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Who collaborates with whom: the role of technological distance in international innovation[*]

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Abstract

This paper aims at investigating the role of technological distance in the globalized production of innovation. It uses aggregate patent-based indicators for a unique panel dataset covering international co-inventions between 29 countries across 21 industries between 1988 and 2005. The empirical findings show a dual impact of technological distance on the intensity of international collaborative innovation at the industry level. On the one hand, the more similar the industry-specific knowledge of two countries, the more easily they collaborate by sharing common industrial knowledge. On the other hand, the more different their non-industry-specific knowledge, the more they collaborate to gain access to broad and interdisciplinary expertise. It suggests that the relative absorptive capacity between partner's economies and the search for novel and complementary knowledge are key drivers of the globalization of innovation. Moreover, the results confirm the additional effect of non-technological distance factors (spatial proximity, ease of communication, institutional proximity, overall economic ties) in cross-border innovative relationships.

Keywords: internationalization, R&D collaboration, technological distance, patent statistics

JEL classification: F23, O14, O30

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1 Introduction

The globalization of economic activities has been highlighted as a major phenomenon characterizing the evolution of the current world economy. Beyond the globalized production of goods and services, the innovation production is also more and more subject to the international slicing of firms' value chain (UNCTAD, 2005; OECD, 2008; UNESCO, 2010). Whereas international innovation activities may be driven by the desire to adapt new product to local market (Patel and Vega, 1999), it has been recognized that international collaboration is required to face more complex and interdisciplinary research. In that context, several authors (Florida, 1997; Kuemmerle, 1999; Miotti and Sachwald, 2003; Narula and Duysters, 2004) have confirmed that innovative firms do not only collaborate within their national borders but are also increasingly going abroad to find the necessary competences.

In order to explain who collaborates with whom in the globalized production of innovation, this paper investigates the impact of technological distance on the international collaborative innovation between partner's economies . In particular, I argue that the relationship between the technological distance and the globalization of innovation is dual at the industry level.

For this purpose, I have developped patent-based indicators for a unique panel dataset covering the international patents per couple of countries across industrial sectors and over time. In particular, I evaluate dyadic international innovations – related to international co-inventions – with an index of revealed collaboration intensity between countries at the industry level from 1988 to 2005. Although this aggregated approach does not include individual firm characteristics, it has the advantage of providing a global analysis of the globalization of innovation (compared to most papers in the literature which used restricted samples based on firm level information[1]). More importantly, the industry-level information allows us to distinguish the dual forces usually associated with the impact of technological distance on collaborative innovations: the similarity of partners' knowledge to guarantee relative absorptive capacity, and the diversity in partners' technological experience to stimulate novel and innovative ideas. The former suggests that successful collaboration requires common knowledge and thus a lower technological distance. According to the latter, the larger the technological distance, the more beneficial is the collaboration since partners gain access to novel and broader knowledge.

While these two arguments could be viewed as "opposing forces" (see for instance, Colombo, 2003 and Nooteboom et al., 2007), I propose to combine them by distinguishing between industry-specific and non-industry-specific technological knowledge. Empirical findings confirm that the two forces are at work. Indeed, the estimation results show that two countries collaborate more intensively in the globalized production of innovation if, on the one hand, their industry-specific technological knowledge are closely related and, on the other hand, their non-industry-specific technological knowledge are different. In other words, the intensity of collaboration between two countries at the industry level is jointly determined by the overlapping of partners' knowledge within the industry and the non-overlapping of partners' expertise outside the scope of the industry.

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[1] See among others, Patel and Pavitt (1991); Cantwell (1995); Patel and Vega (1999); Cantwell and Janne (1999); Cantwell and Piscitello (2005); Fernández-Ribas and Shapira (2009).

Moreover, the analysis of non-technological factors confirms the moderating effect of distance in explaining bilateral innovative relationships between countries. The more countries are closely located and the more easily they communicate, the more they collaborate in innovative projects. In the same vein, a stronger intensity of collaborative efforts in innovation is observed among the 15 "old" member states of the European Union and for pairs of countries with low institutional distance. Finally, the globalization patterns in terms of innovation are also positively related to the overall economic relationships between country-industry pairs.

The rest of the paper is structured as follows. The next section presents the three main hypotheses of this research. The patent-based indicators and descriptive evidence about the international collaboration in innovation are introduced in section 3. The dataset and the empirical approach are described in section 4. The results are presented and discussed in section 5 which also provides robustness checks. Last section concludes and puts forward policy recommendations and ideas for further research.

2 Literature review and development of hypotheses

Previous literature has identified the technological proximity between two countries as an important driver of collaborative innovation (see among many others, Mowery et al., 1998; Cantwell and Colombo, 2000; Guellec and van Pottelsberghe de la Potterie, 2001; Rosenkopf and Almeida, 2003; Lin et al., 2012). Usually, it is recognized that the collaboration between two partners is facilitated when they are close in terms of technological knowledge. This effect is often explained by the general concept of absorptive capacity which is defined as the "the ability of a firm – conferred by prior related knowledge – to recognize the value of new information, assimilate it, and apply it to commercial ends" (Cohen and Levinthal, 1990; p 128). Indeed, several studies (see for instance, Veugelers, 1997; Cassiman and Veugelers, 2006; Czarnitzki et al., 2011) have shown that a partner benefits from external knowledge related to collaboration if it has itself enough internal knowledge.

Others – as recognized by Knoben and Oerlemans (2006) – argue that the key driver in technological collaboration is not only the internal capacity of each partner, but also the concept of relative absorptive capacity. While the absolute absorptive capacity considers that the ability to evaluate and use external knowledge depends mainly on the individual partner capacity, the relative absorptive capacity states that the key is the relationship between the characteristics of both partners. In this respect, Lane and Lubatkin (1998) introduced the concept of relative absorptive capacity by arguing that "the ability of a firm to learn from another firm is jointly determined by the relative characteristics of the student firm and the teacher firm" (Lane and Lubatkin, 1998; p 462). In other words, both partners should have similar knowledge bases to facilitate technological collaboration.

In my aggregated approach, it means that, if countries share common technological knowledge at the industry level, they can understand more easily each other, assimilate partner's knowledge and guarantee mutual learning. They can thus benefit from industry-specific spillovers and specialization externalities (as pointed out by Cantwell and Piscitello, 2005 in their regional-level analysis of foreign-owned R&D of multinational corporations in Europe). To test the impact of technological proximity at the industry level, I therefore formulate the following hypothesis:

H1: The more *similar* the *industry-specific* technological knowledge of two countries, the more they collaborate at the industry level.

However, too much similarity may also reduce places for novelty between both partners knowledge experiences. In this respect, previous works have shown an inverted U-shaped relationship between technological overlap and collaboration (see for instance, Mowery et al., 1998; Wuyts et al., 2005; Nooteboom et al., 2007 or the review in Table 1 of Schulze and Brojerdi, 2012). The arguments concerning the impact of technological distance on collaboration are thus twofold. On the one hand, the smaller the distance, the better are mutual understanding and the ability to absorb partner's knowledge. On the other hand, the larger the distance, the more beneficial is the collaboration since partners would access novel and more diverse knowledge. Comparing these two arguments, Wuyts et al. (2005) presented optimal technological distance as being a trade-off between the advantage of increased technological distance for a higher novelty value of a partner's knowledge, and the disadvantage of less mutual understanding.

In addition to the classical U-shaped relationship with technological proximity, it has also been pointed out that international collaborative innovation is driven by the search for complementary knowledge. In this respect, several surveys of firms confirmed these complementarity motives[2]. Indeed, Brockhoff et al. (1991) showed that the development of synergies from the exchange of complementary technical knowledge was the most important reason for cooperative R&D arrangements between large industrial firms in Germany. Analyzing information on technology arrangements from the MERIT-CATI database, Hagedoorn (1993) found that technology complementarity played a significant role in explaining the motives that led firms to cooperate in their innovative efforts. The study of Japanese R&D consortia sponsored by governmental organizations Sakakibara (1997a,b) confirmed also that sharing of complementary skills among participants was perceived as the single most important objective of cooperative R&D projects. Similar results were found by Narula (2004) for both large and SME's European technology firms. These survey-based findings illustrated that the access to complementary technologies remains a primary motivation to undertake R&D collaboration.

In my aggregated approach, one can thus expect that countries collaborate more intensively with partners which present novel – compared to their own knowledge – technological experience. Indeed, international collaborative innovations are not only driven by the importance of intra-industry spillovers (tested by H1) but also by the presence of inter-industry spillovers and diversity externalities (Cantwell and Piscitello, 2005). In order to test this search for novelty and diversity, I formulate the following hypothesis by considering knowledge experience of both countries outside the scope of the industry:

H2: The more *different* the *non-industry-specific* technological knowledge of two countries, the more they collaborate at the industry level.

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[2] See also Ennen and Richter (2010) for a review of empirical evidence on complementarities in organizations.

These first two hypotheses illustrate that the industry-level approach allows us to reconcile the technological proximity argument – within the industry (H1) – with the technological diversity argument – outside the scope of the industry (H2). Few recent papers have addressed these two types of knowledge relatedness together. Makri et al. (2010) examined high technology mergers and acquisitions and investigated the role of science and technology similarity and complementarity as important drivers of invention. In particular, they showed, using redefined measures of knowledge relatedness, that complementary knowledge was vital to stimulate higher quality and more novel inventions. Moreover, they suggested that research should still be done to consider jointly similarities and complementarities. In this respect, Quintana-garcía and Benavides-velasco (2011) analyzed inter-firm R&D alliances in the pharmaceutical industry and distinguished the same two components of knowledge relatedness. In addition to a well-known curvilinear impact of technological similarity, they confirmed that the technological complementarity among partners contributes to the development of innovation.

However, the empirical approach of previous studies was often restricted to a limited sample of firm-level information while a more representative approach would contribute to integrate information of all patent population for a large sample of countries, industries and over a long period of time[3]. This is the uniqueness of the methodology used in the present paper. To the best of my knowledge, this study is the first one investigating – with a global approach – the dual relationship between technological distance and the globalization of innovation.

The impact of technological distance should, however, not be analyzed in isolation from non-technological proximity measures. For this reason, the following hypothesis is formulated in order to test the impact of other distance factors on the intensity of collaboration between countries:

H3: The lower the non-technological distance between two countries, the more they collaborate.

Several types of non-technological distance may impact the collaborative innovation. First, the geographical proximity remains a key moderating factor of international dyadic economic activities (see among many others, Ghemawat, 2001; Keller, 2002; Anderson and van Wincoop, 2003; Ambos and Ambos, 2009; which confirmed the significant role of distance and its various dimensions). Focusing on innovation, several authors (see for instance, Nagpaul, 2003; Dachs and Pyka, 2010; Picci, 2010; Thomson, 2013)[4] have confirmed that limited geographical distance facilitates direct interactions and the exchange of knowledge between partners. Second, the ease of communication is crucial to guarantee efficient interactions required in the innovation process. In addition to the use of a common language (Guellec and van Pottelsberghe de la Potterie, 2001; De Prato and Nepelski, 2012; Montobbio and Sterzi, 2012), the development of information and communication technologies has stimulated cross-border collaborative innovation. Indeed, Forman and van Zeebroeck (2012) have shown that the use of Internet technology has facilitated collaborative patents from geographically dispersed teams by reducing the coordination costs of research teams. Third, proximity at institutional level

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[3] See section 3 for more details on the sample used in this analysis.

[4] See also Boschma (2005) for an assessment of the impact of geographical proximity on interactive learning and innovation.

could also enhance the interaction. Finally, the presence of other commercial relationships between countries could stimulate collaborations in innovation. In particular, the bilateral trade or investment flows could reflect not only market-driven motives but also proximity in terms of commercial ties between countries (as pointed out by Picci and Savorelli, 2012). In summary, hypothesis 3 states that lower distance would ultimately facilitate coordination and collaboration between innovative partners.

3 Data and descriptive evidence on international collaborative innovation

3.1 Patent-based indicators of globalization of innovation

Although patent data present drawbacks, it remains a major source of information to investigate innovation related research questions[5]. In particular, many authors have examined the globalization of innovation using patent data (Patel and Pavitt, 1991; Cantwell, 1995; Almeida, 1996; Breschi, 1999; Guellec and van Pottelsberghe de la Potterie, 2001, 2004; Song and Shin, 2008; Picci and Savorelli, 2012; Thomson, 2013). In this context, Danguy (2014)[6] has presented patent-based indicators of globalization of innovation for a unique panel dataset covering 21 industries[7] in 29 countries. This previous work analyzed the intensity of globalization of innovation for each country-industry pair with the rest of the world. Using similar global approach – across countries, industries and over time – the current paper extends this study by focusing on the bilateral relationships between countries at the industry level. In other words, I investigate the question of who collaborates with whom in the globalized production of innovation.

Using information contained in EPO worldwide patent statistical database (PATSTAT, April 2009) database, one can identify all international patents – defined in this paper as patents with inventors from at least two different countries (II-type collaborations)[8]. Beyond computing the absolute and relative number of international patents per individual country-industry pair, I computed the count of those patents per couple of countries for each industry. This count reflects the number of dyadic co-inventions and is at the core of this research. The analysis relies on a patent count defined as follows: the number of first and subsequent patent applications which have been filed directly at European Patent Office (EPO) and those which have reached EPO during the regional phase of a PCT application[9].

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[5] For a discussion on the use of patent indicators, see Griliches (1990).

[6] See also this paper for a discussion on the limitations of aggregate patent-based internationalization indicators.

[7] The counts per industry were computed by matching technological information contained in patents, International Patent Classification (IPC) codes, and industry, International Standard Industry Classification (ISIC Rev 3), using the concordance table proposed by Schmoch et al. (2003). Note also that the counts per industry are not fractional. A patent related to multiple industries is thus taken into account equally for each industry.

[8] Similar results (available upon request) were found in terms of dyadic cross-border ownership of innovation (patent with inventors and applicants from different countries, IA-type collaborations).

[9] The same analysis was also performed for the worldwide count of priority filings (PF, introduced by de Rassenfosse et al., 2013) and provided very similar results (see Appendix Table A.4)

3.2 Patterns in international collaborative innovation

The aggregated approach used in this paper provides a global overview on the internationalization of innovation. In particular, the patterns of bilateral collaboration allow us to deepen the descriptive evidence of Danguy (2014) which has shown a strong growth in the intensity of internationalization of innovation. Indeed, like the international trade analysis performed by Helpman et al. (2008), dyadic information helps us to underline if the increasing trends in globalization of innovation are due either to an increasing number of countries which have innovative activities across borders, or simply to a rise in the intensity of collaboration between few partners.

For that purpose, aggregate patent-based indicators provide interesting insights illustrated in Figure 1 for EPO applications. In my panel dataset, an individual is defined as a couple of countries in a particular industry. The bars represent the percentage of individuals with a strictly positive number of international collaborative innovations per year (see the left axis); while the line illustrates the overall intensity of collaboration (see the right axis). Note that, among my panel dataset composed of 21 industries and 29 countries[10], the maximum number of individuals with collaboration is equal to 17052 per year – considering that all countries (29) collaborate with all other countries (28) in all industries (21). The percentages of the following Figure 1 are simply computed as the ratio between the observed number of individuals with collaboration and the maximum number per year. Concerning the intensity of co-invention, the matrix of observed collaborations is perfectly symmetric, which requires to use half of the matrix of all individuals presenting II-type collaborations. The measures of overall intensity of collaboration are given by:

$$intensity\ II_t = \frac{Int.\ patent\ II_t}{Individual\ II_t/2} \tag{1}$$

where, for the priority year t, $Int.\ patent\ II_t$ is the total number of international patent applications being of II-type and $Individual\ II_t$ is the number of individuals with a strictly positive number of II-type collaborations. In other words, these measures correspond to the average number of international patents per collaborative individual (couple of countries in a particular industry).

Figure 1 shows that that the worldwide surge in the globalization of innovation is twofold. First, the number of internationally collaborative individuals has constantly increased (being multiplied by 2 between 1988 and 2005). Second, the average intensity of collaboration has also strongly increased (from about 4 international priority filings per average collaborative individual in 1988 to 8 in 2005). The globalized world of innovation is thus composed of a growing number of partner countries which collaborate together intensively[11]. Although the growth of globalization is significant, the amplitude of these phenomena remains quite limited. Indeed, less than one fifth of the individuals in my sample collaborated internationally for their innovative activities in 2005.

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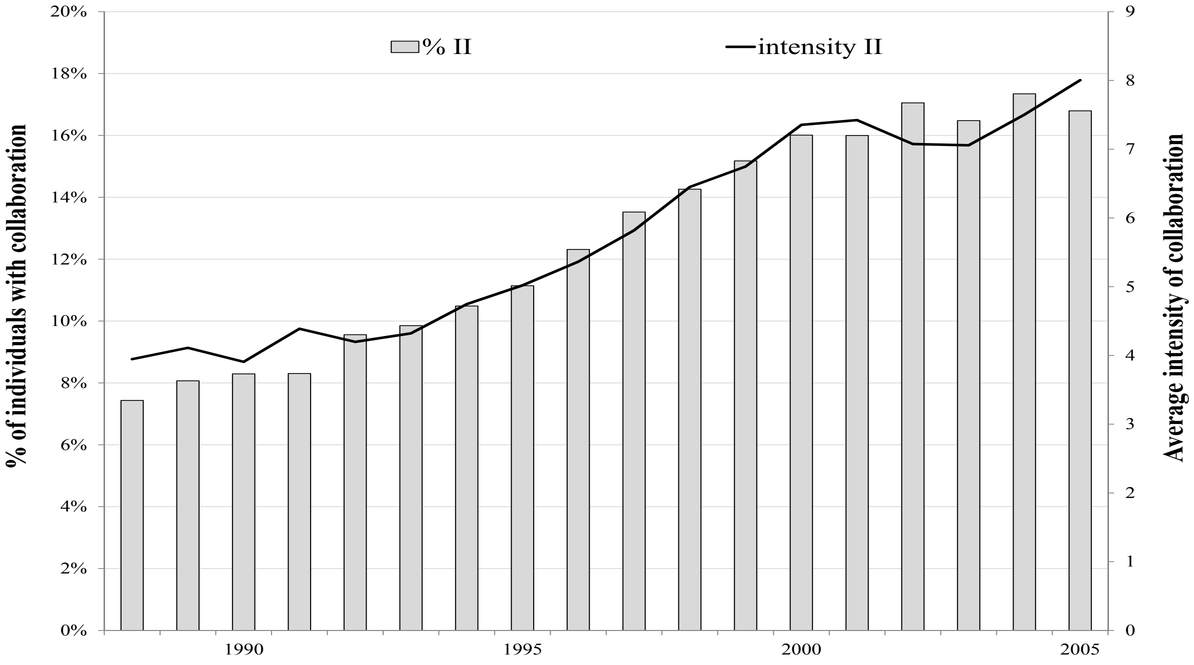
[10] The sample is composed mainly of OECD countries.

[11] Both worldwide increasing trends – in the number of collaborations and in their intensity – are also observed for most of the countries and most of the industries. These additional descriptive results are available upon request.

Figure 1: Bilateral collaboration patterns for EPO applications



Source: own calculations based on PATSTAT Database (April 2009)

4 Empirical approach

4.1 Dependent variable: an index of revealed collaboration intensity

To better understand collaboration patterns in innovation between countries across industrial sectors, I consider not only the count of international patents per couple of countries, but also relative measures of bilateral collaborative innovations. The core variable of the empirical methodology is thus an index equivalent to the one introduced by Guellec and van Pottelsberghe de la Potterie (2001)[12] that analyzed the geographical distribution of the internationalization of technology within a cross section of countries. More precisely, an index of revealed collaboration intensity (rci) is defined – for co-invention II – per couple of countries (i, j) in an industry (k)[13] as follows:

$$rci_{i,j,k}^{II} = \frac{Int.\,patent\,II_{i,j,k} / Int.\,patent\,II_{i,.,k}}{Int.\,patent\,II_{.,j,k} / Int.\,patent\,II_{.,.,k}} \tag{2}$$

where $Int.\,patent\,II_{i,j,k}$ is the number of international patents in industry k with at least one inventor in country i and at least one in country j, $Int.\,patent\,II_{i,.,k}$ ($Int.\,patent\,II_{.,j,k}$) is the total

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[12] Similar index was also used in terms of co-authorship of scientific articles (see for instance, the index of international collaboration on Science & Engineering articles presented by National Science Board, 2012; p 5-40). For a discussion on the measurement of international scientific collaboration, see Luukkonen et al. (1993). See also Zitt et al. (2000); Glänzel and Schubert (2004); Yamashita and Okubo (2006); Chen et al. (2012) for other measures of collaboration.

[13] For simplicity, the year t has been omitted from the formula but this *rci* index has been computed for each priority year between 1988 and 2005.

number of international patents in industry k with at least one inventor in country i (j) and at least one foreign inventor, and $Int.\,patent\,II_{.,.,k}$ is the total number of international patents of II-type in industry k. In other words, it is – for each industry k – the ratio between the share of country j in the international co-inventions of country i and the share of country j in all international co-inventions. This *rci* index takes positive values and is greater than 1 when the intensity of collaboration between two countries is greater than the average of the industry and is lower than 1 for the opposite case. For instance, if France represents relatively a higher share in Belgian international co-inventions in chemistry than the share represented by France in worldwide co-invention in chemistry, the *rci* index between Belgium and France in chemistry will be higher than 1. This *rci* index is computed for all individuals in my panel dataset. Note that this matrix is perfectly symmetric in terms of co-inventions since the co-inventions between Belgium and France are also the co-inventions between France and Belgium.

This kind of index was initially introduced in trade literature to capture the so-called revealed comparative advantage. Based on patent counts, similar indicators have also been used in the literature to measure the revealed technological advantage (RTA) of countries across industrials sectors (Soete, 1987; Patel and Vega, 1999; Le Bas and Sierra, 2002; Frietsch and Schmoch, 2010; Danguy, 2014). While the RTA indicators consider all patent applications, the international collaboration index (*rci*) focuses on those which are international – with inventors from different countries.

Compared to a traditional count of dyadic patents (used largely in gravity-type models such as Picci, 2010; Picci and Savorelli, 2012; Thomson, 2013), this index has the advantage to account for unequal sizes in innovative activities and differences in internationalization patterns among the country-industry pairs. It helps to guarantee that the analysis focused mainly on the understanding of the intensity of bilateral innovative relationships within the panel dataset. This computation is also consistent with the statement made by Luukkonen et al. (1993) which said that "it is important to relate the relative strength of collaborative relations between a pair of countries to their relation with other countries" (Luukkonen et al., 1993; p 23) since the bilateral collaboration between two countries does not occur in isolation of their other collaborations with the rest of the world.

As stated in the previous section, the patent-based indicators used in this paper were computed using the entire population of patent filings[14]. It is fair to assume that all international collaborative patents are thus observed. However, Figure 1 has shown that amplitude of globalization remains limited. It means that many individuals (couple of countries for a particular industry) do not present a collaborative patent. This leads to the presence of a large number of potential zeros in my panel dataset. In this respect, I have considered that the absence of observed collaboration should be seen as informative and should thus be considered as true zeros. In the same vein, Thomson (2013) considered in his analysis that unobserved cross-border patents represent true zeros rather than censored values[15]. Furthermore, like Lybbert and Zolas (2012), I did

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[14] It correpsonds to the entire population of worldwide priority filings and patent applications at EPO, based on the assumption that the PATSTAT database contains the entire population of patent filings.

[15] As it seems to be considered by authors analyzing bilateral flows of patents (see for instance Dachs and Pyka, 2010)

not simply put 0 to all individuals for which no bilateral international patent was observed but I have considered as informative, in terms of globalization, only pairs in which each country has at least one patent. More precisely, it means that the exact definition of rci index is given by conditions (3) within my country-industry framework.

For each industry k :

$$rci^{II}_{i,j,k} \begin{cases} > 0 & if\, Int.\, patent\, II_{i,j,k} > 0 \\ = 0 & if\, Int.\, patent\, II_{i,j,k} = 0 \text{ and } Patent_{i,k} \neq 0 \text{ and } Patent_{j,k} \neq 0 \\ \text{not defined} & if\, Patent_{i,k} = 0 \text{ or } Patent_{j,k} = 0 \end{cases} \tag{3}$$

where $Int.\, patent\, II_{i,j,k}$ is the number of international patents in industry k with at least one inventor in country i and at least one in country j, $Patent_{i,k}$ ($Patent_{j,k}$) is the number of patents in industry k with at least one inventor in country i (j). Since the focus of this paper is on the intensity of bilateral international collaborations between countries across industries, I have excluded country-industry pairs that do not have any patent.[16]

Finally, the rci index is normalized[17] in order to obtain a symmetric measure. Therefore, the dependent variable of the empirical model for the couple of countries (i, j), industry (k) and priority year (t) – is defined as following:

$$RCIc^{II}_{i,j,k,t} = \frac{rci^{II}_{i,j,k,t}}{rci^{II}_{i,j,k,t} + 1} \tag{4}$$

$RCIc$ variable[18] varies between 0 and 1; and are higher than 0.5 for couples of countries which collaborate strongly and lower than 0.5 for couples of countries which collaborate weakly.

4.2 Model and explanatory variables[19]

To test the three hypotheses exposed in section 2, I regress the RCIc variable on different sets of explanatory variables. Since this index of revealed collaboration intensity is restricted on the unit interval, I use a fractional logit estimation proposed by Papke and Wooldridge (1996).[20] The form of the estimated model can thus be expressed as follows:

$$E(y|x) = G(x\beta) \tag{5}$$

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[16] An alternative specification consists in excluding country-industry pairs that do not have any international collaborative patent with any foreign resident. Although it restricts the size of the samples for estimation, it provides similar results which are available upon request.

[17] This kind of normalization has been proposed by Laursen (1998) in terms of revealed comparative advantage and then applied for various revealed-type indexes (see among others, Dalum et al., 1999; Schubert and Grupp, 2011; D'Agostino et al., 2013).

[18] See Appendix Table A.2 for descriptive statistics.

[19] See Appendix Table A.1 for more details on the different variables, see Appendix Table A.2 for the descriptive statistics and see Appendix Table A.3 for correlation matrix.

[20] For a discussion on the econometric methodology used for fractional or proportional series, see among others Kieschnick and McCullough (2003) or Ramalho et al. (2011). For examples which used this estimation technique in applied economics papers, see for instance Wagner (2001, 2003), Czarnitzki and Kraft (2004) and Danguy (2014).

where $G(z)$ is the logistic function, $G(z) = \frac{exp(z)}{1+exp(z)}$, satisfying $0 < G(z) < 1$ for all $z \in \mathbb{R}$ in order to guarantee that the predicted y varies between 0 and 1 for all values of the regressors.

Concerning explanatory variables, the empirical approach is built on two main explanatory variables to investigate the impact of technological distance between countries – across industrial sectors – on their international collaborative innovations.

First, the similarity of industry-specific technological knowledge (hypothesis 1) is evaluated using the technological proximity indicator introduced by Jaffe (1986) to measure the degree of technological overlap. It consists in computing the angular separation or uncentered correlation between the two countries' vectors of patents across technological fields. This indicator has been used largely in the literature to proxy the knowledge relatedness between firms or countries (Jaffe, 1986, 1989; Guellec and van Pottelsberghe de la Potterie, 2001; Cincera, 2005; Lee, 2006). In my aggregated framework, this measure focuses on the industry-specific technological knowledge and is thus computed for each pair of countries across the technological fields within each industrial sector. More precisely, within my panel dataset, the technology proximity (TP) between country i and country j for industry K (composed of N 4-digit IPC classes in the concordance table of Schmoch et al., 2003) is given by the equation (6).

$$TP_{ijt,K} = \frac{\sum_{k=1}^{N} P_{it,k} P_{jt,k}}{\sqrt{\sum_{k=1}^{N} P_{it,k}^2 \sum_{k=1}^{N} P_{jt,k}^2}} \tag{6}$$

where $P_{it,k}$ is the fractional count of patents of country i^{21} in 4-digit IPC class k at priority year t. TP varies between 0 and 1 for all individuals. It is equal to one when both countries present identical shares of patent applications across technological classes and it tends to zero when both vectors of patents are totally different. Note also that this measure is symmetric within a pair of countries, like most distance variables. In other words, $TP_{ijt,K}$ is equal to $TP_{jit,K}$.

Second, the diversity in the non-industry-specific technological knowledge (hypothesis 2) is evaluated by considering 4-digit IPC classes outside the scope of the industry. This dyadic indicator is based on the multidisciplinarity indicator (introduced in Danguy, 2014) which corresponds to the number of distinct 4-digit IPC classes – outside the scope of the industry defined by the concordance table of Schmoch et al. (2003) – associated with patents of each country-industry pair. Since the current paper focuses on bilateral relationships, the empirical test of hypothesis 2 consists in comparing the multidisciplinarity of both countries at the industry level. It thus corresponds to the number of distinct 4-digit IPC classes – outside of the scope of the industry – which are not in common between both partners' patent applications. For instance, consider that country i has only one patent listing $\{IPC_A, IPC_B, IPC_C\}$ and country j has only one patent listing $\{IPC_A, IPC_B, IPC_D\}$. For industry k defined by IPC_A in the concordance table, the diversity indicator is based on 2 distinct IPC classes – $\{IPC_C, IPC_D\}$ – which are not in common between both countries' patent applications related to this industry.

The technological collaborations are most likely determined not only by the technological distance but also by non-technological distance between partners. For that purpose, several other

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[21] Since this analysis focuses on international co-inventions, all patent-based measured are based on the country of inventors.

distance factors are considered to test hypothesis 3. In particular, three variables from the CEPII database[22] are included. The impact of spatial proximity is estimated by the geographical distance (DIST) that was calculated following the great circle formula using latitudes and longitudes of the most important cities; and a dummy variable that equals to 1 for couple of countries which share a common border (BORDER, 0 otherwise). The ease of communication between innovative partners is evaluated by another dummy variable that equals to 1 for couple of countries which share a common official language (COMLANG, 0 otherwise). The use of Internet technology is also considered as faciliting communication between dispered partners. In that purpose, INTERNET variable was defined as the minimum – between both countries – of the percentage of individuals using the Internet. Concerning the institutional distance, I compute the absolute value of the difference – between both countries – for the six worldwide governance indicators developed by the World Bank[23]: voice and accountability (WGI_VA), political stability and absence of violence (WGI_PV), government effectiveness (WGI_GE), regulatory quality (WGI_RQ), rule of law (WGI_RL), control of corruption (WGI_CC). The membership of both countries to the European Union is also considered as a proxy of proximity at the institutional level. The empirical model thus includes a dummy variable (EU) that equals to 1 when both countries are member states of the EU (0 otherwise). This variable varies over time according to the different adhesion phases. Furthermore, the commercial proximity between partners is measured by the bilateral export flows of goods (EXPORT_BIL). While previous distance measures are country based, this commercial ties indicator is based on country-industry information.

In addition to dyadic variables related to the three hypotheses of the paper, two control variables are included in the empirical model to account for individual characteristics of each partner country (CTRYi and CTRYj). First, I control for the multidisciplinarity of innovation performed by each country-industry pair (using the indicator described before, MULTI_PAT_INV). A positive effect is expected since partners with multidisciplinary knowledge (a potential for higher inter-industry spillovers) are more attractive for international collaborations (Cantwell and Piscitello, 2005). In the same vein, international collaboration may be seen as a mean to combine complex and interdisciplinary research. Second, I control for the intensity of R&D expenditures of both countries (R&D_INT). It allows us to evaluate if absolute absorptive capacity of each country plays a significant role in explaining intensity of bilateral innovative collaborations since Cohen and Levinthal (1989) suggested that R&D expenditures do not only help to generate new innovative products but also to enhance ability to learn from external sources of knowledge. Nevertheless, the impact of technological capabilities can be seen as paradoxical because high R&D expenditures may constitute a disincentive to collaborate with others in innovative activities (Song and Shin, 2008). Finally, I control for unobserved heterogeneity in my panel dataset by including dummies for each country, each industry and each priority year.

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[22] See Mayer and Zignago (2011) for more information concerning this database that is extensively used in gravity-type models.

[23] See Kaufmann et al. (1999) and Kaufmann et al. (2010) for more details.

5 Results and discussion

The main estimation results are reported in Table 1 for patent applications at the EPO[24]. The various specifications – testing separately or jointly H1 and H2 – strongly confirm the three hypotheses.

First, the coefficients of technological proximity variables (TP_PAT_II) are strongly significant and positive; showing that countries with related industry-specific technological knowledge tend to collaborate more intensively in innovation production. Beyond the importance of individual technological capabilities, this finding confirms the key role played by the relative absorptive capacity (Lane and Lubatkin, 1998; Knoben and Oerlemans, 2006). Indeed, the relative technological characteristics of both partner economies – measured by the technological proximity at the industry level – remain major determinants of international collaborative innovations.

Second, the number of non-overlapping – among partners' innovative activities – technological classes (NOCOM_PAT_II) has a significant and positive impact on the intensity of collaboration. It highlights that the more different the non-industry-specific technological knowledge of both countries, the more they collaborate in innovative activities. Hypothesis 2 is also confirmed for various specifications, with or without the measure of technological proximity of industry-specific knowledge. Results for H1 and H2 confirm the dual effect of technological distance. On the one hand, the relative absorptive capacity between partners matters since similarity of industry-specific technological knowledge guarantees mutual understanding and facilitates innovative collaborations. On the other hand, the diversity in non-industry-specific knowledge stimulates cross-border innovation and illustrates that international collaboration is a mean to search for novel and complementary competences.

Third, the non-technological distance variables have the expected coefficients. It thus validates hypothesis 3 which states that the intensity of collaboration between countries is higher when the non-technological distance separating both partner economies is lower. Indeed, the negative sign of the geographical distance (DIST) and the positive coefficient of common border (BORDER) confirm that spatial proximity between countries facilitates and stimulates international collaborative innovation. In the same vein, the sharing of a common language guarantees the ease of communication in the innovation process (as shown by the positive and significant coefficient of COMLANG). Moreover, the joint use of Internet technology among partners seems to facilitate cross-country innovation, as indicated by a positive and signifcant coefficient of INTERNET in the main specification of Table 1 (see column (3)) and in several robustness checks (see Tables 2 and 3). Concerning the impact of joint membership to the European Union, the EU variable has a positive and significant impact on cross-border collaborations in columns (1)-(3). However, the EU variable lost his significance when the indicator of institutional distance is included (see column (4) of Table 1 with the 'rule of law' dimension, which is the most

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[24] The results in terms of priority filings (PF) are very similar and are presented in Appendix Table A.4. The samples for PF estimations are smaller since de Rassenfosse et al. (2013) have noticed a coverage problem for few countries which were not taken into account in the estimation for PF.

widely used governance indicator[25]). The negative and significant coefficient of the WGI_RL variable highlights that the more countries are similar at the institutional level, the more likely they collaborate in innovative activities. This shows, on the one hand, that the institutional distance matters in explaning international co-inventions, and on the other hand that EU membership does not have a additional impact on collaborative innovation than the one related to the institutional proximity among EU member states. The last distance factor related to hypothesis 3 is the economic proximity between countries (measured in Table 1 by EXPORT_BIL variable). The positive and significant coefficient shows that collaboration patterns in terms of innovation are positively related to the trade flows between countries at the industry level.

The estimation results of the variables which control for individual characteristics of each collaborative partner provide also interesting insights. Concerning the multidisciplinarity variables (MULTI_PAT_INV_CTRYi and MULTI_PAT_INV_CTRYj), the coefficients are strongly significant and positive for each country-industry pair. It reflects that country-industry pairs which present more diverse technological knowledge are more attractive and more active in international collaborative innovative efforts. This impact was suggested by Danguy (2014) in the analysis of globalization per country-industry pair with respect to the rest of the world and is thus confirmed in the current study of bilateral international collaborative innovations. More importantly, this positive effect is significant in parallel to the positive impact observed for NOCOM_PAT variables. In other words, the intensity of collaboration is positively related not only to the multidisciplinary of each partner but also to the fact that these multidisciplinary technological competences are non-overlapping among partners. Finally, the impact of R&D intensity (R&D_INT_CTRYi and R&D_INT_CTRYj) is largely not significant for both countries. It does not seem to confirm that absolute absorptive capacity is required to intensively collaborate across border in invention process.

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[25] See Appendix Table A.5 for the results concerning the five other dimensions of the worldwide governance indicators. Most of them provide similar results. Note that the sample size of the specifications which include WGI variables is smaller due to their limited availibity. I have thus preferred to keep only the EU variable as a measure of institutional proximity for the rest of the estimations.

Table 1: Main estimation results for EPO applications

	(1)	(2)	(3)	(4)
Dependent variable	$RCIc^{II}$	$RCIc^{II}$	$RCIc^{II}$	$RCIc^{II}$
TP_PAT_II [H1]	0.822***		0.927***	0.878***
	(0.0698)		(0.0704)	(0.0817)
NOCOM_PAT_II [H2]		0.257***	0.309***	0.371***
		(0.0347)	(0.0342)	(0.0390)
DIST [H3]	-0.201***	-0.208***	-0.205***	-0.224***
	(0.0326)	(0.0332)	(0.0323)	(0.0362)
BORDER [H3]	0.603***	0.623***	0.611***	0.605***
	(0.0629)	(0.0638)	(0.0625)	(0.0695)
COMLANG [H3]	0.612***	0.616***	0.600***	0.540***
	(0.0534)	(0.0523)	(0.0521)	(0.0559)
INTERNET [H3]	0.00188	0.00141	0.00261*	0.000997
	(0.00140)	(0.00140)	(0.00140)	(0.00176)
EU [H3]	0.0960**	0.0793*	0.0753*	0.0461
	(0.0441)	(0.0444)	(0.0439)	(0.0605)
WGI_RL [H3]				-0.245***
				(0.0687)
EXPORT_BIL [H3]	0.144***	0.147***	0.144***	0.132***
	(0.0118)	(0.0120)	(0.0119)	(0.0130)
MULTI_PAT_INV_CTRYi	0.305***	0.284***	0.253***	0.253***
	(0.0308)	(0.0313)	(0.0310)	(0.0349)
MULTI_PAT_INV_CTRYj	0.246***	0.255***	0.214***	0.204***
	(0.0299)	(0.0300)	(0.0299)	(0.0376)
R&D_INT_CTRYi	0.118	0.194*	0.117	-0.0705
	(0.111)	(0.110)	(0.111)	(0.194)
R&D_INT_CTRYj	0.00203	0.0854	0.0311	0.352**
	(0.0963)	(0.0962)	(0.0961)	(0.176)
Country$_i$ FE	yes***	yes***	yes***	yes***
Country$_j$ FE	yes***	yes***	yes***	yes***
Industry FE	yes***	yes***	yes***	yes***
Year FE	yes***	yes***	yes***	yes
Pseudo LL	-19435	-19446	-19369	-13039
Observations	87,624	87,409	87,409	57,148

Notes: Robust standard errors in parentheses; ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. The rows "country$_i$ FE", "country$_j$ FE", "industry FE" and "year FE" report the significance levels of the joint effect of these fixed effects.

Robustness checks[26]

Several alternative specifications are estimated to demonstrate the robustness of the results. In particular, the validity of hypothesis 1 and 2 is analyzed in Table 2 which includes an additional variable: the squared value of TP_PAT variable (TP_PAT_II_SQ). It aims at testing the classical inverted U-shaped relationship – largely observed in the literature (see references cited in section 2) – between technological distance and collaborative innovations.

While the positive coefficient of the linear term of technological proximity is confirmed, column (1) shows a negative and significant coefficient for the quadratic term of technological proximity. It thus reflects a concave relationship[27] between the intensity of collaboration and the similarity of the technological knowledge of countries at the industry level. These results are also confirmed in column (2) which includes the indicator of diversity of non-industry-specific technological knowledge (related to hypothesis 2). It is important to notice that NO-COM_PAT variables keep their significant and positive coefficients at the top of the curvilinear relationship with technological proximity. These findings reinforce the argument saying that beyond the relative absorptive capacity, significant differences in technological competences – both in terms of industry-specific and non-industry-specific knowledge – between partners are required to stimulate collaboration in innovation production. In addition to the confirmation of H1 and H2, the interpretations of other variables are maintained across the first two specifications of Table 2.

The robustness of hypothesis 3 is evaluated in two parts. Columns (3)-(6) of Table 2 separates the impact of the joint membership to the EU according to three main adhesion phases. Table 3 includes three additional variables to evaluate the relationship between overall economic ties and international collaborative innovations.

Concerning the EU impact, one can distinguish between three adhesion phases over the time period analyzed: EU_12 for countries which were member states of the EU in 1986 and afterwards, EU_15 for countries which were member states in 1995 and afterwards, and EU_25 for countries which were member states in 2004 and afterwards. Each adhesion phase corresponds to a dummy variable that equals to 1 if both countries were member states of the EU at the corresponding time period (0 otherwise). This distinction allows us to illustrate that the global impact of the EU observed in Table 1 is mainly due to the significant stronger intensity of innovative collaboration among the EU_15 member states (see column (5) in Table 2). This finding confirms the results of the multivariate analysis of the internationalization of innovation in Europe, performed by Dachs and Pyka (2010). In particular, they interpreted the positive coefficient of EU15 dummy variable by claiming that "European Single Market not only fostered economic, but also scientific integration in Europe" (Dachs and Pyka, 2010, p 21). Furthermore, in comparison with Guellec and van Pottelsberghe de la Potterie (2001), the impact of EU is significant in terms of international co-inventions.

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[26] The robustness checks results are represented only for EPO applications but they are similar in terms of priority filings and are available upon request.

[27] Note that we cannot described this relationship as being an inverted U-shaped since its peaks is reached for values of TP higher than 1 (which is outside of the values range for the technological proximity measure).

Table 2: Robustness results for H1, H2 and H3 (EU membership)

	(1)	(2)	(3)	(4)	(5)	(6)
	H1 and H2		H3 – EU membership			
Dependent variable	$RCIc^{II}$	$RCIc^{II}$	$RCIc^{II}$	$RCIc^{II}$	$RCIc^{II}$	$RCIc^{II}$
TP_PAT_II	2.597***	2.330***	0.927***	0.927***	0.927***	0.928***
	(0.245)	(0.251)	(0.0704)	(0.0704)	(0.0704)	(0.0704)
TP_PAT_II_SQ	-1.543***	-1.224***				
	(0.202)	(0.207)				
NOCOM_PAT_II		0.282***	0.309***	0.310***	0.310***	0.311***
		(0.0346)	(0.0342)	(0.0343)	(0.0341)	(0.0342)
DIST	-0.203***	-0.207***	-0.205***	-0.210***	-0.207***	-0.217***
	(0.0327)	(0.0323)	(0.0323)	(0.0336)	(0.0315)	(0.0308)
BORDER	0.606***	0.613***	0.611***	0.603***	0.613***	0.606***
	(0.0629)	(0.0625)	(0.0625)	(0.0618)	(0.0626)	(0.0621)
COMLANG	0.616***	0.604***	0.600***	0.599***	0.596***	0.591***
	(0.0527)	(0.0517)	(0.0521)	(0.0528)	(0.0522)	(0.0522)
INTERNET	0.00224	0.00282**	0.00261*	0.00259*	0.00300**	0.00257*
	(0.00140)	(0.00139)	(0.00140)	(0.00141)	(0.00142)	(0.00140)
EU	0.0954**	0.0766*	0.0753*			
	(0.0440)	(0.0439)	(0.0439)			
EU_12				0.0427		
				(0.0675)		
EU_15					0.0845**	
					(0.0410)	
EU_25						-0.0525
						(0.0451)
EXPORT_BIL	0.144***	0.144***	0.144***	0.145***	0.145***	0.146***
	(0.0118)	(0.0119)	(0.0119)	(0.0119)	(0.0119)	(0.0119)
MULTI_PAT_INV_CTRYi	0.300***	0.255***	0.253***	0.252***	0.251***	0.252***
	(0.0310)	(0.0311)	(0.0310)	(0.0310)	(0.0310)	(0.0311)
MULTI_PAT_INV_CTRYj	0.246***	0.217***	0.214***	0.212***	0.216***	0.212***
	(0.0301)	(0.0300)	(0.0299)	(0.0299)	(0.0299)	(0.0299)
R&D_INT_CTRYi	0.117	0.116	0.117	0.142	0.131	0.140
	(0.111)	(0.111)	(0.111)	(0.110)	(0.110)	(0.110)
R&D_INT_CTRYj	0.0273	0.0490	0.0311	0.0570	0.0485	0.0551
	(0.0963)	(0.0961)	(0.0961)	(0.0956)	(0.0958)	(0.0956)
Country$_i$ FE	yes***	yes***	yes***	yes***	yes***	yes***
Country$_j$ FE	yes***	yes***	yes***	yes***	yes***	yes***
Industry FE	yes***	yes***	yes***	yes***	yes***	yes***
Year FE	yes***	yes***	yes***	yes***	yes***	yes***
Pseudo LL	-19411	-19355	-19369	-19370	-19369	-19370
Observations	87,624	87,409	87,409	87,409	87,409	87,409

Notes: Robust standard errors in parentheses; ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. The rows "country$_i$ FE", "country$_j$ FE", "industry FE" and "year FE" report the significance levels of the joint effect of these fixed effects.

Table 3 shows additional results about the relationship between bilateral economic flows and the collaboration in innovation. In addition to bilateral export flows presented in Table 1, three variables are taken into account: the bilateral import flows (IMPORT_BIL), the inflows of Foreign Direct Investment (FDI_IN) and the outflows of FDI (FDI_OUT). While the bilateral trade information is expressed by couples of countries at the industry level, the bilateral FDI is available only by partner country[28]. All these variables have a significant and positive impact on the intensity of collaboration. The stronger the commercial relationships between countries, the stronger are their collaborative innovation efforts. This finding concerns both the bilateral trade of goods and the cross-border investment decisions. The dual positive impact of in- and out-flows suggests that the commercial proximity between countries matters more than the direction of those economic flows. In other words, the international collaborative innovation does not seem to be strongly market-driven (or driven by the desire to adapt the innovative product to the local economy) but more related to the commercial ties between countries.

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[28] The sample of observations is smaller for FDI series than for trade ones due to data limited availability.

Table 3: Robustness results for H3 – economic ties

	(1)	(2)	(3)	(4)
Dependent variable	$RCIc^{II}$	$RCIc^{II}$	$RCIc^{II}$	$RCIc^{II}$
TP_PAT_II	0.927***	0.916***	0.807***	0.900***
	(0.0704)	(0.0703)	(0.0811)	(0.0825)
NOCOM_PAT_II	0.309***	0.308***	0.281***	0.313***
	(0.0342)	(0.0344)	(0.0388)	(0.0375)
DIST	-0.205***	-0.187***	-0.235***	-0.280***
	(0.0323)	(0.0323)	(0.0305)	(0.0307)
BORDER	0.611***	0.603***	0.644***	0.592***
	(0.0625)	(0.0625)	(0.0646)	(0.0638)
COMLANG	0.600***	0.589***	0.652***	0.618***
	(0.0521)	(0.0522)	(0.0570)	(0.0584)
INTERNET	0.00261*	0.00238*	0.00250	0.00114
	(0.00140)	(0.00140)	(0.00160)	(0.00156)
EU	0.0753*	0.0531	0.0891*	0.0597
	(0.0439)	(0.0439)	(0.0498)	(0.0475)
EXPORT_BIL	0.144***			
	(0.0119)			
IMPORT_BIL		0.168***		
		(0.0124)		
FDI_OUT			0.0964***	
			(0.00958)	
FDI_IN				0.0932***
				(0.00860)
MULTI_PAT_INV_CTRYi	0.253***	0.269***	0.300***	0.262***
	(0.0310)	(0.0318)	(0.0402)	(0.0356)
MULTI_PAT_INV_CTRYj	0.214***	0.172***	0.255***	0.224***
	(0.0299)	(0.0298)	(0.0329)	(0.0359)
R&D_INT_CTRYi	0.117	0.118	0.0794	0.0503
	(0.111)	(0.113)	(0.156)	(0.136)
R&D_INT_CTRYj	0.0311	0.0379	-0.0913	-0.0488
	(0.0961)	(0.0981)	(0.109)	(0.112)
Country$_i$ FE	yes***	yes***	yes***	yes***
Country$_j$ FE	yes***	yes***	yes***	yes***
Industry FE	yes***	yes***	yes***	yes***
Year FE	yes***	yes***	yes***	yes***
Pseudo LL	-19369	-19262	-12996	-13250
Observations	87,409	87,924	49,744	52,702

Notes: Robust standard errors in parentheses; ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. The rows "country$_i$ FE", "country$_j$ FE", "industry FE" and "year FE" report the significance levels of the joint effect of these fixed effects.

6 Conclusions

Using aggregate patent-based indicators, this paper provides new evidence about the collaborative innovative activities performed across borders. The descriptive analysis of patterns in globalization of innovation – in terms of international co-invention – illustrates that the overall growth in internationalization of innovation is due to the increase in the number of international innovative countries and the rise in the average intensity of collaboration. The amplitude of both dimensions has doubled between 1988 and 2005.

A panel dataset – per couple of countries across industrial sectors and over time – is used to investigate the impact of the technological distance on the intensity of collaborative innovation. First, the empirical results confirm that technological distance remains a key determinant explaining bilateral innovative collaborations between countries. Second, this paper claims that the two main arguments related to technological distance – 'similarity versus diversity' – can be reconciled by taking an industry approach. Indeed, the empirical findings show that the impact of technological distance is twofold at the industry level. On the one hand, low technological distance within the industry – similarity of industry-specific knowledge – reflects the presence of common industrial knowledge which facilitates collaborative interactions between partners. On the other hand, high technological distance outside the scope of the industry – diversity of non-industry-specific knowledge – stimulates international collaborations in order to acquire novel competences and experiences.

This dual impact of technological distance is examined in two main steps. First, the significant and positive impact of technological proximity between countries across technological fields of the industry reflects the importance of the relative absorptive capacity. Having strong technological capabilities (revealing high absolute absorptive capacity) is not enough to participate in international co-invention projects as the results for intensity of R&D expenditures indicate. It matters more to have industry-specific technological knowledge which suits to the partner's one. Second, the importance of diversity of the overall technological competences is also undeniable. The intensity of collaboration is higher not only for country-industry pairs which present more multidisciplinary patenting activities – across a larger number of different technologies – but also if these activities are non-overlapping within the couple of countries. In addition to the curvilinear relationship related to technological proximity, the differences in non-industry-specific technological knowledge between partner economies are positively related to the intensity of their innovative collaboration. This result is in line with firm-level evidence which has shown that collaboration is largely perceived as a mean to find complementary knowledge.

The additional effects of non-technological distance factors are also confirmed. The spatial proximity and the ease of communication between countries (common language, use of internet) positively impact their collaborations in innovation. At the institutional level, the positive effect of the joint membership to the EU suggests a stronger knowledge-based integration between the 15 "old" member states, that seems to be mainly due to their institutional similiraties (as shown by the results based on the worldwide governance indicators). Concerning the relationship between internationalization of innovation and other economic cross-border flows, the robustness checks highlight that the commercial proximity matters more than the direction of trade or investment flows in order to explain globalization of innovation. The bilateral patterns in innovation seem thus to be more related to the presence of commercial ties than to market-driven motives.

Policy recommendations may be drawn from these empirical findings. In particular, governments that would like to take part in the globalization of innovation should put in place policies that stimulate both strong specialized technological knowledge and multidisciplinary competences. Policy makers should take in consideration not only the development of strong industrial hubs, but also the diversity of knowledge-based expertise. In other words, this paper enlarges at country-industry level the statement made by Cohen and Levinthal (1990) which said that the ideal structural organization of firms "should reflect only partially overlapping knowledge complemented by non-overlapping diverse knowledge" (Cohen and Levinthal, 1990, p 134).

This paper calls also for further research on the impact of distance in international collaborative innovation. The measurement of technological distance could be improved. In particular, other indicators of the multidisciplinary of technological knowledge and its non-overlapping between countries at the industry level would help to confirm the robustness of the empirical findings. While this paper looks into the patent information across IPC classes, it would be interesting to integrate the distance between each technological field. In addition to illustrate clusters of technological fields, this will enhance the accuracy of technological proximity, multidisciplinarity and diversity patent-based indicators used in this analysis. The challenge is that multiple IPC classes may be associated with patent applications and distance between these classes is much more than a simple dyadic relationship. Furthermore, larger definitions of knowledge-based distance can be considered. In addition to technology-relatedness measures based on patent information, other type of knowledge-relatedness (such as the scientific similarities and complementarities, the commonality of management practices or of absorptive capacity routines) may also explain the collaborative patterns in the international production of innovation.

Appendix Tables

Table A.1: Description of variables

Variables		Description
Dependent Variable *[i,j,k,t]*		
$RCIc^{II}$		Index of Revealed Collaboration Intensity defined by equation (4)
Explanatory variables		
H1	TP_PAT_II *[i,j,k,t]*	Indicator of Technological Proximity described in equation (6)
	TP_PAT_II_SQ *[i,j,k,t]*	Squared value of Technological Proximity variable defined above
H2	NOCOM_PAT_II *[i,j,k,t]*	Number of distinct 4-digit IPC classes (in log) – outside the scope of industry *k* defined by the concordance table of Scmoch et al. (2003) – which are not in common between patents of industry *k* in country *i* and patents of industry *k* in country *j* at priority year *t*
H3	DIST *[i,j]*	Geographical distance (in log)
	BORDER *[i,j]*	Dummy variable equals to 1 if both countries are contingent
	COMLANG *[i,j]*	Dummy variable equals to 1 if both countries share a common official language
	INTERNET*[i,j,t]*	Min (between both countries) of the percentage of individuals using the Internet
	EU *[i,j,t]*	Dummy variable equals to 1 if both countries are members of the EU at year *t*
	EU_12 *[i,j,t]*	Dummy variable equals to 1 if both countries were members of the EU in 1986
	EU_15 *[i,j,t]*	Dummy variable equals to 1 if both countries were members of the EU in 1995
	EU_25 *[i,j,t]*	Dummy variable equals to 1 if both countries were members of the EU in 2004
	WGI_RL *[i,j,t]*	Absolute value of the country scores difference of the world governance indicator – rule of law
	WGI_VA *[i,j,t]*	Absolute value of the country scores difference of the world governance indicator – voice and accountability
	WGI_PV *[i,j,t]*	Absolute value of the country scores difference of the world governance indicator – political stability and absence of violence
	WGI_GE *[i,j,t]*	Absolute value of the country scores difference of the world governance indicator – governement effectiveness
	WGI_RQ *[i,j,t]*	Absolute value of the country scores difference of the world governance indicator – regulatory quality
	WGI_CC *[i,j,t]*	Absolute value of the country scores difference of the world governance indicator – control of corruption
	EXPORT_BIL *[i,j,k,t]*	Export of goods (in log)
	IMPORT_BIL *[i,j,k,t]*	Import of goods (in log)
	FDI_OUT *[i,j,t]*	FDI flows by partner country (in log), outward
	FDI_IN *[i,j,t]*	FDI flows by partner country (in log), inward
MULTI_PAT_INV_CTRYi *[i,k,t]*		Number of distinct 4-digit IPC classes (in log) – outside the scope of industry *k* defined by the concordance table of Schmoch et al. (2003) – listed on patents of industry *k* in country *i* or country *j* at priority year *t*
MULTI_PAT_INV_CTRYj *[j,k,t]*		
R&D_INT_CTRYi *[i,t]*		log of the ratio of R&D expenditures divided by the GDP of country *i* at year *t*
R&D_INT_CTRYj *[j,t]*		log of the ratio of R&D expenditures divided by the GDP of country *j* at year *t*

Sources: own calculation based on PATSTAT April 2009 database for patent-based variables and for EU; CEPII database for DIST, BORDER, COMLANG; world telecommunication/ICT indicators database of the International Telecommunications Union for INTERNET; OECD STAN Bilateral trade for EXPORT_BIL, IMPORT_BIL; OECD International direct investment database for FDI_IN, FDI_OUT; World Bank worldwide governance indicators for WGI variables; OECD Main Science and Technology Indicators 2011 for R&D_INT.

Table A.2: Descriptive statistics

Variables		**Obs.**	**Mean**	**SE**	**Min**	**Max**
Dependent Variable *[i,j,k,t]*						
$RCIc^{II}$		87409	0.105	0.223	0	0.997
Explanatory variables						
H1	TP_PAT_II *[i,j,k,t]*	87409	0.566	0.286	0	1
	TP_PAT_II_SQ *[i,j,k,t]*	87409	0.402	0.302	0	1
H2	NOCOM_PAT_II *[i,j,k,t]*	87409	3.832	1.104	0	5.869
H3	DIST *[i,j]*	87409	7.947	1.229	4.088	9.883
	BORDER *[i,j]*	87409	0.093	0.291	0	1
	COMLANG *[i,j]*	87409	0.112	0.316	0	1
	INTERNET*[i,j,t]*	87409	16.983	20.393	0	83.880
	EU *[i,j,t]*	87409	0.286	0.452	0	1
	EU_12 *[i,j,t]*	87409	0.185	0.388	0	1
	EU_15 *[i,j,t]*	87409	0.202	0.401	0	1
	EU_25 *[i,j,t]*	87409	0.058	0.233	0	1
	WGI_RL *[i,j,t]*	57148	0.533	0.473	0.0007	2.455
	WGI_VA *[i,j,t]*	57148	0.353	0.312	0.0001	1.757
	WGI_PV *[i,j,t]*	57148	0.428	0.376	0	2.129
	WGI_GE *[i,j,t]*	57148	0.586	0.488	0.0003	2.176
	WGI_RQ *[i,j,t]*	57148	0.436	0.327	0.0004	1.644
	WGI_CC *[i,j,t]*	57148	0.788	0.609	0.0005	2.719
	EXPORT_BIL *[i,j,k,t]*	87409	16.670	2.818	0	24.601
	IMPORT_BIL *[i,j,k,t]*	87924	16.780	2.654	1.099	24.913
	FDI_OUT *[i,j,t]*	49744	4.871	2.663	-6.908	12.056
	FDI_IN *[i,j,t]*	52702	4.536	2.678	-6.215	11.595
MULTI_PAT_INV_CTRYi *[i,k,t]*		87409	3.406	1.525	0	6.207
MULTI_PAT_INV_CTRYj *[j,k,t]*		87409	3.534	1.318	0	6.207
R&D_INT_CTRYi *[i,t]*		87409	0.425	0.620	-1.606	1.418
R&D_INT_CTRYj *[j,t]*		87409	0.498	0.461	-1.606	1.418

Notes: The number of observations per variable corresponds to the largest sample used in the main specifications of the empirical model (see column (3) of Table 1). For few variables introduced in the robustness checks, the data availability is different. The patent-based variables concern EPO patent count indicator. The descriptive statistics concerning PF patent count indicator are available upon request.

Table A.3: Correlation matrix

		[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]	[21]	[22]	[23]	[24]	[25]
[1]	TP_PAT_II	1																								
[2]	TP_PAT_II_SQ	0.97	1																							
[3]	NOCOM_PAT_II	0.15	0.09	1																						
[4]	DIST	0.03	0.02	0.10	1																					
[5]	BORDER	0.08	0.09	0.04	-0.50	1																				
[6]	COMLANG	0.11	0.12	0.06	-0.12	0.38	1																			
[7]	INTERNET	0.09	0.09	0.01	0.02	0.01	0.12	1																		
[8]	EXPORT_BIL	0.31	0.29	0.40	-0.27	0.34	0.18	0.04	1																	
[9]	IMPORT_BIL	0.30	0.29	0.41	-0.28	0.33	0.14	0.02	0.74	1																
[10]	FDI_OUT	0.35	0.34	0.23	-0.13	0.22	0.28	0.23	0.51	0.46	1															
[11]	FDI_IN	0.28	0.28	0.22	-0.27	0.24	0.27	0.22	0.49	0.51	0.59	1														
[12]	EU	0.03	0.03	-0.07	-0.56	0.16	-0.09	-0.06	0.20	0.18	0.15	0.13	1													
[13]	EU_12	0.06	0.07	0.01	-0.44	0.17	-0.09	-0.11	0.25	0.23	0.24	0.22	0.67	1												
[14]	EU_15	0.09	0.08	-0.03	-0.52	0.16	-0.07	-0.09	0.21	0.19	0.22	0.15	0.93	0.72	1											
[15]	EU_25	-0.05	-0.04	-0.10	-0.24	0.05	-0.06	0.26	0.04	0.03	0.00	0.06	0.42	0.15	0.21	1										
[16]	WGI_RL	-0.17	-0.17	-0.06	0.00	-0.01	-0.20	-0.15	-0.11	-0.12	-0.35	-0.22	-0.02	-0.06	-0.09	0.13	1									
[17]	WGI_VA	-0.08	-0.08	0.00	0.24	-0.11	-0.21	-0.09	-0.07	-0.07	-0.20	-0.22	-0.14	-0.12	-0.19	0.03	0.68	1								
[18]	WGI_PV	-0.04	-0.04	-0.01	0.13	-0.11	-0.12	0.06	-0.04	-0.04	-0.05	-0.03	-0.08	-0.05	-0.08	0.02	0.38	0.45	1							
[19]	WGI_GE	-0.17	-0.17	-0.04	0.12	-0.08	-0.26	-0.22	-0.13	-0.11	-0.39	-0.25	-0.12	-0.06	-0.17	0.06	0.82	0.70	0.29	1						
[20]	WGI_RQ	-0.09	-0.09	-0.01	0.14	-0.10	-0.19	-0.22	-0.08	-0.06	-0.18	-0.15	-0.10	-0.02	-0.11	-0.07	0.65	0.67	0.29	0.72	1					
[21]	WGI_CC	-0.13	-0.13	-0.03	0.09	-0.09	-0.23	-0.23	-0.10	-0.10	-0.35	-0.24	-0.07	-0.05	-0.12	0.04	0.87	0.71	0.34	0.84	0.71	1				
[22]	MULTI_PAT_INV_CTRYi	0.30	0.25	0.65	0.26	0.03	0.10	0.01	0.44	0.40	0.40	0.18	-0.19	-0.12	-0.13	-0.17	-0.14	0.06	0.05	-0.08	0.05	-0.07	1			
[23]	MULTI_PAT_INV_CTRYj	0.15	0.11	0.63	0.06	-0.01	-0.03	0.04	0.29	0.33	0.04	0.19	-0.03	0.05	-0.01	-0.04	-0.07	-0.01	-0.04	-0.03	0.00	-0.01	0.23	1		
[24]	R&D_INT_CTRYi	0.29	0.27	0.23	0.22	0.02	0.13	0.25	0.23	0.19	0.53	0.21	-0.16	-0.21	-0.07	-0.19	-0.38	-0.02	0.00	-0.34	-0.11	-0.29	0.52	-0.04	1	
[25]	R&D_INT_CTRYj	0.16	0.16	0.10	-0.10	0.05	0.08	0.31	0.04	0.12	0.03	0.30	-0.04	-0.14	-0.01	-0.02	-0.07	-0.05	-0.06	-0.08	-0.04	-0.03	-0.05	0.31	0.01	1

Notes: The patent-based variables concern EPO patent count indicator. The correlations concerning PF patent count indicator are available upon request.

Table A.4: Main estimation results for Priority Filings

	(1)	(2)	(3)	(4)
Dependent variable	$RCIc^{II}$	$RCIc^{II}$	$RCIc^{II}$	$RCIc^{II}$
TP_PAT_II [H1]	0.655***		0.717***	0.605***
	(0.0932)		(0.0939)	(0.105)
NOCOM_PAT_II [H2]		0.141***	0.171***	0.190***
		(0.0370)	(0.0369)	(0.0401)
DIST [H3]	-0.289***	-0.296***	-0.289***	-0.309***
	(0.0384)	(0.0391)	(0.0383)	(0.0410)
BORDER [H3]	0.723***	0.732***	0.722***	0.725***
	(0.0707)	(0.0713)	(0.0704)	(0.0783)
COMLANG [H3]	0.550***	0.567***	0.551***	0.549***
	(0.0684)	(0.0682)	(0.0678)	(0.0787)
INTERNET [H3]	-0.000942	-0.00121	-0.000802	-0.00145
	(0.00150)	(0.00151)	(0.00151)	(0.00187)
EU [H3]	0.171***	0.158***	0.159***	0.142**
	(0.0484)	(0.0489)	(0.0487)	(0.0639)
WGI_RL [H3]				-0.182**
				(0.0717)
EXPORT_BIL [H3]	0.137***	0.140***	0.142***	0.128***
	(0.0128)	(0.0129)	(0.0129)	(0.0145)
MULTI_PAT_INV_CTRYi	0.434***	0.415***	0.396***	0.369***
	(0.0349)	(0.0355)	(0.0357)	(0.0398)
MULTI_PAT_INV_CTRYj	0.328***	0.325***	0.293***	0.268***
	(0.0366)	(0.0372)	(0.0371)	(0.0430)
R&D_INT_CTRYi	0.0824	0.136	0.103	-0.0142
	(0.118)	(0.118)	(0.117)	(0.194)
R&D_INT_CTRYj	0.0467	0.102	0.0835	0.207
	(0.110)	(0.110)	(0.109)	(0.193)
Country$_i$ FE	yes***	yes***	yes***	yes***
Country$_j$ FE	yes***	yes***	yes***	yes***
Industry FE	yes***	yes***	yes***	yes***
Year FE	yes***	yes***	yes***	yes***
Pseudo LL	-16414	-16428	-16401	-11153
Observations	77,943	77,928	77,928	51,429

Notes: Robust standard errors in parentheses; ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. The rows "country$_i$ FE", "country$_j$ FE", "industry FE" and "year FE" report the significance levels of the joint effect of these fixed effects.

Table A.5: Estimation results for all world governance indicators (WGI)

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable	$RCIc^{II}$	$RCIc^{II}$	$RCIc^{II}$	$RCIc^{II}$	$RCIc^{II}$	$RCIc^{II}$
TP_PAT_II	0.878***	0.882***	0.886***	0.887***	0.888***	0.881***
	(0.0817)	(0.0815)	(0.0818)	(0.0816)	(0.0816)	(0.0816)
NOCOM_PAT_II	0.371***	0.357***	0.357***	0.358***	0.353***	0.362***
	(0.0390)	(0.0394)	(0.0399)	(0.0391)	(0.0397)	(0.0388)
DIST	-0.224***	-0.216***	-0.225***	-0.222***	-0.225***	-0.224***
	(0.0362)	(0.0358)	(0.0366)	(0.0364)	(0.0361)	(0.0360)
BORDER	0.605***	0.601***	0.597***	0.605***	0.605***	0.599***
	(0.0695)	(0.0694)	(0.0700)	(0.0703)	(0.0698)	(0.0696)
COMLANG	0.540***	0.547***	0.552***	0.544***	0.538***	0.543***
	(0.0559)	(0.0560)	(0.0560)	(0.0562)	(0.0564)	(0.0559)
INTERNET	0.000997	0.00220	0.00358**	0.00313*	0.00261	0.00145
	(0.00176)	(0.00171)	(0.00170)	(0.00170)	(0.00176)	(0.00177)
EU	0.0461	0.0523	0.0428	0.0388	0.0383	0.0386
	(0.0605)	(0.0609)	(0.0606)	(0.0605)	(0.0607)	(0.0605)
WGI_RL	-0.245***					
	(0.0687)					
WGI_VA		-0.281***				
		(0.0953)				
WGI_PV			-0.138***			
			(0.0496)			
WGI_GE				-0.0684		
				(0.0542)		
WGI_RQ					-0.106*	
					(0.0616)	
WGI_CC						-0.123***
						(0.0413)
EXPORT_BIL	0.132***	0.135***	0.133***	0.135***	0.135***	0.133***
	(0.0130)	(0.0131)	(0.0132)	(0.0131)	(0.0131)	(0.0130)
MULTI_PAT_INV_CTRYi	0.253***	0.257***	0.254***	0.258***	0.259***	0.256***
	(0.0349)	(0.0348)	(0.0349)	(0.0349)	(0.0349)	(0.0349)
MULTI_PAT_INV_CTRYj	0.204***	0.206***	0.201***	0.206***	0.207***	0.206***
	(0.0376)	(0.0376)	(0.0377)	(0.0376)	(0.0376)	(0.0375)
R&D_INT_CTRYi	-0.0705	-0.0222	-0.118	-0.0683	-0.0547	-0.0751
	(0.194)	(0.195)	(0.194)	(0.192)	(0.193)	(0.193)
R&D_INT_CTRYj	0.352**	0.362**	0.331*	0.359**	0.363**	0.360**
	(0.176)	(0.176)	(0.176)	(0.176)	(0.176)	(0.176)
Country$_i$ FE	yes***	yes***	yes***	yes***	yes***	yes***
Country$_j$ FE	yes***	yes***	yes***	yes***	yes***	yes***
Industry FE	yes***	yes***	yes***	yes***	yes***	yes***
Year FE	yes	yes	yes	yes	yes	yes
Pseudo LL	-13039	-13041	-13042	-13044	-13044	-13040
Observations	57,148	57,148	57,148	57,148	57,148	57,148

Notes: Robust standard errors in parentheses; ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. The rows "country$_i$ FE", "country$_j$ FE", "industry FE" and "year FE" report the significance levels of the joint effect of these fixed effects.

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