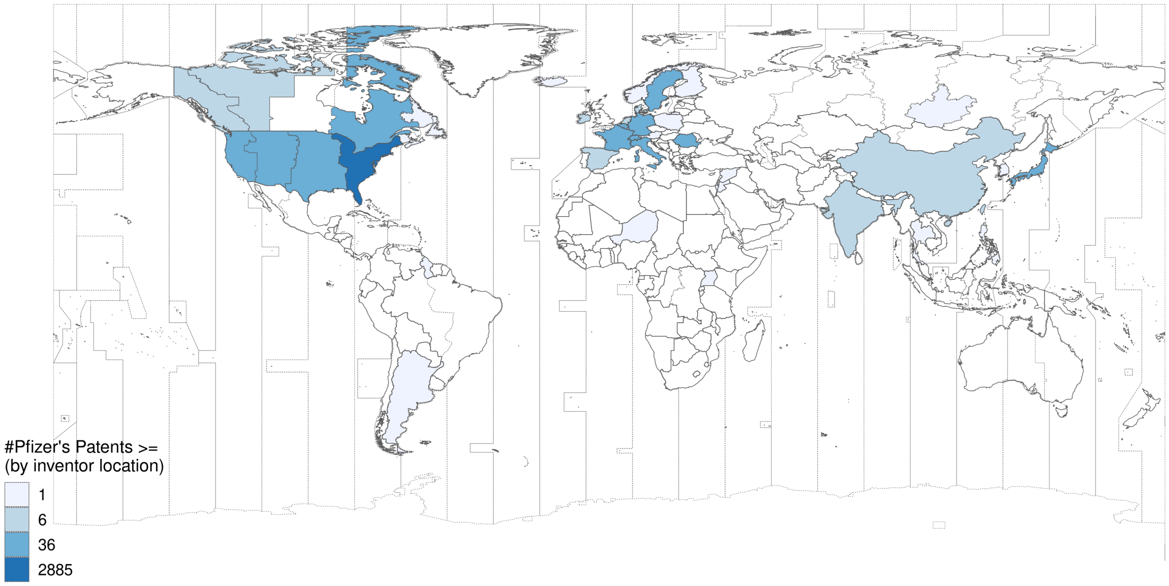
[8] In our estimation sample of patents with at least one inventor based at a foreign affiliate, around 7.7% of patents are affiliate-affiliate collaborations without HQ-involvement. 29.8% of patents are in collaboration with HQ inventors (40.9% weighted by citations). Thus, collaboration indeed seems 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.

on the inventors' location of residence to identify the country and time zone where they are located.[9] 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, 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.

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[9] We use the R package lutz to infer the time zone from inventor locations.

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.

- 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 Boylaud 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.

- 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.[10] 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%.

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[10] We capture any patent that appears in the USPTO's PatentsView data. This dataset contains patents granted from 1976 onwards.

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.

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.

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	34077	58.63	12.92	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[11]. Figure C.3 shows the sharply increasing call volumes during the liberalization period[12].

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 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.

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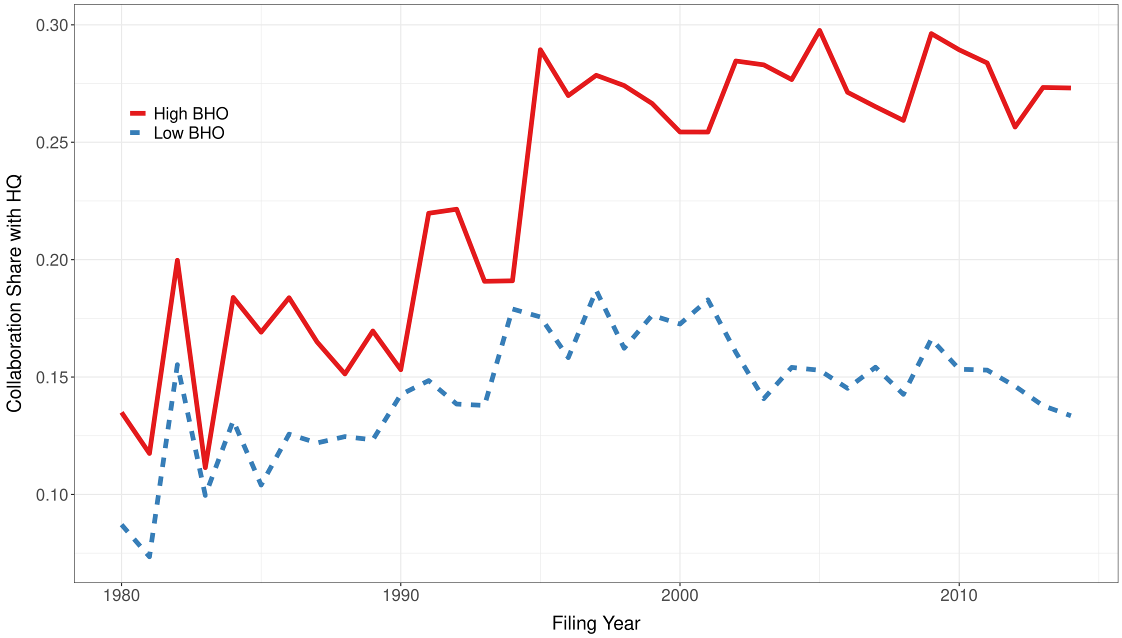
[11] In figure **??** we plot a histogram of bilateral price changes between 1990 to 2003.

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

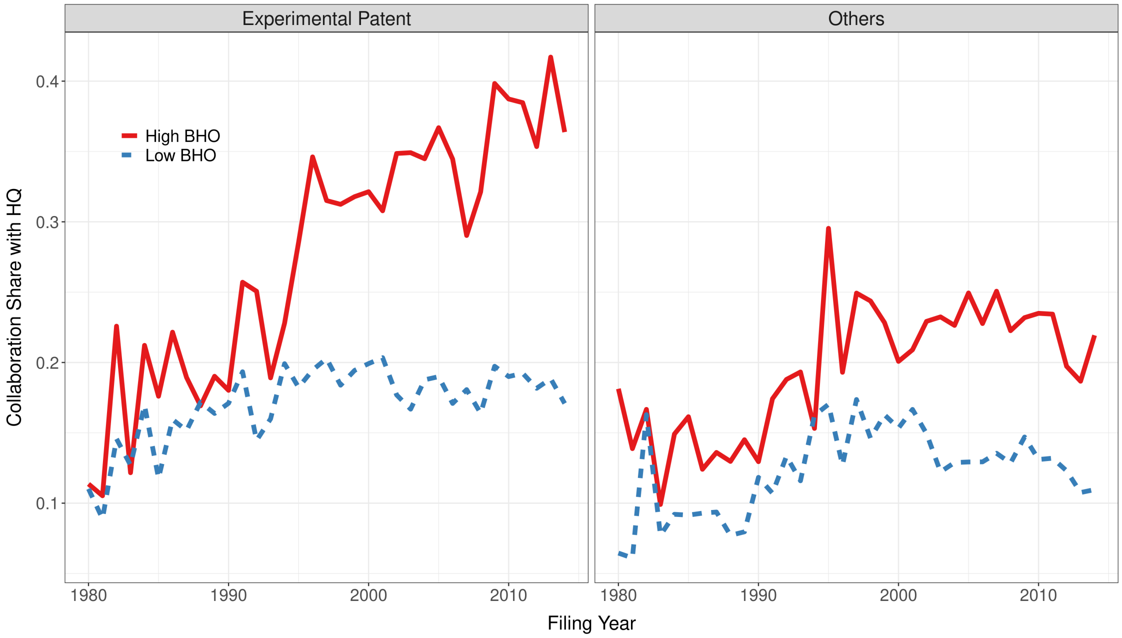
Figure 2: Cross-border Collaboration over Time



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.

The rise in cross-border collaboration has been stronger in experimental technology classes. 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 pronounced rise has been registered in non-experimental technology classes or in affiliates with with a greater temporal distance to HQ (see figure 3).

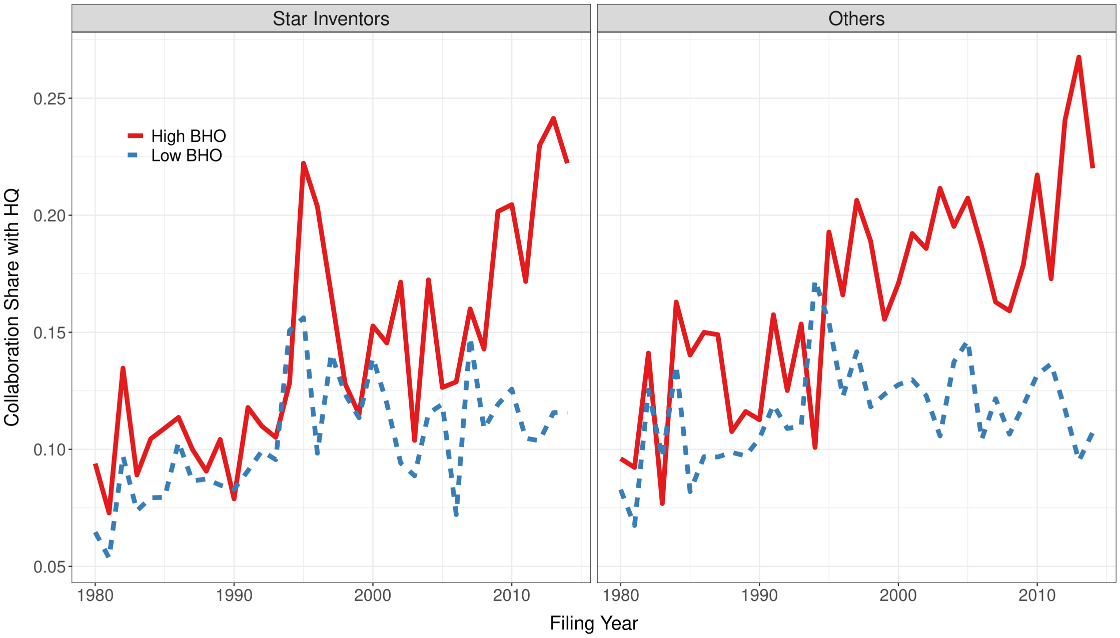
Figure 3: Cross-border Collaboration over Time by Technology



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. 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:

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

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.[13] 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 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 (Overlap_{ah}) and its interaction with an indicator for experimental technology classes. The

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

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 MNE fixed effect 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.[14]

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. We thus interact our main independent variable with an indicator variable that captures whether t is an experimental technology class (Experimental_t) and expect $\alpha_2 > 0$.

The 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 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 39% 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, e.g. because of increased travel time. In columns 3 and 4, we show that controlling for geographical distance barely changes our estimated coefficients. As previous studies we find a negative effect of geographical distance on collaboration. While an important determinant of collaboration, we find that physical distance matters less than temporal distance. Inventors based in Tokyo collaborate 8% less with their Berlin HQ than their colleagues in Warsaw. Finally, we find no evidence that the effect of physical distance matters more for experimental technologies, suggesting that 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

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[14] The results are robust to clustering at the firm level.

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 yields a highly significant effect.

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.

Table 2: Collaboration, Business Hour Overlap and Distance

	Share Collaboration			
	(1)	(2)	(3)	(4)
Overlap	0.0646***	0.0593***	0.0582***	0.0526***
	(0.0019)	(0.0020)	(0.0033)	(0.0034)
× Experimental		0.0111***		0.0120**
		(0.0028)		(0.0059)
log(distance)			-0.0100***	-0.0103***
			(0.0034)	(0.0035)
× Experimental				0.0014
				(0.0050)
Observations	316,875	316,875	316,875	316,875
R^2	0.47	0.47	0.47	0.47
Dependent variable mean	0.36	0.36	0.36	0.36
Fixed Effects				
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.

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 shows 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:

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

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 alternatively for affiliate-country-time ($c(a)y$) or 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 are supportive of 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. In most 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 telecom liberalization has its biggest impact when temporal distance is lowest, i.e. a business hour overlap of at least 6 hours.

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.

Table 3: Telecom Liberalization and Collaboration

	Share Collaboration					
	Full Sample (1)	Experimental (2)	Non-experim. (3)	Full Sample (4)	Experimental (5)	Non-experim. (6)
Liberalization	0.0154	0.0234	0.0050			
	(0.0143)	(0.0167)	(0.0209)			
× Overlap	0.0208***	0.0258***	0.0124**			
	(0.0059)	(0.0081)	(0.0052)			
× 0-2 hours				0.0260*	0.0384**	0.0081
				(0.0141)	(0.0149)	(0.0212)
× 2-4 hours				0.0422	0.0372	0.0548**
				(0.0345)	(0.0474)	(0.0213)
× 4-6 hours				0.0446**	0.0452*	0.0561**
				(0.0201)	(0.0251)	(0.0236)
× 6-8 hours				0.0639***	0.0858***	0.0306*
				(0.0140)	(0.0176)	(0.0182)
Observations	575,780	293,241	282,539	575,780	293,241	282,539
R^2	0.84	0.81	0.87	0.84	0.81	0.87
Dependent var. mean	0.27	0.28	0.26	0.27	0.28	0.26
Fixed Effects						
Est. Pair-Technology	✓	✓	✓	✓	✓	✓
Year-Host Country	✓	✓	✓	✓	✓	✓
Year-Technology	✓	✓	✓	✓	✓	✓

Notes: This table reports the results of estimating equation 2. Standard errors are clustered at the country-pair level. ***, **, * denote statistical significance at the 1%, 5% and 10% levels, respectively.

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 6.4pp (22%). In contract, collaborative patents in the Japanese subsidiary will increase by 2.6pp (10%).[15] Thus, the effect of telecom liberalization on collaboration is more than twice as large for the Polish affiliate, both in absolute and relative terms.

Table D.6 shows that the result is robust to focusing on affiliates that already existed in the 1980s. This further alleviatates concerncs 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. Finally, instead of splitting the sample, we interact our liberalization and overlap variables with the indicator capturing experimental technologies. Table D.8 shows that this triple interaction term yields a statistically significant coefficient, again supporting our conjecture that experimental technologies are affected more.

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

5.2 Event Study

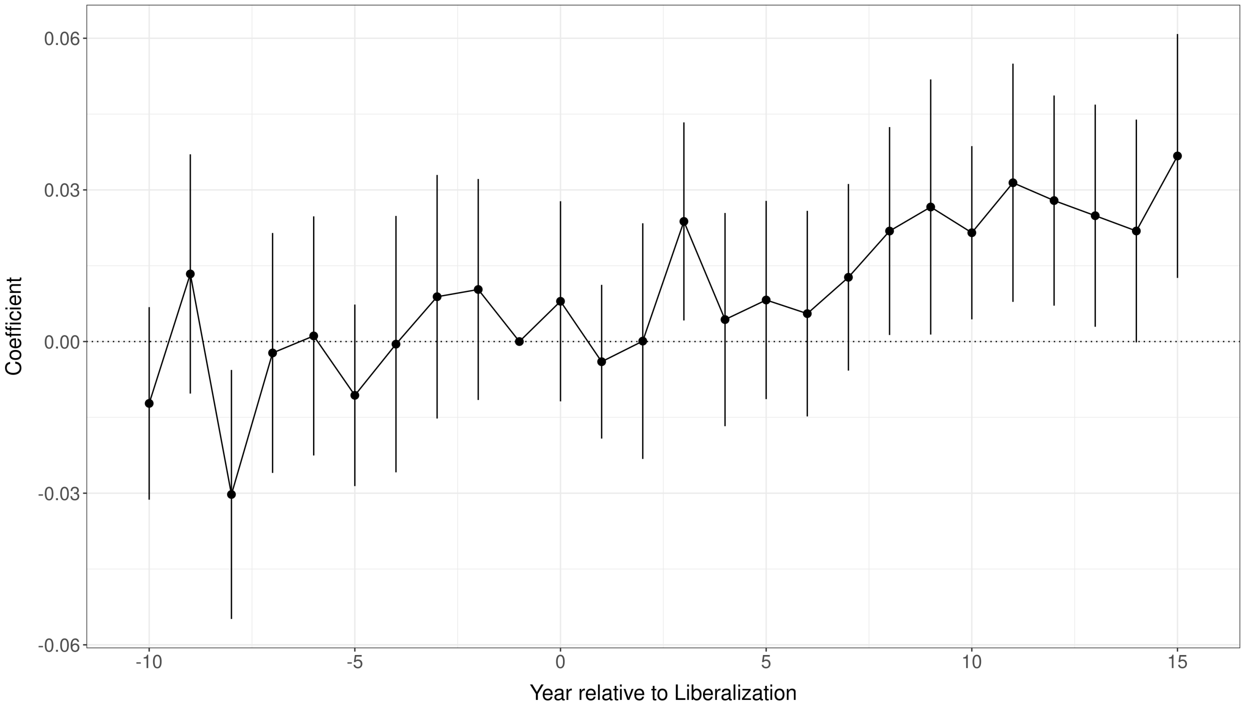
The panel nature of our data allow us to conduct event studies. Specifically, we test whether collaboration patterns were already on the rise prior to telecom liberalization in country pairs with high business hour overlap relative to those with low business hour overlap. This test also allows us to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

$$\begin{aligned}\text{Collaboration}_{ahty} &= \sum_{\substack{d=-10\\ d\neq -1}}^{d=15} \beta_{1,d}\mathbb{1}\{y = d + y_{0c(a)c(h)}\} + \\ &+ \sum_{\substack{d=-10\\ d\neq -1}}^{d=15} \beta_{2,d}\mathbb{1}\{y = d + y_{0c(a)c(h)}\} \times \text{Overlap}_{ah} + \text{FE}_{aht} + \text{FE}_{c(a)y} + \text{FE}_{ty} + \epsilon_{ahty} \qquad (3)\end{aligned}$$

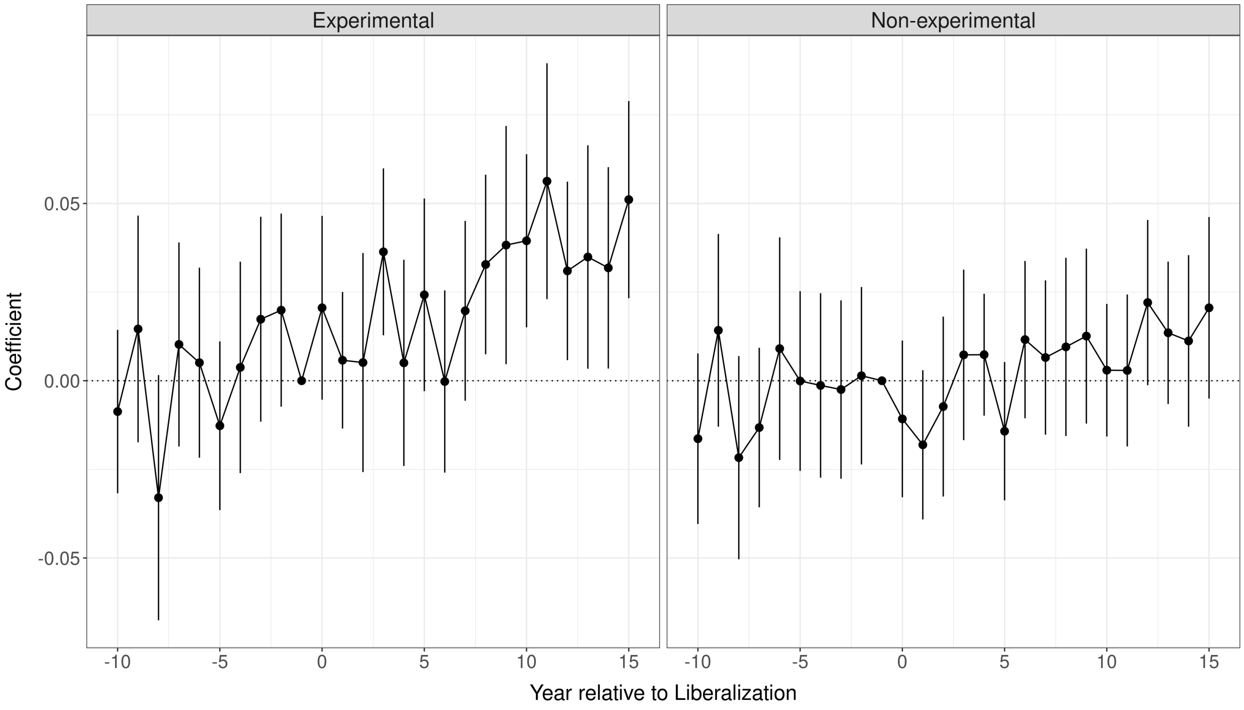
This specification resembles equation 2, but we allow for a time-varying impact of liberalization rather than relying on a simple pre- versus post-liberalization comparison. $y_{0c(a)c(h)}$ denotes the first year where both the affiliate country and HQ country have liberalized their telecom markets. Again, we estimate this model on the full sample and the two subsamples of technology types separately.

Figure 5 shows our estimates for β_2. We do not detect any changing collaboration patterns by business hour overlap 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. Panel b shows that the effect is more pronounced for experimental technologies. It takes around five years for the effect to kick in. This is to be expected as it takes time to start new collaborations and develop new patentable ideas.

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). Standard errors are clustered at the country-pair level. 90% confidence intervals are shown.

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.[16] 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 of 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.[17] 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). 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).

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:

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

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

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[16] See Roth et al. (2022) for an overview of this literature.

[17] To achieve the imputation estimates, we can only include unit (affilitate and HQ country pair) and time (filing year) fixed effects in this revised specification.

with 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.[18] 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 would translate to 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.

Table 4: International Call Prices and Collaboration

	Share Collaboration					
	Full Sample (1)	Experimental (2)	Non-experim. (3)	Full Sample (4)	Experimental (5)	Non-experim. (6)
log(Minimum Call Price)	0.0008	-0.0055	0.0101			
	(0.0124)	(0.0149)	(0.0120)			
× Overlap	-0.0131***	-0.0136***	-0.0127***			
	(0.0027)	(0.0037)	(0.0037)			
× 0-2 hours				-0.0079	-0.0152	0.0022
				(0.0127)	(0.0149)	(0.0119)
× 2-4 hours				-0.0268*	-0.0118	-0.0549***
				(0.0154)	(0.0181)	(0.0192)
× 4-6 hours				-0.0306	-0.0448	-0.0153
				(0.0198)	(0.0436)	(0.0318)
× 6-8 hours				-0.0355***	-0.0430**	-0.0255**
				(0.0131)	(0.0167)	(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 var. mean	0.31	0.33	0.30	0.31	0.33	0.30
Fixed Effects						
Est. Pair-Technology	✓	✓	✓	✓	✓	✓
Period-Host Country	✓	✓	✓	✓	✓	✓
Period-Technology	✓	✓	✓	✓	✓	✓

Notes: This table reports the results of estimating equation 4. Standard errors are clustered at the country-pair level. ***, **, * denote statistical significance at the 1%, 5% and 10% levels, respectively.

5.4 Team Size

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

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[18] As 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.

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

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[19].

The results, presented in column 1 of table 5 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 based in a foreign affiliate (column 2) and in HQ (column 3). Greater response of HQ-based inventors seems to be driving the results.

Table 5: Liberalization and Team Size

	log(Team Size)		
Inventors Located in	HQ or Affiliate (1)	Affiliate (2)	HQ (3)
Liberalization	-0.0216	-0.0271	0.0056
	(0.0212)	(0.0229)	(0.0257)
× Overlap	0.0226**	-0.0039	0.0358***
	(0.0091)	(0.0099)	(0.0082)
Observations	575,780	575,780	575,780
R^2	0.79	0.73	0.88
Dependent variable mean	0.94	0.62	0.40
Fixed Effects			
Establishment Pair-Technology	✓	✓	✓
Year-Host Country	✓	✓	✓
Technology-Year	✓	✓	✓

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

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

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 inventor-level analyses. 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:

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

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), controlling for any time-invariant inventor characteristics.

The inventor-level analysis confirms the findings of the affiliate-level analysis. The estimates in table 6 show that liberalization matters for cross-border collaboration when the overlap in business hours is high. Importantly, the results remain similar after including inventor fixed effects. This implies that our earlier results were not driven by a change in the composition of employees at the establishment level around liberalization episodes, but rather that individual inventors start collaborating more with HQ after liberalization.

Table 6: Telecom Liberalization and Collaboration - Inventor Level

	Share Collaboration			
	(1)	(2)	(3)	(4)
Liberalization	0.0030	-0.0202		
	(0.0195)	(0.0147)		
× Overlap	0.0242***	0.0220***		
	(0.0041)	(0.0034)		
× 0-2 hours			0.0182	-0.0101
			(0.0217)	(0.0156)
× 2-4 hours			0.0340	0.0205
			(0.0298)	(0.0326)
× 4-6 hours			0.0255	0.0007
			(0.0254)	(0.0246)
× 6-8 hours			0.0514**	0.0338**
			(0.0199)	(0.0165)
Observations	526,808	526,808	526,808	526,808
R^2	0.54	0.77	0.54	0.77
Dependent var. mean	0.16	0.16	0.16	0.16
Fixed Effects				
Establishment Pair	✓	✓	✓	✓
Year-Host Country	✓	✓	✓	✓
Inventor		✓		✓

Notes: This table reports the results of estimating equation 6.2. 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 on 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 akin to the previous equation , the only difference being that we introduce an inventor-level indicator for being highly productive (Star_i) and all interaction terms that are not captured by fixed effects. Note that we estimate this specification with a reduced sample, since our definition of Star_i requires an inventor to be present in 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.

We find a negative estimate for β_4 which is significant at the 5 percent level. This is independent of the way we define star inventors and is robust to including inventor fixed effects, controlling for any time-invariant differences between inventors. This means that less experienced inventors are more sensitive to an exogenous change in communication frictions. We also find some evidence that star inventors a priori collaborate more ($\hat{\beta}_5 > 0$).

Table 7: Telecom Liberalization and Collaboration - Inventor Heteregoneity

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

Notes: This table reports the results of estimating equation 6.2. Standard errors are clustered at the country pair level. ***, **, * denote statistical significance at the 1%, 5% and 10% levels, respectively.

7 Conclusion

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 diffusion of knowledge inside the firm.

We first show that business hour overlap is crucial for collaboration between affiliate and HQ-based inventors. Inventors in technology classes involving experimentation, potentially requiring a higher frequency of communication, are most sensitive to this communication cost.

In addition to this cross-sectional observation, we study the evolution of collaboration across time. We focus on the liberalization of the telecom sector during the 1980s and 1990s. The price of international phone calls decreased drastically as a consequence, leading to an increase of cross-border communication. We find that affiliate-based inventors start collaborating with HQ alongside, especially in experimental technologies at affiliates which are temporally close to HQ. This finding shows that while cheap communication matters, it cannot overcome underlying geographic features. Recent technological advances such as video calls using Zoom and other platforms are likely subject to the same limitations.

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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Appendix

A Details on Orbis IP (matching patents to firms)

We provide details on the matching of patents to firms in this appendix section.

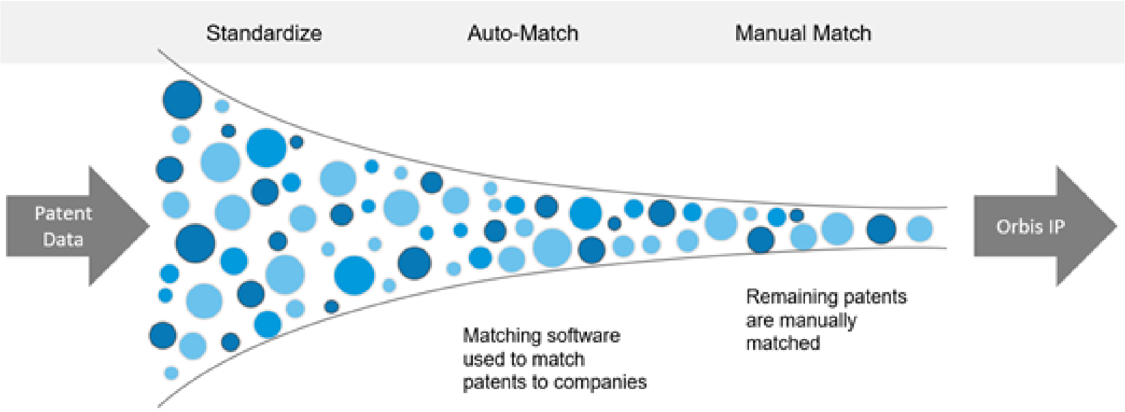
Orbis IP sources its patent information from LexisNexis. At the time of our access to Orbis IP in October-November 2020, the database had approximately 110 million patent documents, covering information from patent offices in 109 countries. Bureau van Dijk (BvD) describes their procedure of matching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

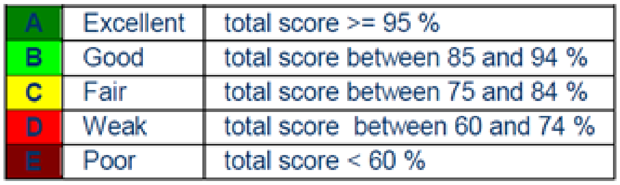
Specific normalisation rules are defined for each possible matching data field, and for each country. The normalisation rules are applied on BvD records (in the Orbis database) and patent records, hence the normalised values are taken into account for comparison/matching. For example, punctuation marks 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

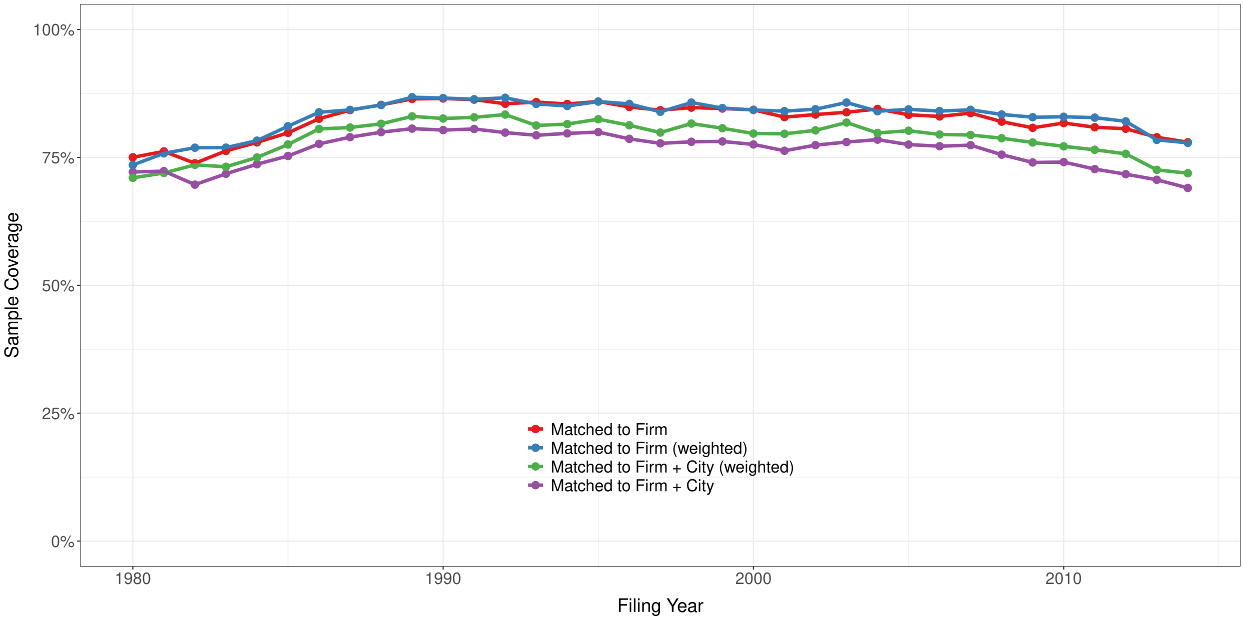
This section of the appendix provides details on the sample coverage of our dataset.

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. Noteably, 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



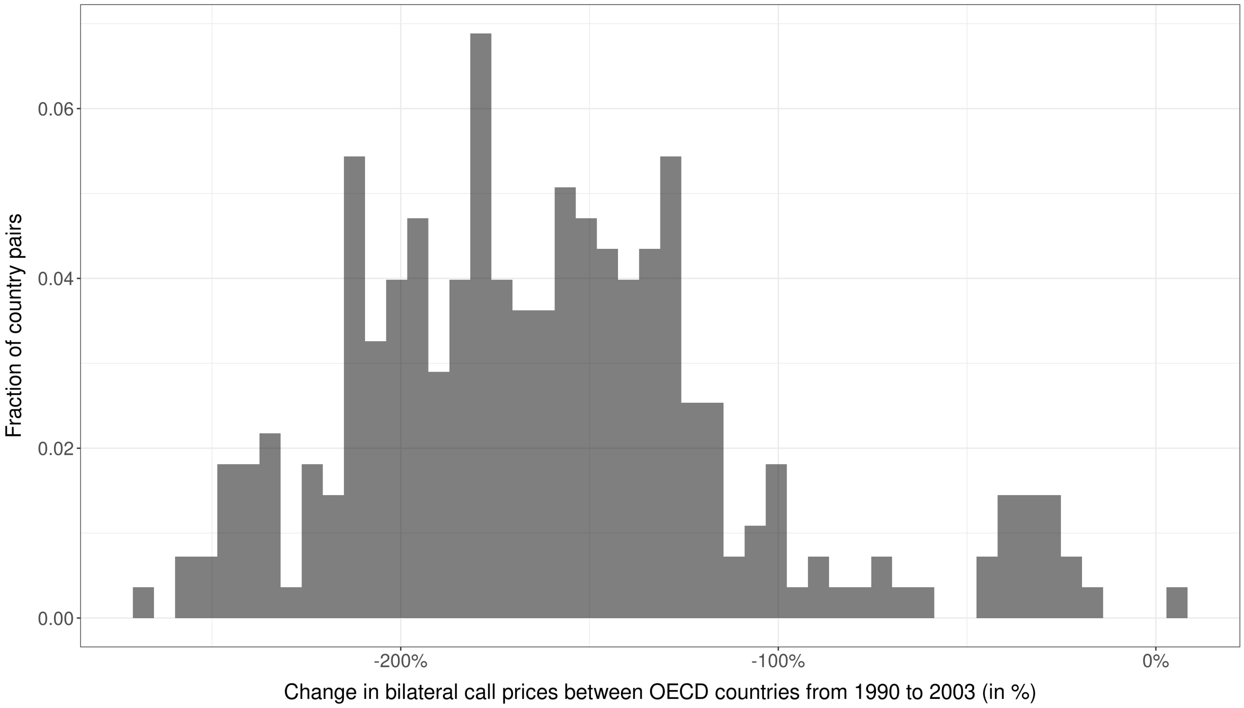
Notes: This figure shows the yearly share of granted triadic patents that our sample covers.

C Additional Figures

Figure C.1: Experimental Technology Classes vs other Classifications

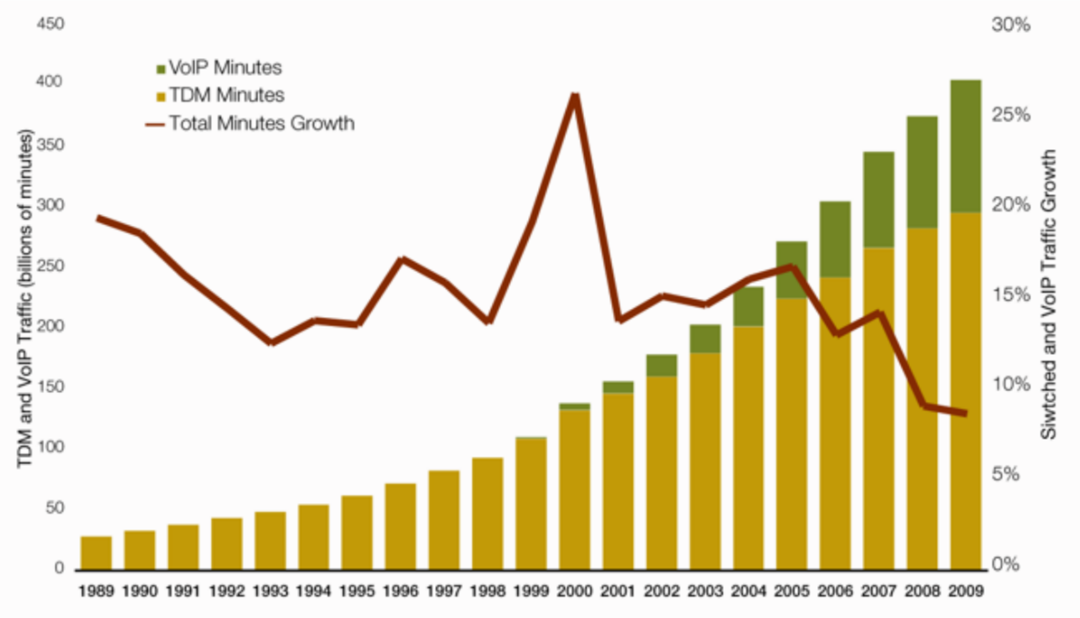
Notes: Each dot represents a technology class. The x-axis captures our measure of experimental technology class, i.e. the share mentioning experiments or trials. In panel A, the y-axis plots the share of patents containing a process claim (based on data from Ganglmair et al. (2022)) and in panel B the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

Figure C.2: Rate Change



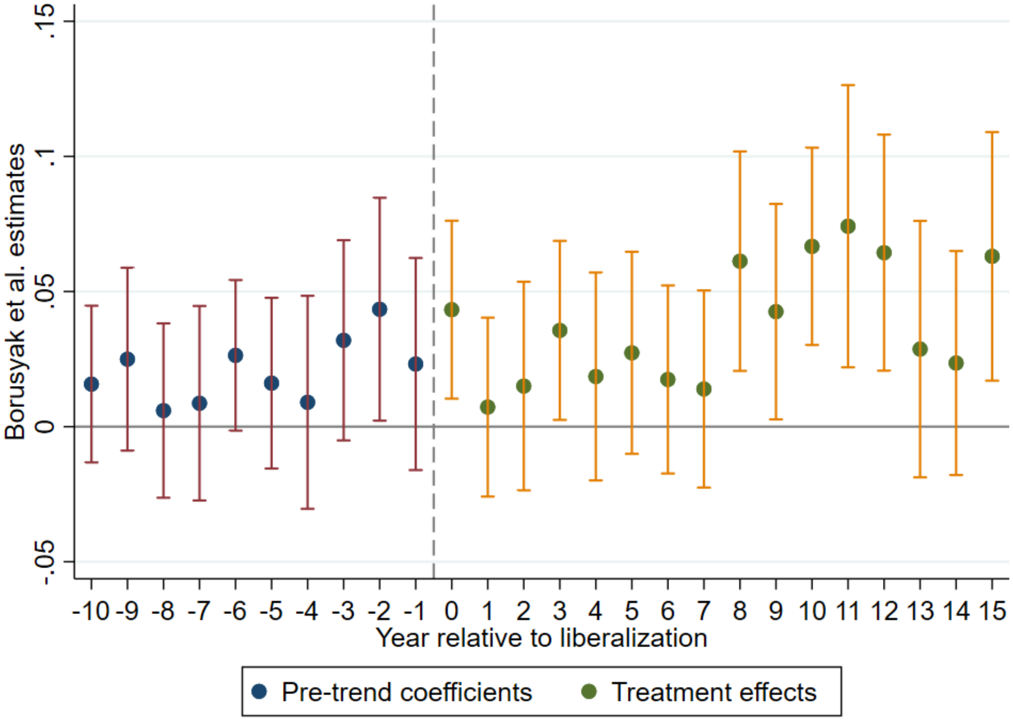
Source: OECD.

Figure C.3: Volume of international calls

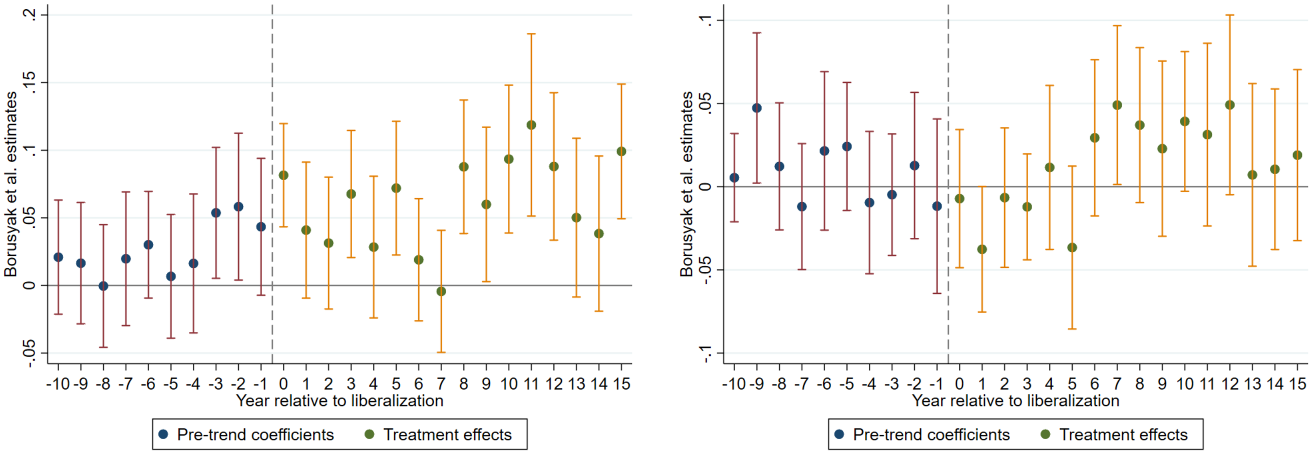


Notes: This picture is taken from a 2009 Telegeography report. It shows the rise of international call volumnes during our sample period.

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	122025
Performing Operations, Transporting	0.34	120374
Physics	0.28	120271
Mechanical Engineering, Lighting, 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.

Table D.2: Classification of Top-15 Technologies

Technology Code	Technology	Share Mentioning Experiment/Trial	Classified as Experimental	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.

Table D.3: Liberalization and Call Prices

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	34077	58.63	12.92	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

Table D.4: Collaboration and Business Hour Overlap

	Share Collaboration			
	(1)	(2)	(3)	(4)
Overlap	0.0646***	0.0593***	0.0557***	0.0584***
	(0.0019)	(0.0020)	(0.0023)	(0.0021)
× Experimental		0.0111***		0.0117***
		(0.0028)		(0.0032)
× Share Experimental			0.0446***	
			(0.0098)	
× Cites Science				-0.0042
				(0.0034)
× Process				0.0053*
				(0.0029)
Observations	316,875	316,875	316,875	316,875
R^2	0.47	0.47	0.47	0.47
Dependent var. mean	0.36	0.36	0.36	0.36
Fixed Effects				
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-experim. (3)	Full Sample (4)	Experimental (5)	Non-experim. (6)
Liberalization	0.0112	0.0166	0.0046			
	(0.0167)	(0.0191)	(0.0220)			
× Overlap	0.0245^{***}	0.0316^{***}	0.0118^{**}			
	(0.0069)	(0.0092)	(0.0056)			
× 0-2 hours				0.0261	0.0367^{**}	0.0094
				(0.0158)	(0.0168)	(0.0218)
× 2-4 hours				0.0417	0.0359	0.0562^{**}
				(0.0340)	(0.0468)	(0.0221)
× 4-6 hours				0.0312	0.0243	0.0455^{*}
				(0.0199)	(0.0218)	(0.0232)
× 6-8 hours				0.0623^{***}	0.0888^{***}	0.0180
				(0.0156)	(0.0187)	(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 var. mean	0.19	0.20	0.16	0.19	0.20	0.16
Fixed Effects						
Est. Pair-Technology	✓	✓	✓	✓	✓	✓
Year-Host Country	✓	✓	✓	✓	✓	✓
Year-Technology	✓	✓	✓	✓	✓	✓

Notes: This table reports the results of estimating equation 2, keeping only affiliates that already existed in the 1980s. 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	Experimental	Non-experim.	Full Sample	Experimental	Non-experim.
	(1)	(2)	(3)	(4)	(5)	(6)
Liberalization	-0.0072	-0.0081	-0.0049			
	(0.0072)	(0.0081)	(0.0121)			
× Overlap	0.0176***	0.0263***	0.0004			
	(0.0055)	(0.0071)	(0.0057)			
× 0-2 hours				-0.0015	0.0013	-0.0064
				(0.0064)	(0.0070)	(0.0113)
× 2-4 hours				0.0261	0.0356	0.0135
				(0.0308)	(0.0406)	(0.0167)
× 4-6 hours				0.0217	0.0294	0.0083
				(0.0180)	(0.0211)	(0.0198)
× 6-8 hours				0.0380***	0.0560***	0.0007
				(0.0097)	(0.0125)	(0.0147)
Observations	575,780	293,241	282,539	575,780	293,241	282,539
R^2	0.84	0.81	0.87	0.84	0.81	0.87
Dependent var. mean	0.27	0.28	0.26	0.27	0.28	0.26
Fixed Effects						
Est. Pair-Technology	✓	✓	✓	✓	✓	✓
Year-Source Country	✓	✓	✓	✓	✓	✓
Year-Technology	✓	✓	✓	✓	✓	✓

Notes: This table reports the results of estimating equation 2. 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)
Liberalization	0.0099	
	(0.0175)	
× Experimental	0.0083	0.0078
	(0.0142)	(0.0156)
× Overlap	0.0103^{*}	
	(0.0058)	
× Experimental × Overlap	0.0167^{**}	0.0233^{***}
	(0.0072)	(0.0070)
Observations	575,780	575,780
R^2	0.84	0.86
Dependent variable mean	0.27	0.27
Fixed Effects		
Establishment Pair-Technology	✓	✓
Year-Host Country	✓	
Year-Technology	✓	✓
Year-Location Pair		✓

Notes: This table reports the results of estimating equation 2. Standard errors are clustered at the country pair level. ***, **, * denote statistical significance at the 1%, 5% and 10% levels, respectively.