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Trade Patterns and International Technology Spillovers: Theory and Evidence from Patent Citations*

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Abstract

In this paper, we develop a two-country model of monopolistic competition with quality differentiation by extending the model of Melitz and Ottaviano (2008) and examine the relationship between the bilateral trade structure and international technology spillovers. We show that bilateral trade patterns and the extent of technology spillovers will change, depending on the technology gap between two countries. We then test predictions of the model by using bilateral trade data among 44 countries and patent citation data at the U.S., European, and Japanese Patent Offices. We use patent citations as a proxy for spillovers of technological knowledge. Trade patterns are categorized into three types: one-way trade (OWT), horizontal intra-industry trade (HIIT), and vertical intra-industry trade (VIIT). Each of OWT and VIIT is further divided into two subcategories, based on the direction of trade. We find that intra-industry trade plays a significant role in technology spillovers. In particular, HIIT is associated with larger technology spillovers than VIIT, which confirms the predictions of the model.

Keywords: technology spillovers; patent citations; intra-industry trade; firm heterogeneity.

JEL classification: F12; O31; O33.

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1 Introduction

The issue of international technology diffusion has been attracted great attention in economics.[1] This is because international technology diffusion is an important factor to determine the speed at which the world's technology frontier expands. It also contributes to income convergence across countries.

For example, Eaton and Kortum (1996) estimate innovation and technology diffusion among 19 OECD countries to test predictions from a quality ladders model of endogenous growth with patenting. They find that each OECD country other than the United States (U.S.) obtains more than half of its productivity growth from technological knowledge originated abroad. They also find that more than half of the growth in every OECD country is derived from innovation in the U.S., Japan, and Germany. Eaton and Kortum (1999) fit a similar model to research employment, productivity, and international patenting among the five leading research economies, i.e., the U.S., Japan, Germany, the United Kingdom (U.K.), and France. They find that research performed abroad is about two-thirds as potent as domestic research. In particular, technological knowledge from Japan and Germany diffuses most rapidly, while France and Germany are the quickest to exploit knowledge. They also show that the U.S. and Japan together contribute to over 65 percent of the growth in each of the five countries.

Previous studies have identified international trade as a major channel of international technology spillovers.[2] Coe and Helpman (1995) examine R&D spillovers among OECD countries and find large spillover effects from foreign R&D capital stocks to domestic productivity that is measured by total factor productivity (TFP). They also show that countries exhibit higher productivity levels by importing goods from countries with high levels of technological knowledge, which supports the existence of trade-related international R&D spillovers. However, Keller (1998) provides a finding that casts doubt on Coe and Helpman's result by employing a Monte-Carlo-based robustness test. He finds that estimated international R&D spillovers among randomly matched trade partners turn out to be large (and even larger than those among actual trade partners). Xu and Wang (1999) estimate that about half of the return on R&D investment in 7 OECD countries spilled over to other OECD countries and that trade in capital goods is a significant channel of R&D spillovers. More recent study by Acharya and Keller (2009) find that the diffusion of technological knowledge is strongly varying across country-pairs. They show that imports are crucial for technology diffusion from Germany, France, and the U.K., while non-trade channels are relatively more important for the U.S., Japan, and Canada.

[1] See Keller (2004) for a survey of the literature.

[2] Trade works as a channel of technology spillover because, for example, firms can obtain information on advanced technology by reverse engineering of imported goods. International trade also provides channels of cross-border communication that facilitates learning of production and organizational methods and market conditions (Grossman and Helpman, 1991). Another major channel is foreign direct investment (FDI). Technological spillovers through FDI are empirically confirmed by a number of studies (Branstetter, 2006; Haskel, Pereira, and Slaughter, 2007; Javorcik, 2004; Keller and Yeaple, 2009), while some studies do not find significant spillovers (Aitken and Harrison, 1999; Haddad and Harrison, 1993).

Although a number of studies have investigated technological knowledge spillovers through trade, none of the existing studies have paid attention to the relationship between bilateral trade patterns and technology spillovers. However, it is expected that technology spillovers through imports will differ, depending on whether a country exports products with similar quality or with different quality in the same industry as imports or the country does not export products in the same industry. Therefore, in this paper we examine the relationship between the bilateral trade structure and technology spillovers from both theoretical and empirical points of view. Here, by the term "technology spillovers" we refer to "the process by which one inventor learns from the research outcomes of others' research projects and is able to enhance her own research productivity with this knowledge without fully compensating the other inventors for the value of this learning" (Branstetter, 2006: 327–328). In this sense, we distinguish technology spillovers from imitation or technology adoption.

Empirical studies on intra-industry trade categorize bilateral trade flows into one way trade (OWT), or inter-industry trade, and two-way trade, or intra-industry trade (IIT). IIT is further decomposed into horizontal intra-industry trade (HIIT) and vertical intra-industry trade (VIIT) (e.g., Fontagné and Freudenberg, 1997; Greenaway, Hine, and Milner, 1995; Fukao, Ishido, and Ito, 2003). The difference between HIIT and VIIT reflects the differences in quality of products in the same category traded between two countries. In HIIT, horizontally differentiated products (i.e., products with similar quality but different varieties) are traded, whereas vertically differentiated products (i.e., products with different qualities) are traded in VIIT.[3] On data HIIT and VIIT can be distinguished by using unit values (i.e., total value of import or export in one product category divided by quantity of import or export in that product category) under the assumption that unit values are increasing in product quality.

The theoretical literature on intra-industry trade has been separated into two branches for a long period. As is well known, trade models with monopolistic competition could explain HIIT (e.g., Krugman, 1979, 1980; Helpman, 1981; Eaton and Kierzkowski, 1984). However, in these models, product varieties are symmetric and not differentiated in quality. Trade models with vertical differentiation, on the other hand, could explain VIIT but could not explain HIIT (e.g., Falvey, 1981; Shaked and Sutton, 1984; Falvey and Kierzkowski, 1987; Flam and Helpman, 1987; Lambertini, 1997; Motta, Thisse, and Cabrales, 1997; Herguera and Lutz, 1998). Given the fact that HIIT and VIIT arise in continuous phenomena, this divergence in the theory would not be acceptable. More recently, a number of studies have attempted to introduce quality differentiation into the monopolistically competitive trade model. Some studies use a quality-augmented type of Dixit-Stiglitz demand specification in the framework

[3]Note that in the literature the terms of HIIT and VIIT are sometimes used in different meanings. In an alternative definition, HIIT means trade of final goods in the same industry across countries, while VIIT involves trade of intermediate goods with final goods in the same industry (Yomogida, 2004). Since we do not consider the distinction between intermediate goods and final goods in this paper, this alternative definition of HIIT and VIIT is not applicable.

of Melitz (2003)[4] with the assumption that higher quality is associated with higher marginal cost (Baldwin and Harrigan, 2007; Gervais, 2008; Helble and Okubo, 2008; Johnson, 2010; Kugler and Verhoogen, 2010; Mandel, 2010).[5] On the other hand, Antoniades (2008) introduces quality differentiation into the quasi-linear utility with a quadratic subutility specification in the framework of Melitz and Ottaviano (2008) and considers endogenous quality upgrading by heterogeneous firms. He shows that firms with higher productivity choose higher qualities and charge higher prices. However, his model faces some limitations when extended to the case of two-country trade. In this paper, we also introduce quality differentiation into the framework of Melitz and Ottaviano (2008). We employ a different approach from Antoniades (2008). We assume that firms randomly draw their product quality so that firms with identical productivity are heterogeneous in product quality. This reflects the stochastic nature of product R&D. This formulation of quality differentiation turns out to be tractable. Then, we show that our model can explain OWT, HIIT, and VIIT in one unified framework. Using this framework, we examine how international technology spillovers are associated with bilateral trade structure.

For empirical analysis of international technology spillovers, we use data on patent citations as a proxy for spillovers of technological knowledge. There is a relatively small but growing literature on empirical analysis of knowledge flow based on patent citations (e.g., Jaffe, Trajtenberg, and Henderson, 1993; Jaffe and Trajtenberg, 1999; Hu and Jaffe, 2003; MacGarvie, 2006; Mancusi, 2008; Haruna, Jinji, and Zhang, 2010).[6] In the literature, patent citation data are used as a direct measure of technology spillovers (Hall, Jaffe, and Trajtenberg, 2001). Hu and Jaffe (2003) use data on patents granted in the U.S. and examine patent citations by inventors residing in Korea, Japan, Taiwan, and the U.S. to infer the pattern of technological knowledge flows from the U.S. and Japan to Korea and Taiwan. They find that Korean patents are much more likely to cite Japanese patents than U.S. patents, while Taiwanese patents cite both Japanese and U.S. patents evenly. Mancusi (2008) estimates technological knowledge diffusion within and across sectors and countries by using European patents and citations for 14 OECD countries. She finds that international knowledge diffusion is effective in increasing innovative productivity in technologically laggard countries, while technological leaders (the U.S., Japan, and Germany) are a source rather than a destination of knowledge flows. Using French firms' patent citations and firm-level trade data, MacGarvie (2006) finds that the patents of importing firms

[4]Originally, Melitz (2003) mentions that differences in productivity may be interpreted as differences in product quality at equal cost.

[5]Sugita (2010) also uses a quality-augmented type of Dixit-Stiglitz demand and considers matching between intermediate good producers and final good producers. He shows that improvements in matching due to trade liberalization result in improvements in product quality.

[6]However, Jaffe, Trajtenberg, and Henderson (1993) admit that patent citation is a coarse and noisy measure of knowledge flow, because not all inventions are patented and not all knowledge flows can be captured by patent citations. Based on a survey of inventors, Jaffe, Trajtenberg, and Fogarty (2000) suggest the validity of patent citations as indicators of technology spillovers, despite the presence of noise.

are significantly more likely to be influenced by technology in the exporting country than are the patents of firms that do not import. In contrast, she finds no significant evidence of exporting firms' citing more patents from their destination countries. Moreover, in our previous work (Haruna, Jinji, and Zhang, 2010), we investigate whether the trade structure plays an important role as a channel of technological knowledge diffusion between Asian economies (Korea, Taiwan, China, and India) and G7 countries including the U.S. and Japan. In that paper, we use a modified version of the Balassa's index of Revealed Comparative Advantage (RCA), which represents the share of country i in sector j relative to the country's export (or import) share for all sectors. Then, we find that trade specialization, especially import specialization, has a direct effect on knowledge diffusion.

In this paper, we take our study one step further and investigate the relationship between bilateral trade patterns and international knowledge flow in more detail. In order to accomplish this task, we develop a two-country model of monopolistic competition with quality differentiation, in which inter- and (horizontal and vertical) intra-industry trade patterns endogenously arise, depending on the conditions of trading countries. Our model is an extension of the model developed by Melitz and Ottaviano (2008). In our model, firms are heterogeneous in product quality rather than in productivity. Then, after deriving hypotheses from the model, we test them by using data on bilateral trade among 44 countries and patent citations at the U.S., European, and Japanese Patent Offices.

The main results in this paper are as follows. Our model predicts that the bilateral trade pattern is HIIT when the two countries have access to a similar level of technology, while it is VIIT when there is technological difference between them. Moreover, if the technological difference is sufficiently large, the bilateral trade pattern becomes OWT. Our model also predicts that technology spillovers are highest when the bilateral trade pattern is HIIT, followed by VIIT and OWT. Our estimation results basically confirm those predictions of the model. We find that an increase in the share of intra-industry trade in the bilateral trade has a positive effect on the number of patent citations between the two countries. HIIT has a larger effect than VIIT. On the other hand, the effects of OWT on the number of citations are much weaker than those of IIT.

The remainder of the paper is organized in the following way. Section 2 sets up a closed-economy model of monopolistic competition with quality differentiation. Section 3 extends the model to the case of two-country trade and derives testable implications from the theoretical model. Section 4 conducts an empirical analysis. Section 5 concludes this paper.

2 The Basic Model

In this section, we describe the basic structure of the model in a closed economy. Then, we extend the basic model to the case of two-country trade in the next section.

Consider an economy with two sectors: a homogenous agricultural sector and a differentiated manufacturing sector.[7]

2.1 Demand

We introduce quality differentiation into the quasi-linear (instantaneous) utility with a quadratic subutility, which is developed by Ottaviano, Tabuchi, and Thisse (2002) and Melitz and Ottaviano (2008).[8] There are L consumers in the economy. Preferences are identical across consumers and defined over a continuum of differentiated varieties indexed by $i \in \Omega$ and a homogenous numeraire good. The representative consumer maximizes an additively separable intertemporal utility function of the form,

$$U = \int_0^\infty u(t) e^{-\rho t} \mathrm{d}t, \tag{1}$$

where ρ is the common subjective discount rate and $u(t)$ is the instantaneous utility given by

$$u(t) = q_{0t}^c + \int_{i\in\Omega_t} \alpha_{it} q_{it}^c \mathrm{d}i - \frac{1}{2}\gamma \int_{i\in\Omega_t} (q_{it}^c)^2 \mathrm{d}i - \frac{1}{2}\eta \left(\int_{i\in\Omega_t} q_{it}^c \mathrm{d}i \right)^2, \tag{2}$$

where q_{0t}^c and q_{it}^c are the individual consumption levels of the numeraire and variety i at time t and $\alpha_{it} > 0$ measures the product quality of variety i at time t.[9] The parameter $\gamma > 0$ measures the degree of horizontal differentiation, or the substitutability between varieties and the parameter $\eta > 0$ captures the degree of substitution between the differentiated varieties and the numeraire.

We assume that consumers have positive demands for the numeraire. The inverse demand for variety i at time t is then given by

$$p_{it} = \alpha_{it} - \gamma q_{it}^c - \eta Q_t^c, \tag{3}$$

as long as $q_{it}^c > 0$, where $Q_t^c = \int_{i\in\Omega_t} q_{it} \mathrm{d}i$ is the total consumption level over all varieties. Let $\Omega_t^* \subset \Omega_t$ be the subset of varieties that are actually consumed. Then, from Eq. (3), the market demand for variety $i \in \Omega_t^*$ can be expressed as

$$q_{it} \equiv L q_{it}^c = \frac{L}{\gamma}\alpha_{it} - \frac{\eta L N_t}{\gamma(\eta N_t + \gamma)}\bar{\alpha}_t - \frac{L}{\gamma} p_{it} + \frac{\eta L N_t}{\gamma(\eta N_t + \gamma)}\bar{p}_t, \tag{4}$$

[7] In this section, we develop a simple two-sector model. The analysis can be extended to a model with many differentiated manufacturing sectors to fit the empirical study in the next section. However, such an extension will not change qualitatively the main results in this section.

[8] The quadratic utility is also widely employed for the analysis of oligopoly. See, for example, Dixit (1979), Singh and Vives (1984), and Vives (1985). Quality-augmented versions of the quadratic utility function are developed by recent studies of Häckner (2000) and Symeonidis (2003a, 2003b).

[9] Häckner (2000) provides the same treatment of product quality in a discrete version of quadratic utility.

where N_t is the measure of consumed varieties in Ω_t^*, and $\bar{\alpha}_t = (1/N_t)\int_{i\in\Omega_t^*}\alpha_{it}\mathrm{d}i$ and $\bar{p}_t = (1/N_t)\int_{i\in\Omega_t^*}p_{it}\mathrm{d}i$ are their average quality and price, respectively.

2.2 Supply

In both sectors, labour, which is inelastically supplied in the competitive labour market, is the only production factor. One unit of labour is required to produce one unit of the homogenous agricultural (numeraire) good. Thus, the wage rate w is equal to one.

In the differentiated manufacturing sector, each firm produces a different variety. Every product variety has generations (or versions), depending on the date of development. For simplicity, we assume that each generation of a product variety loses its consumption value after one period. Thus, each firm must engage in product R&D to develop a new generation of the product variety in every period. While the cost of product R&D, f (measured in units of labour), is identical for all manufacturing firms, the outcome of product R&D, α_{it}, is stochastic.[10] Since R&D actually involves uncertainty in its outcome, it would be quite natural to model R&D as a stochastic process. To simplify the analysis, we model product R&D in the following way. Let α_{Mt} be the maximum product quality that could be obtained by the current technology in the economy, or the frontier of the current technology, at time t. Firm i randomly draws the degree of successfulness of R&D, a_{it}, from a time-invariant common (and known) probability density function $g(a)$ with support on $[\underline{a}, 1]$, where $0 < \underline{a}$. We assume that $g'(a) < 0$ so that the probability of higher degree of success is lower. Then, firm i's product quality is given by $\alpha_{it} = a_{it}\alpha_{Mt}$. This implies that the product R&D can be equivalently expressed as a random draw from a cumulative distribution function $G_t(\alpha)$ with support on $[\underline{\alpha}_t, \alpha_{Mt}]$ at time t, where $\underline{\alpha}_t = \underline{a}\alpha_{Mt}$. As is explained below, $G_t(\alpha)$ shifts as time passes. We normalize that $\alpha_{M0} = 1$. That is, let the maximum quality of the first generation of the product be one.

Each firm must decide whether to spend the cost of R&D before knowing its outcome. If a firm does not conduct R&D at time t, it does not enter the market in that period.

The market competition in the manufacturing sector takes a form of three-stage game. In stage one, all potential entrants decide whether to engage in product R&D (by paying the cost of f). In stage two, those firms conducted R&D in the previous stage know the outcome of R&D and then decide whether to stay in the market or exit. In stage three, the firms that stay in the market choose prices to maximize their own profits.[11]

A variety of the manufacturing good is produced under constant-returns-to-scale at unit labour requirement c, which is identical across all firms and independent of the product quality α_{it}.[12] Since

[10] As is evident, the cost of product R&D f serves as a fixed entry cost. Since firms pay a fixed entry cost and draw their productivity parameter in Melitz (2003) and Melitz and Ottaviano (2008), firms engage in stochastic *process* R&D in their cases. In our model, on the other hand, firms engage in stochastic *product* R&D.

[11] In the two-country model in Section 3, each firm chooses price in each market independently.

[12] We assume identical productivity across all firms to simplify the analysis. Our model can be extended to incorporate

$w = 1$ as long as the numeraire good is produced in the economy, c is the (constant) marginal cost. Since the R&D cost is sunk, firms that can cover their marginal costs survive and supply manufacturing goods to the market. All other firms exit. Surviving firms maximize their profits in each period by taking the average quality level $\bar{\alpha}$, the average price level $\bar{p}$, and the number of firms N in that period as given.[13] Given the market demand for variety i (Eq. (4)), it is easily seen that the price elasticity of demand, $\varepsilon_i \equiv -(\partial q_i/\partial p_i)(p_i/q_i)$, does not tend to infinity as N goes to infinity. Thus, the manufacturing sector is characterized by monopolistic competition.[14] Let $p_{\max}(\alpha)$ be the price at which demand for a variety with quality α is driven to 0. Eq. (4) yields that

$$p_{\max}(\alpha) \equiv \alpha - \frac{\eta N}{\eta N + \gamma}(\bar{\alpha} - \bar{p}). \tag{5}$$

Then, any $i \in \Omega^*$ satisfies $p_i \leq p_{\max}(\alpha_i)$. Given Eq. (4), firm i's gross profit is given by $\pi_i = p_i q_i - c q_i$. From the first-order condition (FOC) for profit maximization, we obtain

$$q(\alpha) = \frac{L}{\gamma}[p(\alpha) - c], \tag{6}$$

where $q(\alpha)$ and $p(\alpha)$ are profit-maximizing output and price for the product with quality α. Let α_D be the quality level for the firm that earns zero profit due to $p(\alpha_D) = p_{\max}(\alpha_D) = c$. Using Eq. (5), it yields that

$$\alpha_D = \frac{\eta N}{\eta N + \gamma}(\bar{\alpha} - \bar{p}) + c. \tag{7}$$

Then, substitute Eq. (4) into Eq. (6) and use Eq. (7) to obtain

$$p(\alpha) = \frac{\alpha - \alpha_D}{2} + c. \tag{8}$$

This implies that firms with positive demands (i.e., $\alpha_i > \alpha_D$) charge prices above the marginal cost and that the prices are increasing in product quality. Note that the average price $\bar{p}$ is given by

$$\bar{p} = \frac{\bar{\alpha} - \alpha_D}{2} + c. \tag{9}$$

Then, (7) and (9) yield the mass of surviving firms

$$N = \frac{2\gamma(\alpha_D - c)}{\eta(\bar{\alpha} - \alpha_D)}. \tag{10}$$

Note that the average product quality of surviving firms $\bar{\alpha}$ is expressed as $\bar{\alpha} = [\int_{\alpha_D}^{\alpha_M} \alpha \mathrm{d}G_t(\alpha)]/[1 - G_t(\alpha_D)]$ and that the mass of entrants is given by $N_E = N/[1 - G_t(\alpha_D)]$.

Although we do not use a specific parametrization for the distribution $G_t(\alpha)$, we assume the following condition:

heterogeneous productivity among firms, like Melitz (2003) and Melitz and Ottaviano (2008).

[13] Hereafter, we omit the time index unless necessary.

[14] In contrast to the standard model of monopolistic competition with constant elasticity of substitution (CES) demand developed by Dixit and Stiglitz (1977), the price elasticity of demand is not uniquely determined by the degree of product differentiation in this quasi-linear utility with quadratic subutility specification. Behrens and Murata (2007) and Zhelobodko, Kokovin, and Thisse (2010) also investigate implications of relaxing the CES assumption in the monopolistic competition.

Assumption 1 $0 < \mathrm{d}\bar{\alpha}/\mathrm{d}\alpha_D < 1$.

This condition means that an increase in the cut-off quality increases the average quality of products supplied in the market but the extent of the increase in the average quality is smaller than the increase in α_D. This condition restricts the shape of the distribution $G_t(\alpha)$. We need this assumption to obtain an unambiguous effect of a change in the cut-off product quality on the size of product varieties, which will be shown below. Note that in Melitz and Ottaviano (2008) a similar property holds for the relationship between the cut-off productivity and the average productivity by assuming a Pareto distribution for the distribution of cost draws.

Following Melitz and Ottaviano (2008), let $\mu(\alpha) = p(\alpha) - c$, $r(\alpha) = p(\alpha)q(\alpha)$, and $\pi(\alpha) = r(\alpha) - q(\alpha)c$ be the absolute mark-up, revenue, and profits of a firm that produces a product with quality α. Then, these performance measures can be written as

$$\mu(\alpha) = \frac{\alpha - \alpha_D}{2}, \tag{11}$$

$$q(\alpha) = \frac{L(\alpha - \alpha_D)}{2\gamma}, \tag{12}$$

$$r(\alpha) = \frac{L}{4\gamma}\left((\alpha - \alpha_D)^2 + 2c(\alpha - \alpha_D)\right), \tag{13}$$

$$\pi(\alpha) = \frac{L}{4\gamma}(\alpha - \alpha_D)^2. \tag{14}$$

Since the expected profit prior to entry at time t is given by $\int_{\alpha_D}^{\alpha_M} \pi(\alpha)\mathrm{d}G_t(\alpha) - f$, the equilibrium free entry condition is given by

$$\int_{\alpha_D}^{\alpha_M} \pi(\alpha)\mathrm{d}G_t(\alpha) = \frac{L}{4\gamma}\int_{\alpha_D}^{\alpha_M} (\alpha - \alpha_D)^2 \mathrm{d}G_t(\alpha) = f. \tag{15}$$

The first equality is obtained by using Eq. (14). From Eqs. (10) and (15), we obtain the following lemma:

Lemma 1 *(i) Given $G_t(\alpha)$, α_D and $\bar{\alpha}$ are both decreasing in f (R&D cost) and γ (the degree of horizontal differentiation) and increasing in L (the market size).*
(ii) Under Assumption 1, for a given $G_t(\alpha)$, a higher α_D leads to a higher N (more varieties) and a higher N_E (more entrants).

Proof. The first part is directly obtained from Eq. (15). For the second part, differentiate Eq. (10) with respect to α_D to yield

$$\frac{\mathrm{d}N}{\mathrm{d}\alpha_D} = \frac{2\gamma}{\eta(\bar{\alpha} - \alpha_D)} - \frac{2\gamma(\alpha_D - c)}{\eta(\bar{\alpha} - \alpha_D)^2}\frac{\mathrm{d}(\bar{\alpha} - \alpha_D)}{\mathrm{d}\alpha_D} > 0.$$

Assumption 1 ensures that the right-hand-side is positive. Then, since $N_E = N/[1 - G_t(\alpha_D)]$, a higher α_D and a higher N lead to a higher N_E. ∎

This lemma shows that the effects of parameters on the cut-off quality and the average quality in our model are similar to the effects of parameters on the cut-off productivity and the average productivity in Melitz and Ottaviano (2008).

2.3 Technology spillovers

The individual firm's technological knowledge spillovers to other firms in the manufacturing sector. In the spirit of Romer (1990) and Grossman and Helpman (1990, 1991), we assume that technological knowledge has a public-good nature. That is, individual firm's R&D output contributes to "general knowledge" in the economy and all firms equally have access to the general knowledge without any costs. We capture technology spillovers by the expansion of the technology frontier, α_{Mt}. More specifically, we assume that α_{Mt} changes in the following way:

$$\dot{\alpha}_{Mt} = \lambda K_t \alpha_{Mt}, \tag{16}$$

where $\lambda > 0$ and K_t is the knowledge flow at time t. Assuming that knowledge flow is proportional to the number of varieties actually produced, we have

$$K_t = N_t \tag{17}$$

by choosing units for K_t. Note that N_t is the mass of surviving firms that produces quality level $\alpha \geq \alpha_{Dt}$.

Since technology spillovers shift the distribution $G(\alpha)$ to the right without changing its shape, it has the following properties:

Lemma 2 *An upward shift of $G(\alpha)$ leaves $\mu(\alpha)$, $q(\alpha)$, $r(\alpha)$, and $\pi(\alpha)$ unchanged and increases N and N_E.*

Proof. Let $G^0(\alpha^0)$ and $G^1(\alpha^1)$ be the distributions before and after the change, respectively. Let α_M^0 and α_M^1 be the upper bound of $G^0(\alpha^0)$ and $G^1(\alpha^1)$, respectively, and set $\alpha_M^1 = \alpha_M^0 + k$ with $k > 0$. Then, since $\alpha^1 = \alpha^0 + k$ holds for any α^0 and α^1 that take the same relative position in each distribution, Eq. (15) for $G^0(\alpha^0)$ can be transformed to that for $G^1(\alpha^1)$. Thus, Eqs. (11) to (14) are unchanged. However, since $\bar{\alpha} - \alpha_D$ is unchanged and $\alpha_D^1 = \alpha_D^0 + k$, Eq. (10) yields a higher N and hence a higher N_E. ∎

This lemma implies that as long as all firms equally have access to the general knowledge, technology improvement in the sense of an upward shift of $G(\alpha)$ increases the absolute levels of product quality for all varieties but keeps their relative positions in the industry unchanged. However, Lemma 2 also implies that there are more varieties in the economy with advanced technology than in the economy with lagged technology.

3 Trade between Two Countries

3.1 A two-country setting

Now, we consider two countries, Home and Foreign with L^H and L^F consumers in each country. Consumers in both countries share the same preferences given by Eqs. (1) and (2). We assume that the markets in the two countries are segmented, while firms can produce in one location and supply their products to the market in the other country by incurring a per-unit trade cost.

Manufacturing firms in the two countries have the same marginal cost c but draw product qualities α^H and α^F from their domestic distributions $G_t^H(\alpha)$ and $G_t^F(\alpha)$ with support on $[\underline{\alpha}_t^H, \alpha_{Mt}^H]$ and $[\underline{\alpha}_t^F, \alpha_{Mt}^F]$, respectively.

Following Melitz and Ottaviano (2008), we assume that firms in country h must incur the unit cost of $\tau^l c$ with $\tau^l > 1$ to deliver one unit of their products to the market in the country l. We also assume that the homogenous numeraire good is always produced in each country after opening up to trade, so that the wage rate is equal to one in both countries.

The price threshold for positive demand in market l is given by

$$p_{\max}^l(\alpha) \equiv \alpha - \frac{\eta N^l}{\eta N^l + \gamma}(\bar{\alpha}^l - \bar{p}^l), \tag{18}$$

where N^l is the mass of firms selling in country l, which includes both domestic firms in country l and exporters from country h, and $\bar{\alpha}^l$ and $\bar{p}^l$ are respectively average quality and price across both local and exporting firms in country l. Let N_D^l and N_X^l denote the mass of firms producing in country l that supply products to the domestic market and the other country's market, respectively. Then, $N^l = N_D^l + N_X^h$ holds $(l, h = H, F, l \neq h)$.

Firms maximize their profits earned from local and export sales independently (due to the assumptions of segmented market and constant-returns-to-scale technology). Let α_D^l and α_X^l be the quality levels for the firm producing in country l that earns zero profits from local sales and export sales, respectively. From $p(\alpha_D^l) = p_{\max}^l(\alpha_D^l) = c$ and $p(\alpha_X^l) = p_{\max}^h(\alpha_D^l) = \tau^h c$, we obtain

$$\alpha_D^l = \frac{\eta N^l}{\eta N^l + \gamma}(\bar{\alpha}^l - \bar{p}^l) + c, \tag{19}$$

$$\alpha_X^l = \frac{\eta N^h}{\eta N^h + \gamma}(\bar{\alpha}^h - \bar{p}^h) + \tau^h c. \tag{20}$$

Thus, it holds that

$$\alpha_X^h = \alpha_D^l + (\tau^l - 1)c. \tag{21}$$

Let $\pi_D^l(\alpha) = [p_D^l(\alpha) - c]q_D^l(\alpha)$ and $\pi_X^l(\alpha) = [p_X^l(\alpha) - \tau^h c]q_X^l(\alpha)$ be the maximized value of profits for a firm with quality α producing in country l from domestic sales and export sales, respectively, where $p_D^l(\alpha)$ and $p_X^l(\alpha)$ are profit-maximizing prices for domestic and export sales, respectively, and $q_D^l(\alpha)$ and $q_X^l(\alpha)$ are corresponding quantities. From the first-order conditions, it holds that

$q_D^l(\alpha) = (L^l/\gamma)[p_D^l(\alpha) - c]$ and $q_X^l(\alpha) = (L^h/\gamma)[p_X^l(\alpha) - \tau^h c]$. Then, use the same procedure to derive (9) and (12) in the closed economy to yield the optimal prices and outputs for domestic and export sales, respectively:

$$p_D^l(\alpha) = \frac{\alpha - \alpha_D^l}{2} + c, \quad q_D^l(\alpha) = \frac{L^l(\alpha - \alpha_D^l)}{2\gamma}, \tag{22}$$

$$p_X^l(\alpha) = \frac{\alpha - \alpha_X^l}{2} + \tau^h c, \quad q_X^l(\alpha) = \frac{L^h(\alpha - \alpha_X^l)}{2\gamma}. \tag{23}$$

Then, the maximized profits from domestic sales and export sales are respectively given by

$$\pi_D^l(\alpha) = \frac{L^l}{4\gamma}(\alpha - \alpha_D^l)^2, \tag{24}$$

$$\pi_X^l(\alpha) = \frac{L^h}{4\gamma}(\alpha - \alpha_X^l)^2. \tag{25}$$

The equilibrium free entry condition in country l at time t is given by

$$\int_{\alpha_{Dt}^l}^{\alpha_{Mt}^l} \pi_D^l(\alpha) \mathrm{d}G_t^l(\alpha) + \int_{\alpha_{Xt}^l}^{\alpha_{Mt}^l} \pi_X^l(\alpha) \mathrm{d}G_t^l(\alpha) = f. \tag{26}$$

Substitute (21), (24), and (25) into this to yield two equilibrium free entry conditions:

$$L^H \int_{\alpha_{Dt}^H}^{\alpha_{Mt}^H} \left(\alpha - \alpha_{Dt}^H\right)^2 \mathrm{d}G_t^H(\alpha) + L^F \int_{\alpha_{Dt}^F + (\tau^F - 1)c}^{\alpha_{Mt}^H} \left[\alpha - \alpha_{Dt}^F - (\tau^F - 1)c\right]^2 \mathrm{d}G_t^H(\alpha) = 4\gamma f, \tag{27}$$

$$L^F \int_{\alpha_{Dt}^F}^{\alpha_{Mt}^F} \left(\alpha - \alpha_{Dt}^F\right)^2 \mathrm{d}G_t^F(\alpha) + L^H \int_{\alpha_{Dt}^H + (\tau^H - 1)c}^{\alpha_{Mt}^F} \left[\alpha - \alpha_{Dt}^H - (\tau^H - 1)c\right]^2 \mathrm{d}G_t^F(\alpha) = 4\gamma f, \tag{28}$$

which jointly determine the cut-off qualities for domestic sales in the Home and Foreign at time t, α_{Dt}^H and α_{Dt}^F. We then assume the following:

Assumption 2 $\int_{\underline{\alpha}^l}^{\alpha_M^l} \pi_D^l(\alpha) \mathrm{d}G^l(\alpha) + \int_{\underline{\alpha}^l}^{\alpha_M^l} \pi_X^l(\alpha) \mathrm{d}G^l(\alpha) > f.$

Under Assumption 2, there are always some firms that exit the market in country l even if no firm enters the market in country h.

Since the mass of firms selling in country l at time t is still determined by (10), N_t^l is given by

$$N_t^l = \frac{2\gamma(\alpha_{Dt}^l - c)}{\eta(\bar{\alpha}_t^l - \alpha_{Dt}^l)}, \tag{29}$$

where $\bar{\alpha}_t^l$ is the average quality of products sold in country l at time t, which is given by

$$\bar{\alpha}_t^l = \frac{\int_{\alpha_{Dt}^l}^{\alpha_{Mt}^l} \alpha \, \mathrm{d}G_t^l(\alpha) + \int_{\alpha_{Dt}^l + (\tau^l - 1)c}^{\alpha_{Mt}^h} \alpha \, \mathrm{d}G_t^h(\alpha)}{2 - G_t^l(\alpha_{Dt}^l) - G_t^h(\alpha_{Dt}^l + (\tau^l - 1)c)}.$$

Similar to Assumption 1 in the case of the closed economy, we assume

Assumption 3 $0 < \mathrm{d}\bar{\alpha}^l / \mathrm{d}\alpha_D^l < 1.$

Let N_{Et}^l be the mass of entrants producing in country l at time t, which is determined by

$$[1 - G_t^H(\alpha_{Dt}^H)]N_{Et}^H + [1 - G_t^F(\alpha_{Xt}^F)]N_{Et}^F = N_t^H, \tag{30}$$

$$[1 - G_t^F(\alpha_{Dt}^F)]N_{Et}^F + [1 - G_t^H(\alpha_{Xt}^H)]N_{Et}^H = N_t^F, \tag{31}$$

where $[1 - G_t^l(\alpha_{Dt}^l)]N_{Et}^l = N_{Dt}^l$ and $[1 - G_t^l(\alpha_{Xt}^l)]N_{Et}^l = N_{Xt}^l$. The equilibrium free entry conditions (27) and (28) will hold so long as there is a positive mass of entrants $N_{Et}^l > 0$ in country l at time t. Otherwise, $N_{Et}^l = 0$ and country l specializes in the numeraire good.

In this two-country setting, knowledge spills over both within a country and across countries. As was the case in the closed economy (Eq. (16)), knowledge flow expands the technology frontier of country l in the following way:

$$\dot{\alpha}_{Mt}^l = \lambda K_t^l \alpha_{Mt}^l, \quad l = H, F. \tag{32}$$

We assume that knowledge spillover is perfect within a country but imperfect across countries.

Instead of Eq. (17), knowledge flow in country l is given by

$$K_t^l = N_{Dt}^l + \phi^l(\alpha_{Mt}^l, \alpha_{Mt}^h)N_{Xt}^h, \quad l = H, F, \ h \neq l, \tag{33}$$

where

$$\phi^l(\alpha_{Mt}^l, \alpha_{Mt}^h) \begin{cases} = 1, & \text{if } \alpha_{Mt}^l = \alpha_{Mt}^h, \\ \in (0, 1), & \text{otherwise,} \end{cases} \tag{34}$$

which controls the degree of international knowledge spillovers, depending on the technology gap between two countries. We assume $\partial\phi^l/\partial\alpha_M^l > 0$ for $\alpha_M^l < \alpha_M^h$.

In Eq. (33), our primary interest is in technology spillovers from country h to country l at time t, S_{lh}, which are measured by

$$S_{lht} = \phi^l(\alpha_{Mt}^l, \alpha_{Mt}^h)N_{Xt}^h, \quad l = H, F, \ h \neq l. \tag{35}$$

As is evident, we consider international technology spillovers only through imports.[15] We assume that international technology spillover is proportional to the number of varieties actually imported. However, the degree of international technology spillovers is reduced unless the two countries share the

[15] Thus, we ignore the "learning-by-exporting" effect. Some empirical studies find the existence of learning-by-exporting (Aw et al., 2007; De Loecker, 2007; Salomon and Shaver, 2005), while Bernard and Jensen (1999) and Lileeva and Trefler (2007) find only limited evidence and Clerides, Lach, and Tybout (1998) and Damijan and Kostevc (2006) fail to find conclusive evidence of such an effect. See Greenaway and Kneller (2007) for a survey of the literature. The majority of the studies in this literature consider productivity improvements by exporting as learning-by-exporting, which is beyond the scope of technology spillovers in our definition. The only exception is Salomon and Shaver (2005), who find that exporters increase their product innovations and patent applications subsequent to exporting. However, evidence from patent citations data is much less supportive. MacGarvie (2006) finds no significant evidence of exporting firms' citing more patents from their destination countries. Haruna, Jinji, and Zhang (2010) find that the effect of export specialization on knowledge diffusion is relatively weak.

same technology level. When country l has a higher technology than country h, knowledge spillover from h to l is reduced because a country with advanced technology (country l) benefits less from knowledge of the technological lagger. When country l has a lower technology than country h, on the other hand, knowledge spillover from h to l may be again reduced because a country with inferior technology (country l) only has lower absorptive capacity. The relative size of ϕ^l and ϕ^h under $\alpha_M^l \neq \alpha_M^h$ is generally ambiguous, unless the functional form of $\phi^l(\cdot)$ is specified.

3.2 Trade patterns and technology spillovers

We now investigate the relationship between trade patterns and international technology spillovers and derive testable hypotheses.

Consider first the case in which the two countries share the same technology at a given time t: that is, $\alpha_{Mt}^H = \alpha_{Mt}^F$. If the size of the market and the trade barrier are symmetric (i.e., $L^H = L^F$ and $\tau^H = \tau^F$), then the countries have the same average quality and the same average price of export goods. Thus, the trade pattern between the two countries is characterized by HIIT. In this case, international technology spillovers occur in both directions by the same degree because $\phi^H = \phi^L = 1$ and $N_{Xt}^H = N_{Xt}^F$.

We then examine how trade patterns and technology spillovers between the two countries will change if there is a technology gap between the home and foreign countries. Without loss of generality, we assume that the home country is technologically superior to the foreign country at a given time. We continue to assume that the market size is the same in the two countries (i.e., $L^H = L^F$). We compare the (symmetric) case in which $G^H(\alpha)$ and $G^F(\alpha)$ are identical with the (asymmetric) case in which $G^H(\alpha)$ remains the same but $G^F(\alpha)$ is distributed over the interval with some smaller values. Comparing the overall distribution of product qualities (of domestic products plus imported products) in each market in these two cases, the distribution in the asymmetric case first-order stochastically dominates that in the symmetric case in either market. This implies that competition in each market is less intensive in the asymmetric case than in the symmetric case. Consequently, α_D^H and α_D^F are both lower in the asymmetric case and hence from Eq. (29) N^H and N^F are both smaller in the asymmetric case under Assumption 3, which also implies that the mass of entrants in each country (i.e., N_E^H and N_E^F) is also smaller in the asymmetric case. The lower values of α_D^H and α_D^F imply that α_X^F and α_X^H are also lower in the asymmetric case. As a result, the mass of varieties exported from each country (i.e., N_X^H and N_X^F) is smaller in the asymmetric case.

In order to investigate the structure of trade patterns, we need to know the average quality and price of goods exported from each country. The average quality and price of goods exported from country l at time t, $\bar{\alpha}^l_{Xt}$ and $\bar{p}^l_{Xt}$, are respectively given by

$$\bar{\alpha}^l_{Xt} = \frac{\int_{\alpha^l_{Xt}}^{\alpha^l_{Mt}} \alpha \, \mathrm{d}G^l_t(\alpha)}{1 - G^l_t(\alpha^l_{Xt})} \tag{36}$$

$$\bar{p}^l_{Xt} = \frac{\bar{\alpha}^l_{Xt} - \alpha^l_{Xt}}{2} + \tau^h c. \tag{37}$$

Then, in the asymmetric case, because of the transport cost, the overall distribution of product qualities in the market of the (technologically inferior) foreign country first-order stochastically dominates that in the market of the (technologically advanced) home country.[16] It implies that competition is more intensive in the home market than in the foreign market, and hence α^H_D is higher than α^F_D and α^F_X is higher than α^H_X. However, $\alpha^H_M > \alpha^F_M$ holds and this difference is larger than the difference in α^F_X and α^H_X unless the tranport cost is highly asymmetric. Consequently, with regard to the average quality and price of exports, from Eqs. (36) and (37) it yields that $\bar{\alpha}^H_X > \bar{\alpha}^F_X$ and $\bar{p}^H_{Xt} > \bar{p}^F_{Xt}$. That is, the home country exports varieties with higher quality on average at higher price on average. Since the two countries trade products in the same industry with (on average) different quality with each other, the trade pattern becomes VIIT when the gaps in the average quality and in the average price are sufficiently large.

Recall that the size of technology spillovers from country h to country l,S_{lh}, is measured by Eq. (35), which consists of ϕ^l (a parameter that controls the degree of international knowledge spillovers) and N^h_{Xt} (the mass of varieties exported from country h to country l). Then, as for technology spillovers under VIIT, ϕ^H and ϕ^F are both smaller in the asymmetric case than in the symmetric case and N^H_X and N^F_X are also both smaller in the asymmetric case, Thus, we obtain the following hypothesis:

Hypothesis 1 *Compared to the case in which the trade pattern is HIIT, the size of technology spillovers is lower in either direction when the trade pattern is VIIT.*

Moreover, the size of technology spillovers is asymmetric under VIIT. Since $\alpha^H_D > \alpha^F_D$ and $\bar{\alpha}^H_X > \bar{\alpha}^F_X$, the mass of varieties exported from the home country is greater than that exported from the foreign country. That is, $N^H_X > N^F_X$. However, this does not necessarily imply that the size of technology spillovers is larger from the home country to the foreign country than in the opposite direction. The reason is that $\phi^H < \phi^L$ may hold and that it may cause $S_{HF} > S_{FH}$ to hold in Eq. (35). Thus, the following hypothesis is obtained:

Hypothesis 2 *When the trade pattern is VIIT, the relative size of technology spillovers from the home country to the foreign country and in the opposite direction is ambiguous.*

[16] Note that if $\tau^H = \tau^L = 1$, then the overall distribution of product qualities is identical in the two markets.

We next consider the case in which the technology gap between the two countries is widened further, so that $\alpha_M^F < \alpha_X^F$ holds or the free entry condition in the foreign country (Eq. (28)) becomes

$$L^F \int_{\alpha_{Dt}^F}^{\alpha_{Mt}^F} \left(\alpha - \alpha_{Dt}^F\right)^2 \mathrm{d}G_t^F(\alpha) + L^H \int_{\alpha_{Dt}^H+(\tau^H-1)c}^{\alpha_{Mt}^F} \left[\alpha - \alpha_{Dt}^H - (\tau^H - 1)c\right]^2 \mathrm{d}G_t^F(\alpha) < 4\gamma f.$$

In the former case, some foreign firms may still enter the manufacturing sector but no foreign firm can export goods to the home country. In the latter case, on the other hand, $N_{Et}^F = 0$ holds and the foreign country is specialized in the numeraire good. In either case, the trade pattern is characterized by pure OWT, or pure inter-industry trade. International technology spillovers still occur from the home country to the foreign country but no spillovers in the opposite direction. As is evident from the above discussion on the case of VIIT, a widened technology gap between the two countries causes α_D^H and α_D^F to be lower under OWT than under VIIT. Then, α_X^F and α_X^H are also lower under OWT than under VIIT, which implies that the mass of varieties exported from the home country (i.e., N_X^H) is smaller under OWT. Moreover, since the gap between α_M^H and α_M^F is widened, the values of ϕ^H and ϕ^F decrease. Therefore, we obtain the following hypothesis:

Hypothesis 3 *Compared to the case in which the trade pattern is VIIT, the size of technology spillovers is lower when the trade pattern is OWT.*

As will be argued in the next section, OWT does not necessarily mean that the trade pattern is *completely* inter-industry. In the empirical analysis, a small amount of intra-industry trade that is below some critical value is categorized as OWT. Thus, the direction of technology spillovers in the case of OWT is not necessarily one-way.

From the theoretical investigation, we obtained three testable hypotheses on the relationship between trade patterns and international technology spillovers. In the next section, we empirically test these three hypotheses.

4 Empirical Analysis

In the previous section, we have shown that technology spillovers across countries may be related with patterns of bilateral trade. In this section, we empirically test predictions of the theoretical model by using bilateral trade data and patent citation data.

4.1 Estimation framework

We first explain the method of categorizing bilateral trade flows. In the previous studies, trade patterns are usually categorized into three types, namely, one-way trade (OWT), horizontal intra-industry trade (HIIT), and vertical intra-industry trade (VIIT) (e.g., Fontagné and Freudenberg, 1997; Greenaway, Hine, and Milner, 1995; Fukao, Ishido, and Ito, 2003). The standard method of categorization is given by Fontagné and Freudenberg (1997), which is summarized in Table A.2.[17] This method is based on the assumption that the gap between the unit values of imports and exports for each commodity reflects the qualitative differences of the products exported and imported between two countries. We extend the standard method to take the direction of trade into account and categorize bilateral trade flows into five types.

Let X_{ijk} and M_{ijk} be the values of country i's exports to and imports from country j of product k, respectively. Then, the trade pattern in industry k is *one-way trade with importing* (OWT_M) if

$$\frac{\min(X_{ijk}, M_{ijk})}{\max(X_{ijk}, M_{ijk})} \leq \theta \quad \text{and} \quad X_{ijk} < M_{ijk}$$

hold and *one-way trade with exporting* (OWT_X) if

$$\frac{\min(X_{ijk}, M_{ijk})}{\max(X_{ijk}, M_{ijk})} \leq \theta \quad \text{and} \quad X_{ijk} > M_{ijk}$$

hold. The trade pattern in industry k is *two-way trade*, or *intra*-indutry trade (IIT), if

$$\frac{\min(X_{ijk}, M_{ijk})}{\max(X_{ijk}, M_{ijk})} > \theta$$

holds. IIT is further divided into three types. Let UV^X_{ijk} and UV^M_{ijk} be average unit values of country i's exports to and imports from country j of product k. Then, the trade pattern in industry k is *horizontal intra-industry trade* (HIIT) if

$$1 - \xi \leq \frac{UV^X_{ijk}}{UV^M_{ijk}} \leq 1 + \xi$$

holds (This condition is the same as that in the standard method). The trade pattern in industry k is *vertical intra-industry trade with importing higher-quality products* (VIIT_M) if

$$\frac{UV^X_{ijk}}{UV^M_{ijk}} < 1 - \xi$$

holds and *vertical intra-industry trade with exporting higher-quality products* (VIIT_X) if

$$\frac{UV^X_{ijk}}{UV^M_{ijk}} > 1 + \xi$$

[17] There is another method of categorizing trade patterns proposed by Greenaway, Hine, and Milner (1994, 1995), which is based on a decomposition of Grubel–Lloyd index. In their method, intra-industry trade in industry k is measured by

$$IIT_k = 1 - \frac{\sum_n |X^z_{kn} - M^z_{kn}|}{\sum_n (X^z_{kn} + M^z_{kn})},$$

where n refers to products and z denotes HIIT or VIIT. In order to disentangle total IIT into HIIT and VIIT, they also use the ratio of unit values. Fontagné, Freudenberg, and Gaulier (2006) investigate the difference between these two methods. They argue that, while the two methods diverge on the definition of IIT, they rely on the same assumption regarding the relationship between unit values and the quality of traded products.

holds. Then, the share of each trade pattern is defined by

$$\frac{\sum_k (X^z_{ijk} + M^z_{ijk})}{\sum_k (X_{ijk} + M_{ijk})},$$

where z denotes one of the five trade types, i.e., OWT_M, OWT_X, HIIT, VIIT_M, and VIIT_X. In the above conditions, the choice of θ and ξ is to a large extent arbitrary. Altough Fontagné and Freudenberg (1997) and some other studies use $\xi = 0.15$, Fontagné, Freudenberg, and Gaulier (2006) report the sensitivity of the relative importance of HIIT to total intra-industry trade and argue that defining θ as 0.1 and ξ as 0.25 is quite reasonable. Fukao, Ishido, and Ito (2003) also employ $\theta = 0.1$ and $\xi = 0.25$. They argue that a 25% threshold would be reasonable because of the possible effects of exchange rate fluctuations on the value recorded in trade statistics and noise in the measurements of unit values at 6-digit level of trade statistics. Thus, we also use $\theta = 0.1$ and $\xi = 0.25$ in our analysis.

We then use patent citations to measure technology spillovers. The use of patent citations in measuring technology spillovers has been pioneered by Jaffe, Trajtenberg, and Henderson (1993), in which patent citations are used to measure the extent of technology spillovers within the U.S. Every U.S. patent applicant is required to disclose any knowledge of the “prior art” in his or her application. Hall, Jaffe, and Trajtenberg (2001) point out that the presumption for using patent citations as a proxy for learning technology is that the citations to the “prior art” are informative of the causal links between those patented innovations, because citations made may constitute a “paper trail” for diffusion, i.e., the fact that patent B cites patent A may be indicative of knowledge flowing from A to B. This logic is also practicable to the case of the patent citations between countries.

On the other hand, the patent citations between the two countries may be associated with the past records of patenting in both the cited and the citing countries. The number of patents filed by the citing country is related to the scale of human resource in this country, and reflects the indigenous capacity to absorb foreign technology. The number of patents in the cited country implies a potential opportunity of citations for the citing country. Based on the reasoning above, our regression model is defined as follows:

$$\begin{aligned}\log c^*_{ijt} &= \beta' x_{ijt} + \epsilon_{ijt} \\ &= \beta_1 Share_{ijt}(OWT_M, OWT_X, HIIT, VIIT_M, \text{ or } VIIT_X) + \beta_2 \log P_{it} \times P_{jt} + u_{ij} + e_{ijt}\end{aligned}$$

where c^*_{ijt} is the number of patent citations made by patents filed by country i (the citing country) to country j (the cited country) in year t, $Share_{ijt}$ is bilateral OWT_M, OWT_X, HIIT, VIIT_M, or VIIT_X share between country i and j in year t, P_{it} and P_{jt} are the number of patent applications filed by country i and j respectively in year t.[18] Thus, we use c^*_{ijt} as a proxy for technology spillovers from country j to country i. The term $P_{it} \times P_{jt}$ is included to control the effect of the citing country's absorptive capacity of technology and the cited country's potential opportunity of citations.

[18]The stochastic nature of product R&D assumed in our theoretical model is not directly reflected in our estimation framework. As we have shown in the previous sections, however, the average quality and the distribution of quality

Since patent citations are rarely happened among some countries, there are substantial zero values in c^*_{ijt}. We then use a random-effects panel Tobit model to deal with this issue. In that case, the dependent variable is now a latent variable, where

$$\log c_{ijt} = \begin{cases} \log c^*_{ijt} & \text{if } c^*_{ijt} > 0, \\ 0 & \text{otherwise,} \end{cases}$$

and

$$\epsilon_{ijt} = u_{ij} + e_{ijt}, \quad u \sim NID(0, \sigma_u^2), \quad e \sim NID(0, \sigma_e^2), \quad \rho = \frac{\sigma_u^2}{\sigma_u^2 + \sigma_e^2}.$$

In general independence between the u and e is assumed. On the other hand, there is neither a convenient test nor estimation method for test of random versus fixed-effects of Tobit model as well as for estimation of a conditional fixed-effects model.[19] In order to assess the robustness of the estimated results by the random-effects Tobit model, we try to use a fixed-effects negative binomial model proposed by Hausman, Hall, and Griliches (1984) for our same sample.

4.2 Data

4.2.1 Trade data

There are several kinds of datasets for empirical analysis on international trade such as International Trade Commodity Statistics (ITCS–SITC) released by OECD, and Personal Computer Trade Analysis System (PC–TAS) published by the United Nations Statistical Division. As indicated by Gaulier and Zignago (2008), the empirical analysis is suffered from the two different figures for the same trade flow, because the import values are generally reported in CIF (cost, insurance and freight) and export values in FOB (free on board). To reconcile the two figures, Gaulier and Zignago (2008) develop a procedure to estimate an average CIF cost and remove it from the declarations of imports to provide FOB import values for bilateral trade flows drawn on United Nations COMTRADE data. In this paper, we utilize this reconstructed trade dataset called as BACI. The BACI dataset covers more than 200 countries and 5,000 products between 1995 and 2007.[20]

4.2.2 Patent citation data

The data of patents and patent citations used in this paper consist of two sources, i.e., EPO Worldwide Patent Statistical Database (PATSTAT) and the Institute of Intellectual Property (IIP) dataset. We collect the patent statistics of the United States Patent and Trademark Office (USPTO) and European

among actually supplied products in an industry are invariant for a given distribution $G_t(\alpha)$. Since we use the industry average to determine the bilateral trade patterns, we think that our empirical framework is consistent with the theoretical model in the previous sections.

[19]Honore (1992) has developed a semiparametric estimator for fixed-effect Tobit models.

[20]Please see the website of CEPII (http://www.cepii.fr) for the details of BACI dataset.

Patent Office (EPO) from the former, and these of Japanese Patent Office (JPO) from the latter. The two datasets include the dates of patent applications, International Patent Classification (IPC), the information of citation and the country names both of citing and cited patent applicants.

Unlike the patent application in the USPTO, patent applicants in JPO have no legal duty to list the patents that he/she cites in the front-page of document, although some referenced information provided by the applicants lies scattered across the patent body text. The information of citations in the front-page is usually added by the examiners in JPO as well as in EPO (Hall, Thoma, and Torrisi, 2007). According to Goto and Motohashi (2007), about two thirds of JPO citations are decided by the examiners since 1990s.

Although the decision regarding which patents to cite ultimately depends on the patent examiner, implying that the inventors may have been unaware of the cited patents, the presumption that the citations are relevant as the indicator of technology links between the citing and the cited is widely recognized in many empirical studies such as Jaffe, Trajtenberg, and Henderson (1993), Jaffe and Trajtenberg (1996, 1999), and Hall, Jaffe, and Trajtenberg (2001) for the U.S. patents, Maurseth and Verspagen (2002), and MacGarvie (2006) for the European patents.

4.2.3 Sample selection

We start to select our sample from top 60 trade countries in 2008, according to the quantity of their import and export in the world. Because crude oil makes up the most of trade in some top trade countries such as Saudi Arabia, Nigeria, Russia and Venezuela, we exclude these countries from our sample. At the same time, we also exclude countries such as Kazakhstan, Peru and Vietnam, since they rarely made or received patent citations in USPTO, JPO or EPO. As a result, we obtain a sample which covers 44 countries across advanced, emerging and developing economies in the world.[21]

The patent statistics used in this paper are classified according to the IPC, which is based either on the intrinsic nature of the invention or on the function of the invention. Schmoch et al. (2003) provide a concordance between technical fields and industrial sectors. This concordance table refers to IPC for patents, and international classifications, namely European Union's Classification of Economic Activities within the European Communities (NACE), the United Nations' International Standard Industrial Cassification (ISIC) and the U.S. Standard Industrial Classification (SIC) with 44 industrial sectors. The empirical analyses in Schmoch et al. (2003) show that this concordance with 44 industrial sectors (or technical fields) has a reasonable level of disaggregation, because the economic data for international comparisons are not available in the finer differentiation. Thus, we use their concordance table to allocate the patents statistics into 44 industrial sectors.[22] Since the number of citations is very limited in some sectors, especially for products in some light manufacturing sectors such as textiles,

[21] See the list of sample countries in Table A.3.
[22] See Table A.4 for the details of the 44 industrial sectors.

wearings, and paints, we focus our analysis on five fields, i.e., non-metal products, metal products, machinery, ICT relation equipments, and motor vehicle. The five fields correspond with Sectors 17 and 18, Sector 20, Sectors 21-25, Sectors 28 and 34-38, and Sector 42 in Schmoch et al. (2003).

In order to match the data for trade with patents, we map the 6-digit Harmonized System (HS6) and the ISIC rev. 3 according to the industrial concordance table provided by Jon Haveman.[23] Then, we use the method explained above to measure the shares of OWT, HIIT and VIIT for our sample countries in the five fields discussed above for the periods of 1995-1996, 1997-1998, 1999-2000, 2001-2002, and 2003-2004 (i.e., five periods). The descriptive statistics for the shares of OWT, HIIT and VIIT, and the number of citations are presented in Table A.1. On one hand, there are substantial citations between some developed countries, especially between the U.S. and Japan. For instance, the U.S. patents belonged to Sector 28 made more than 56,300 citations to Japanese patents during the period of 2003 and 2004. On the other hand, among about four fifths of observations citations are not identified in our sample period.

Table 1 describes the shares of OWT, HIIT and VIIT for some selected sample countries averagely across five fields and five periods. From the table, we find that the remarkable bilateral IIT (HIIT+VIIT) intensities are observed among European countries. More than 91% of trade is IIT for the trade between Germany and France, 79% for France and Belgium–Luxembourg, 92% for Netherlands and Belgium–Luxembourg. These figures largely coincide with those reported by Fontagné, Freudenberg, and Gaulier (2006) for the same country pairs (86.2%, 80.4% and 85.0%, respectively), based on trade statistics of year 2000.

Table 2 presents how patent citations have been made by the patents of some selected countries filed to USPTO, JPO and EPO respectively. Although the scale of citations is different across the patent offices, the patterns of citations between the selected countries are similar across the patent offices. For example, the U.S., Japan and Germany are the largest targets of citations not only for other countries, but also for each other, while citations are relatively less received as well as made by Chinese patents yet.

4.3 Estimation results

Table 3 summarizes the results for full fields, estimated based on the patent citations in USPTO, JPO and EPO respectively. We added dummy variables to control for the fields and time periods, and, as we expected, the coefficients estimates of the number of patents hold by citing and cited countries are positively significant. To assess the robustness of the estimated results in Table 3 at the same time, we also apply an alternative regression technique, namely, a fixed-effects negative binomial model proposed by Hausman, Hall, and Griliches (1984), to the same sample. Table 4 summarizes

[23] See http://www.macalester.edu/research/economics/page/haveman/trade.resources/tradedata.html

the fixed-effects negative binomial estimates, where the number of citations is used as a dependent variable.

In Tables 3 and 4, we see that all coefficient estimates for HIIT and most of those for VIIT are significant and positive, implying that intra-industry trade plays a significant role in technology spillovers. The coefficients for HIIT are estimated as 1.92, 2.38 and 2.21 in Table 3, which are evidently larger than those for VIIT, when the two variables are used in the same regression for the three different patent statistics. This pattern remains true also in Table 4. Compared with the vertical intra-industry trade, the horizontal intra-industry trade shows a dominant effect on technology spillovers.

Unlike the intra-industry trade, the estimations for the relationship between OWT and the number of citations reveal somewhat mixed results. In Table 3, the estimated coefficients of OWT are significantly positive. However, the magnitudes of the coefficients are quite smaller than those for HIIT and VIIT. In Table 4, the estimated coefficients of OWT are weakly significant or insignificant in the cases of JPO and EPO, while they are significantly negative in the case of USPTO. These results imply that the effect of OWT on technology spillovers is much weaker than that of IIT and may be negligible.

5 Conclusions

In this paper, we have examined how technology spillovers across countries would differ according to the bilateral trade patterns. We first developed a two-country model of monopolistic competition with quality differentiation by extending the model of Melitz and Ottaviano (2008). In our model, quality of each product in the manufacturing sector is differentiated and stochastically determined by firms' engaging in product R&D. The structure of our model is quite similar to that of Melitz and Ottaviano (2008), except for that firms are heterogeneous in the product quality rather than in productivity. We then introduced technology spillovers in our model as the process of expanding the technology frontier of the industry. We assumed that, in a given sector, all firms in the same country equally have access to the "general knowledge" without paying any cost. However, technology spillovers are imperfect across countries. In particular, the degree of international technology spillovers falls as the technology gap between the two countries increases. We then showed that in our model the trade pattern is intra-industry when the technology gap between the two countries is small, while it is inter-industry when the technology gap is sufficiently large. Since products are differentiated in quality in our model, both horizontal and vertical intra-industry trade patterns also emerge endogenously.

From the model, we derived three testable hypotheses. The first hypothesis was that technology spillovers are larger when the trade pattern between the two countries is horizontal intra-industry trade (HIIT) than when it is vertical intra-industry trade (VIIT). The second hypothesis was that when the trade pattern is VIIT, the relative size of technology spillovers from the country exporting high quality products on average to the country exporting low quality products on average and in the opposite direction is ambiguous. The third hypothesis was that technology spillovers are lower when the trade pattern is inter-industry trade, or one-way trade (OWT), than when it is VIIT.

We then empirically tested those hypotheses obtained from the model by using bilateral trade data among 44 countries at 6-digit level patent citations data at the U.S., European, and Japanese Patent Offices. Following Jaffe, Trajtenberg, and Henderson (1993) and other recent studies on technology spillovers, we measure international technology spillovers by patent citations among countries.

Our estimation results basically confirmed the predictions of our model. That is, we found that an increase in the shares of HIIT and VIIT has a significantly positive effect on international technology spillovers. Our estimation results showed that HIIT has a larger effect on spillovers than VIIT does. On the other hand, the relative magnitudes of technology spillovers between the country exporting high quality products and the country exporting low quality products on average under VIIT are generally ambiguous. We also found that the effect of OWT on technology spillovers tends to be much weaker than that of other trade patterns. Therefore, we concluded that intra-industry trade plays a significant role in technology spillovers.

In this paper, we primarily focused on technology spillovers through international trade and did not take the effects of foreign direct investment (FDI) into account. As argued in the introduction, however, a number of existing studies have empirically confirmed that FDI is also a major channel for international technology spillovers. In our estimations, we found that an increase in the share of OWT has a significantly positive effect on technology spillovers in some cases, in particular in the cases of JPO and EPO. The positive effect of OWT with exporting the good in question even exceeds that of HIIT and/or VIIT in some cases in Table 4, which contradicts the predictions by our theoretical model. This may be due to FDI. Thus, it is our future research to incorporate the effects of FDI into our framework.

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Table 1. Shares of OWT, HIIT and VIIT for Selected Countries(1) (2)

	China	U.S.	Japan	France	Italy	Netherlands	U.K.	Belgium	Canada	Korea
Germany	0.63	0.25	0.36	0.08	0.19	0.11	0.12	0.16	0.52	0.58
	0.03	0.20	0.21	0.51	0.31	0.48	0.37	0.40	0.09	0.05
	0.25	0.54	0.42	0.41	0.50	0.40	0.51	0.43	0.29	0.29
China		0.63	0.50	0.59	0.53	0.64	0.63	0.50	0.63	0.42
		0.04	0.07	0.04	0.04	0.02	0.03	0.02	0.01	0.12
		0.30	0.39	0.23	0.34	0.19	0.25	0.18	0.16	0.37
U.S.			0.48	0.28	0.41	0.36	0.21	0.44	0.08	0.58
			0.12	0.19	0.08	0.09	0.24	0.12	0.28	0.06
			0.40	0.52	0.51	0.52	0.53	0.41	0.28	0.35
Japan				0.51	0.48	0.57	0.44	0.59	0.67	0.42
				0.15	0.10	0.04	0.13	0.02	0.04	0.06
				0.28	0.33	0.30	0.40	0.22	0.12	0.50
France					0.19	0.20	0.08	0.11	0.34	0.51
					0.37	0.28	0.45	0.42	0.10	0.06
					0.43	0.51	0.47	0.47	0.42	0.26
Italy						0.29	0.26	0.32	0.50	0.53
						0.13	0.26	0.28	0.05	0.07
						0.55	0.47	0.39	0.28	0.21
Netherlands							0.14	0.07	0.37	0.46
							0.25	0.42	0.07	0.03
							0.60	0.50	0.38	0.18
U.K.								0.20	0.32	0.58
								0.26	0.11	0.03
								0.53	0.51	0.28
Belgium(3)									0.45	0.35
									0.03	0.06
									0.22	0.23
Canada										0.57
										0.02
										0.15

(1) The upper, middle and lower figures are for OWT, HIIT and VIIT respectively.
(2) The sum of OWT, HIIT and VIIT could be less than 1.0 due to unavailability for the unit value in some cases.
(3) Luxembourg is included in Belgium.

Table 2. Patent Citations for Selected Countries(1)

		Cited Country										
		Germany	China	U.S.	Japan	France	Italy	Netherlands	U.K.	Belgium	Canada	Korea
		Citations in USPTO										
	Germany		15	19905	16403	1772	554	513	1238	107	416	1212
	China	57		529	359	20	1	10	16	3	27	126
	U.S.	31886	323		151745	14808	3077	6464	13030	1087	7701	17794
	Japan	12040	66	89969		4278	1084	1935	3069	445	1432	13404
	France	1324	6	7444	4719		143	252	397	27	242	547
	Italy	578	0	1633	1207	184		37	111	11	23	137
	Netherlands	741	5	6936	4343	250	59		211	27	87	567
	U.K.	1024	4	6201	2824	450	88	137		28	142	217
	Belgium	120	1	584	435	86	8	17	24		14	21
	Canada	890	5	8147	3385	365	65	125	353	28		442
	Korea	1327	38	18312	26438	810	222	526	399	57	355	
		Citations in JPO										
	Germany		8	5834	63171	835	350	499	578	85	117	317
	China	18		127	1550	21	3	3	3	0	6	15
Citing Country	U.S.	3855	21		177390	1729	463	1277	1457	182	400	1369
	Japan	32394	173	108506		10506	2939	7545	7001	1296	1870	15195
	France	737	0	2371	19458		102	207	213	25	48	162
	Italy	322	0	490	4327	152		33	35	2	21	19
	Netherlands	451	0	2374	23097	166	58		172	22	23	231
	U.K.	435	1	1560	10452	169	35	108		14	41	56
	Belgium	55	0	188	1844	33	5	8	24		8	16
	Canada	143	0	483	3608	43	9	27	50	4		21
	Korea	457	6	3790	67141	284	84	229	150	18	77	
		Citations in EPO										
	Germany		1	2041	2221	323	220	160	295	34	41	39
	China	6		48	62	9	0	0	4	0	9	3
	U.S.	940	9		4581	513	247	300	538	99	129	178
	Japan	1121	10	6809		517	245	474	478	126	109	395
	France	247	1	1046	862		68	81	117	11	37	49
	Italy	136	0	303	318	58		16	34	5	2	14
	Netherlands	76	1	301	314	58	15		23	2	5	17
	U.K.	70	1	381	281	41	12	22		9	7	8
	Belgium	40	0	135	138	25	6	16	11		3	3
	Canada	20	1	226	117	14	4	9	6	2		9
	Korea	77	3	678	1357	59	12	54	35	5	24	

Table 3: The Random-Effects Panel Tobit Estimates for Patent Citation(1)

Coefficient	USPTO citations				JPO citations				EPO citations			
$HIIT$	2.049*** (2) (17.0)(3)	2.027*** (16.8)		1.706*** (13.8)	2.615*** (15.3)	2.699*** (15.7)		2.290*** (13.1)	2.434*** (18.9)	2.433*** (18.8)		1.974*** (15.2)
$VIIT_M$	1.836*** (17.0)	1.801*** (16.7)	1.821*** (16.1)		2.338*** (15.3)	2.420 *** (15.7)	2.548 *** (16.0)		2.137 *** (17.7)	2.100 *** (17.5)	2.107*** (16.8)	
$VIIT_X$	1.697*** (15.0)	1.675*** (14.8)	1.687*** (14.3)		2.399*** (15.1)	2.466*** (15.4)	2.580*** (15.7)		2.183*** (17.5)	2.195*** (17.6)	2.169*** (16.8)	
OWT_M	0.729*** (8.4)		0.758 *** (8.0)	0.378*** (4.2)	1.268*** (10.0)		1.600*** (11.7)	1.037 *** (8.0)	1.116*** (11.0)		1.205*** (11.1)	0.754*** (7.6)
OWT_X		0.606*** (7.0)	0.666*** (7.1)	0.293*** (3.3)		1.498*** (11.8)	1.737*** (12.9)	1.180*** (9.2)		1.128*** (11.0)	1.214*** (11.1)	0.781*** (7.7)
$\log P_i \times P_j$	0.310*** (48.1)	0.312*** (48.3)	0.318 *** (48.0)	0.325*** (48.3)	0.152*** (33.6)	0.151*** (33.3)	0.153*** (33.7)	0.158*** (33.9)	0.076*** (24.5)	0.076*** (24.4)	0.081*** (25.3)	0.081*** (25.1)
$Period_1$	0.120 *** (3.7)	0.120*** (3.7)	0.104 *** (3.2)	0.132*** (4.0)	1.430*** (20.8)	1.438 *** (20.8)	1.389 *** (20.1)	1.401*** (20.3)	-0.793*** (-16.5)	-0.791*** (-16.5)	-0.857*** (-17.6)	-0.811*** (-16.8)
$Period_2$	0.198*** (6.1)	0.196*** (6.1)	0.175*** (5.4)	0.211*** (6.5)	1.323*** (19.0)	1.324*** (18.9)	1.257*** (18.0)	1.296*** (18.5)	-0.764*** (-15.4)	-0.762*** (-15.5)	-0.843*** (-16.8)	-0.787*** (-15.8)
$Period_3$	0.411*** (12.8)	0.410*** (12.7)	0.388*** (11.9)	0.440*** (13.6)	1.472*** (21.1)	1.477*** (21.1)	1.417 *** (20.3)	1.479*** (21.1)	-0.709*** (-14.1)	-0.709*** (-14.1)	-0.787*** (-15.4)	-0.712*** (-14.1)
$Period_4$	0.433*** (12.3)	0.430*** (12.1)	0.397*** (11.0)	0.434*** (12.0)	1.355*** (19.1)	1.357*** (19.1)	1.292 *** (18.2)	1.352*** (18.9)	-0.602*** (-11.9)	-0.599*** (-11.9)	-0.679*** (-13.2)	-0.617*** (-12.1)
$Field_2$	0.096 (1.2)	0.098 (1.2)	0.077 (0.9)	0.209*** (2.6)	-0.326*** (-2.9)	-0.338*** (-3.0)	-0.384** (-3.4)	-0.244 *** (-2.1)	-0.416*** (-4.4)	-0.417*** (-4.4)	-0.428*** (-4.6)	-0.319*** (-3.4)
$Field_3$	-0.025 (-0.4)	-0.026 (-0.4)	-0.079 (-1.1)	-0.044 (-0.6)	0.184* (1.9)	0.195** (2.0)	0.128 (1.3)	0.178 * (1.8)	0.208*** (2.6)	0.214*** (2.7)	0.143* (1.8)	0.194** (2.5)
$Field_4$	-0.107 (-1.5)	-0.106 (-1.5)	-0.214 *** (-3.1)	-0.098 (-1.4)	0.295*** (3.0)	0.286 *** (2.9)	0.121 (1.2)	0.310*** (3.2)	0.565 *** (7.4)	0.574 *** (7.5)	0.426 *** (5.6)	0.569 *** (7.5)
$Field_5$	0.148* (1.9)	0.154 ** (2.0)	0.136* (1.8)	0.122 (1.6)	-0.190* (-1.8)	-0.210* (-1.9)	-0.251** (-2.3)	-0.254** (-2.3)	-0.070 (-0.8)	-0.060 (-0.7)	-0.085 (-1.0)	-0.120 (-1.4)
$1/\sigma_u$	1.338*** (54.8)	1.337*** (54.8)	1.357*** (53.7)	1.382 *** (53.2)	1.991*** (53.2)	1.992*** (53.1)	2.000*** (52.8)	2.044*** (52.2)	1.379*** (46.0)	1.387*** (45.8)	1.414*** (46.4)	1.443*** (46.8)
$1/\sigma_e$	0.870*** (86.7)	0.872*** (86.7)	0.877*** (85.4)	0.875*** (84.7)	1.064*** (74.3)	1.063*** (74.2)	1.066*** (73.8)	1.066*** (72.6)	0.718*** (60.6)	0.715 *** (60.6)	0.720*** (59.4)	0.712 *** (58.1)
ρ	0.703 (0.7)	0.702 (0.7)	0.706 (0.7)	0.714 (0.7)	0.778 (0.8)	0.778 (0.8)	0.779 (0.8)	0.786 (0.8)	0.787 (0.8)	0.790 (0.8)	0.794 (0.8)	0.804 (0.8)
No. of obs.	46764	46764	46764	46764	46764	46764	46764	46764	46764	46764	46764	46764
Log likelihood	-15143	-15154	-15261	-15356	-13169	-13148	-13201	-13324	-8099	-8099	-8218	-8338
Ward test(Prob4>chi^2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LR test(Prob>chi^2) (4)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

(1) The regression is based on full sample and includes constant term.
(2) "***","**" and "*" denote 1%, 5% and 10% significant levels, respectively.
(3) The values in the parentheses are t-statistics.
(4) Likelihood ratio test for RE model vs. pooled model.

Table 4: Fixed-effects Negative Binomial Estimates for Patent Citation(1)

Coefficient	USPTO citations				JPO citations				EPO citations			
$HIIT$	0.779*** (2)	0.673***		0.350***	0.400***	0.871***		0.343**	0.469**	0.636***		0.234
	(7.7) (3)	(6.5)		(3.8)	(2.6)	(5.8)		(2.5)	(2.4)	(3.2)		(1.4)
$VIIT_M$	0.510***	0.400***	0.111		0.130	0.609***	0.235*		0.295	0.459**	0.219	
	(5.4)	(4.2)	(1.2)		(0.9)	(4.3)	(1.7)		(1.5)	(2.3)	(1.2)	
$VIIT_X$	0.689***	0.580***	0.291***		0.493***	0.974***	0.598***		0.598***	0.773***	0.518***	
	(7.1)	(5.9)	(2.9)		(3.4)	(6.6)	(4.1)		(3.0)	(3.8)	(2.8)	
OWT_M	0.253***		-0.108	-0.147*	-0.259*		-0.110	-0.248*	0.235		0.192	0.052
	(2.7)		(-1.1)	(-1.7)	(-1.8)		(-0.8)	(-1.8)	(1.2)		(1.0)	(0.3)
OWT_X		-0.038	-0.292***	-0.329***		0.968***	0.657***	0.514 ***		0.608***	0.407**	0.264
		(-0.4)	(-3.1)	(-3.8)		(7.2)	(4.8)	(4.1)		(3.1)	(2.1)	(1.5)
$\log P_i \times P_j$	0.252***	0.251***	0.256***	0.257***	0.058***	0.056***	0.058***	0.058***	0.024***	0.024***	0.024***	0.023***
	(27.7)	(27.4)	(27.8)	(28.1)	(12.2)	(11.8)	(12.1)	(12.2)	(6.5)	(6.5)	(6.6)	(6.5)
$Period_1$	0.193***	0.194***	0.193***	0.198***	2.373***	2.402***	2.370***	2.374***	-0.181***	-0.183 ***	-0.188***	-0.172***
	(6.8)	(6.8)	(6.7)	(6.9)	(31.0)	(31.3)	(30.9)	(30.9)	(-3.2)	(-3.2)	(-3.3)	(-3.0)
$Period_2$	0.409	0.412	0.415	0.417	2.385	2.406	2.378	2.382	-0.039	-0.047	-0.048	-0.032
	(14.9)	(15.0)	(15.0)	(15.1)	(30.8)	(31.0)	(30.6)	(30.7)	(-0.7)	(-0.8)	(-0.8)	(-0.6)
$Period_3$	0.726***	0.730***	0.733***	0.736***	2.567***	2.581***	2.564***	2.570***	0.119**	0.113*	0.119**	0.138 **
	(26.1)	(26.2)	(26.0)	(26.2)	(33.2)	(33.3)	(33.0)	(33.2)	(2.0)	(1.9)	(2.0)	(2.3)
$Period_4$	1.019***	1.025***	1.029***	1.026***	2.608***	2.618***	2.602***	2.607***	0.318***	0.307***	0.313***	0.329***
	(29.6)	(29.8)	(29.4)	(29.4)	(33.3)	(33.4)	(33.2)	(33.3)	(5.4)	(5.2)	(5.3)	(5.6)
No. of obs.	11874	11874	11874	11874	8900	8900	8900	8900	6110	6110	6110	6110
Log likelihood	-15538	-15542	-15562	-15559	-11335	-11311	-11327	-11332	-6216	-6212	-6217	-6220
Ward test(Prob4>chi^2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

(1) The regression is based on full sample.

(2) "***","**" and "*" denote 1%, 5% and 10% significant levels, respectively.

(3) The values in the parentheses are t-statistics.

Table A.1: Descriptive Statistics

Variable	No. of Obs	Mean	StdDev	Min	Max
$HIIT$	46764	0.05	0.10	0.00	1.00
$VIIT$	46764	0.17	0.19	0.00	1.00
OWT	46764	0.28	0.24	0.00	1.00
USPTO citations	47300	14.9	400.0	0	56342
P_i in USPTO	47300	412.0	2803.6	0	59160
P_j in USPTO	47300	412.0	2803.6	0	59160
JPO citations	47300	14.5	419.0	0	39332
P_i in JPO	47300	2382.7	19395.3	0	279823
P_j in JPO	47300	1527.8	11114.7	0	233511
EPO citations	47300	0.9	18.3	0	1614
P_i in EPO	47300	275.1	1273.5	0	16533
P_j in EPO	47300	275.1	1273.5	0	16533

Table A.2: Fontagné and Freudenberg's (1997) Decomposition

Type of Trade (z)	Trade Overlap	Unit Value	Shares of Types
One-way trade (OWT)	$\frac{\min(X_{ijk},M_{ijk})}{\max(X_{ijk},M_{ijk})} \leq \theta$		$\frac{\sum_k (X^z_{ijk}+M^z_{ijk})}{\sum_k (X_{ijk}+M_{ijk})}$
Horizontal intra-industry trade (HIIT)	$\frac{\min(X_{ijk},M_{ijk})}{\max(X_{ijk},M_{ijk})} > \theta$	$1-\xi \leq \frac{UV^X_{ijk}}{UV^M_{ijk}} \leq 1+\xi$	
Vertical intra-industry trade (VIIT)		$\frac{UV^X_{ijk}}{UV^M_{ijk}} > 1+\xi$ or $\frac{UV^X_{ijk}}{UV^M_{ijk}} < 1-\xi$	
Intra-industry trade non-allocated (IITna)		Unit value not available	

Table A.3: Sample Countries

No	Country	No	Country
1	Germany	23	Australia
2	China	24	Norway
3	United States	25	Poland
4	Japan	26	Czech Republic
5	France	27	Ireland
6	Italy	28	Indonesia
7	Netherlands	29	Turkey
8	United Kingdom	30	Denmark
9	Belgium-Luxembourg	31	Hungary
10	Canada	32	Finland
11	Korea	33	South Africa
12	Singapore	34	Chile
13	Mexico	35	Slovak Republic
14	Spain	36	Argentina
15	Taiwan	37	Israel
16	Malaysia	38	Philippines
17	Sweden	39	Portugal
18	Switzerland	40	Ukraine
19	Brazil	41	Romania
20	Austria	42	Colombia
21	Thailand	43	New Zealand
22	India	44	Slovenia

Table A.4: Correspondence derived by Schmoch et al. between technical fields and ISIC industrial classifications[1]

Field No.	Sector	ISIC ver. 3
1	food	15
2	tobacco	16
3	textiles	17
4	wearing	18
5	leather	19
6	wood products	20
7	paper	21
8	publishing	22
9	petroleum	23
10	basic chemicals	241
11	pesticides	2421
12	paint	2422
13	pharmaceuticals	2423
14	soaps	2424
15	other chemicals	2429
16	man-made fibres	243
17	plastic products	25
18	mineral products	26
19	basic metals	27
20	metal products	28
21	energy machinery	2911, 2912, 2913
22	non-specific machinery	2914, 2915, 2919
23	agricultural machinery	2921
24	machine-tools	2922
25	special machinery	2923, 2924, 2925, 2926, 2929
26	weapons	2927
27	domestic appliances	293
28	computers	30
29	electrical motors	311
30	electrical distribution	312, 313
31	accumulators	314
32	lightening	314
33	other electrical	315
34	electronic components	321
35	telecommunications	322
36	television	323
37	medical equipment	3311
38	measuring instruments	3312
39	industrial control	3313
40	optics	332
41	watches	333
42	motor vehicles	34
43	other transport	35
44	consumer goods	36

[1] Tables 3-1 and 3-5 in Schmoch et al. (2003).