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TECHNOLOGY SPILLOVERS AND THEIR EFFECTS - A REVIEW

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ABSTRACT: The paper discusses the content of the technology spillover concept and reviews recent literature on spillovers and their effects. The importance of externalities in the growth process and the basic characteristics of spillovers are first discussed. Then the methods that have been used in empirical studies to measure spillovers are reviewed. Research results concerning domestic inter-industry and intra-industry technology flows as well as international spillovers are presented.

KEY WORDS: Technology flows, externalities, spillovers, productivity, growth

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TIIVISTELMÄ: Raportissa tarkastellaan tahattomien teknologiavirtojen käsitettä ja esitetään katsaus viimeaikaisiin tahattomia teknologiavirtoja ja niiden vaikutuksia koskeviin tutkimuksiin. Aluksi tarkastellaan ulkoisvaikutusten merkitystä taloudellisen kasvun kannalta ja esitellään tahattomien teknologiavirtojen käsitteen keskeisiä ominaisuuksia. Tämän jälkeen tarkastellaan menetelmiä, joiden avulla on pyritty arvioimaan tahattomien teknologiavirtojen suuruutta ja merkitystä. Katsauksessa esitellään kotimaisia toimialojen välisiä ja toimialojen sisäisiä sekä eri maiden välisiä teknologiavirtoja koskevia tutkimustuloksia.

AVAINSANAT: Teknologiavirrat, ulkoisvaikutukset, tahattomat teknologiavirrat, tuottavuus, kasvu

YHTEENVETO

Raportissa tarkastellaan tahattomien teknologiavirtojen (technology spillovers) käsitettä ja esitetään katsaus viimeaikaisiin tahattomia teknologiavirtoja ja niiden vaikutuksia koskeviin tutkimuksiin. Aluksi tarkastellaan ulkoisvaikutusten merkitystä taloudellisen kasvun kannalta ja esitellään tahattomien teknologiavirtojen käsitteen keskeisiä ominaisuuksia. Käsitettä pyritään myös täsmentämään esittämällä useiden muiden käyttämää käsitesisältöä kapeampi määritelmä. Erityisesti pyritään erottamaan toisistaan välituotepanoksiin ja investointitavaroihin sisältyvä teknologia sekä tahattomat teknologiavirrat. Tämän jälkeen tarkastellaan menetelmiä, joiden avulla on pyritty arvioimaan tahattomien teknologiavirtojen suuruutta ja merkitystä.

Tahattomien teknologiavirtojen vaikutuksia koskevat empiiriset tutkimukset voidaan luokitella niissä käytettyjen menetelmien ja/tai käytettyjen aineistojen mukaan. Tämän raportin luvussa 3 esitetään yhteenveto aikaisempien, kotimaisia toimialojen välisiä ja toimialojen sisäisiä (eli yritysten välisiä) teknologiavirtoja koskevien tutkimusten tuloksista. Tulosten mukaan tahattomia teknologiavirtoja on olemassa ja niiden merkitys saattaa olla hyvinkin suuri. Näiden ulkoisvaikutusten vuoksi tutkimustoiminnan kansantaloudellinen tuotto, joka vaihtelee melkoisesti toimialoittain, saattaa olla huomattavasti suurempi kuin liiketaloudellinen tuotto. Niiden on myös useissa tutkimuksissa todettu selvästi parantavan kokonaistuottavuutta. Tahattomia teknologiavirtoja esiintyy sekä yritysten, toimialojen että kansantalouksien välillä.

Luvussa 4 esitetään keskeisiä tutkimustuloksia eri maiden välisiä tahattomia teknologiavirtoja koskevista tutkimuksista. Useimmiten nämä tutkimukset ovat koskeneet Yhdysvaltoja, Kanadaa ja/tai Japania. Tulosten mukaan maiden välisiä teknologiavirtoja on olemassa, mutta niiden merkitys on joissakin tapauksissa odotettua pienempi. Suuret maat, erityisesti Yhdysvallat, jotka toteuttavat valtaosan maailman kaikesta tutkimustoiminnasta, näyttävät olevan merkittävä tahattomien teknologiavirtojen lähde. Näitä virtoja vastaanottaviin toimialoihin kohdistuvien vaikutusten suuruuteen vaikuttavat kyseisen kansantalouden avoimuus sekä yritysten kyky omaksua ja soveltaa uusia teknologioita ja tuoteideoita omaan käyttöön (absorptiokyky). Tämä kyky liittyy läheisesti yritysten valmiuteen kehittää osaamistaan eri tavoin. Myös teknologinen läheisyys johtavien teknologiantuottajien kanssa on selvä etu, toisin sanoen se, että aikaisemmat teknologiat ja tuotteet, joihin uutuudet osaksi perustuvat, ovat entuudestaan tuttuja.

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1. Innovation, externalities and growth: basic concepts[1]

This paper focuses on technology spillovers. Its aim is to provide an introduction to the spillover concept: what are the basic characteristics of spillovers, starting from a broader perspective on innovation and growth, and referring also to a few closely related concepts. The paper then reviews several approaches and empirical studies dealing with the measurement of spillovers and their effects. Since there are already several reviews (see, for example, Griliches 1992, Mohnen 1990 and 1996, Mairesse and Mohnen 1994, Nadiri 1993) which, with slightly different points of departure, have looked at the existing studies, there is no attempt in this paper to be anything like exhaustive. Instead, the aim is to provide a brief overview of this increasingly important research area, and discuss a few approaches that are central for the further development of our insight into the process of technological change.

Several somewhat different, but often related, approaches have recently been used to analyse the innovation process and its effects. Some of these can be characterised as *systems approaches*. Smith (1995) distinguishes between three types of such approaches: technological systems approaches, industrial cluster approaches, and analyses of national innovation systems. These approaches have several common features, including their focus on the interactions between the various partners in the systems.

A further development is the concept of knowledge system and its so-called *distribution power*. This approach analyses different types of knowledge and their forms of interaction (see David and Foray 1995 and the discussion in Smith 1995). In a complex structure of differentiated knowledges, "what determines performance is not so much knowledge creation as the distribution power of the system: the system's capability to ensure timely access by innovators to the relevant stocks of knowledge. The

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distribution power of the system affects risks in knowledge creation and use, speed of access to knowledge, the amount of socially-wasteful duplication and so on." (Smith 1996, p. 83)

Another large group of studies has developed largely on the basis of neoclassical production theory. These studies are often labelled as representing "new" growth theory. However, the models which they use often have quite a lot in common with the older ones, or take up ideas which had perhaps been presented decades earlier (see Eliasson 1994, Nelson 1994 and Verspagen 1992). Originally, these models have analysed growth in the economy on an aggregate level (see Romer 1994), but their features have also been adopted in several empirical micro-level studies. One central concept in these models is *externalities*.

The existence of externalities in the innovation process is closely connected with the existence of increasing returns to scale in the aggregate production function. Externalities imply that when one firm increases its inputs, the inputs of other firms also increase. This results in more than a proportionate increase in aggregate output. This is in contrast with earlier (neo-classical) models, where constant returns to scale in the production process are in general assumed. (Verspagen 1992 p. 636)

Following Weder and Grubel (1993), new growth theory distinguishes between four factors of production. Thus, the aggregate production function can be written as $Y = F(K, L, H; A)$, where Y is national output, K is physical capital, H is human capital and A is knowledge or technology. Knowledge is considered as a partially excludable and nonrival input factor. *Excludability* involves that the originator of research is able to exclude others from an unauthorized use of the acquired knowledge. This can be done through some kind of intellectual property rights, for instance, patents, which thus creates the incentive to conduct R&D. However, a crucial assumption in the theory is that patents etc. can only partially exclude the use of some aspect of the knowledge in other economic activities. Thus, research and development efforts create positive externalities.

Nonrivalry implies that an idea can be used by someone in an economic activity without reducing the usefulness of the idea when used by someone else. Thus, knowledge can be used by an infinite number of firms and in an infinite number of periods without additional costs and without reducing the value of this factor. In addition, the low cost of using existing knowledge also lowers the cost of producing new knowledge. Therefore, knowledge capital formation involves dynamic scale economies, which may lead to intertemporal positive externalities from private R&D. (Weder and Grubel 1993 p. 490)

Some authors distinguish between pecuniary and technological externalities (see Liebowitz and Margolis 1994). *Pecuniary externalities* are described as external effects that work through the price mechanism. In this case those on one side of the market, such as buyers, benefit, while those on the other side of the market, such as sellers, suffer. The market solution involves internalizing all the external effects. *Technological externalities* are related to market failures, such as pollution, congestion etc. In such cases benefits or costs are imposed outside of market mechanisms. Such problems may be solved by means of property rights, private negotiations or government interventions which allow the externalities to be internalized (Liebowitz and Margolis 1994).

This distinction is related to the concept of *network externalities*. Liebowitz and Margolis use a narrower definition of these externalities than several other authors. They define a network effect as a circumstance in which the net value of an action is affected by the number of agents taking equivalent actions. Network externalities are defined as a specific kind of network effect in which the equilibrium exhibits unexploited gains from trade regarding network participation. These can be further divided into direct and indirect network externalities.

Direct network externalities are generated through a direct physical effect of the number of purchasers on the quality of the product. A well-known example of such effects is a telephone network. Indirect externalities occur in situations where complementary goods become more plentiful and lower in price as the number of users of the good increases. For example, software may become more plentiful and cheaper when the number of computer users increases. Similarly, the supply of post-purchase service for durable goods, such as cars, may be expected to increase with the number of such goods in use. The concepts pecuniary externalities and indirect network externalities are closely related (Liebowitz and Margolis 1994, and Katz and Shapiro 1985, as cited by the former authors).

Weder and Grubel (1993) take a critical view towards a typical policy implication based on new growth theory, namely that because of the positive externalities related to R&D investments, government interventions and, specifically, R&D subsidies are required to promote growth. They claim, on the basis of principles developed by R. Coase, that these externalities will induce the creation of private institutions capable of internalizing them. There are many ways in which private agents may capture the spillovers from R&D. These institutions may be grouped into three categories: industrial associations, company structures and industrial clusters. The first two kinds of institutions bind together and coordinate through sets of rules the behaviour of otherwise legally and economically independent firms. The third category internalizes externalities from the operations of individual firms located in regional clusters of industries, and through physical proximity, facilitates the operations of associations and company structures.

Therefore, Weder and Grubel conclude that rather than following a strict antitrust policy combined with R&D subsidies, public policy should allow or encourage the operation of such efficiency-enhancing institutions, since they correct the potential market failure inherent in the private R&D investment process. Policymakers should also limit the tendency for rent-seeking activities of private agents by establishing constraints on cooperative agreements which are unrelated to the internalization of externalities from private knowledge creation. (Weder and Grubel 1993).

It is easy to agree with Grossman and Helpman (1994) that "Growth theory has taken a step in the right direction by including aspects of reality - imperfect competition, incomplete appropriability, international interdependence, and increasing returns to scale - that [...] are important to understanding how much an economy will invest in knowledge of various kinds." Much further research is needed, however, before theoretical and empirical research will be sufficiently linked together to provide a satisfactory description of technological change.

2. *The spillover concept*

Another widely used concept in the recent literature on technological change is technology spillovers. Spillovers are a specific kind of externality and thus, the spillover concept is narrower than the externality concept. In general, however, the spillover concept has been only vaguely defined (if at all), and consequently its content varies considerably across studies. Some authors clearly use a much broader spillover concept than others, and this causes an unnecessary loss of clarity. The lack a well-defined spillover concept is, in particular, found in some empirical studies.

Partly this confusion seems to be based on the inherently abstract nature of the spillover phenomenon and the consequently few links between theoretical and empirical studies dealing with the subject. Thus, the empirical ones consist of, at best, crude approximations of the amounts of knowledge or technology that are being transferred. It would be desirable to find a narrower and more precise definition of spillovers, which would allow more comparison between research results and perhaps a deeper understanding of the phenomenon itself. This section discusses the characteristics of spillovers and aims at clarifying the concept.

Spillovers are one form of technology diffusion, which thus is a broader concept. There are several related concepts, which can be classified as in Figure 1. The indirect technology sources (approximately equivalent to technology diffusion) used by a firm or industry, which are distinct from its own research activities, have here been further divided into transactions-based technology use and other technology diffusion. This distinction is important from the point of view of spillovers, as shown below.

Figure 1. Sources of technology in output

Direct technology inputs	Indirect technology inputs (Technology diffusion)
1. R&D by final producer	2. Transactions-based technology use a. Technology embodied in intermediate inputs - Domestic - Imported b. Technology embodied in capital inputs - Domestic - Imported c. Other transactions-based technology - Patents, licences etc. 3. Other technology diffusion - Spillovers - Education, learning etc.

Sources: Based on Davis 1988 and Vuori 1995

Recent OECD reports distinguish between disembodied technology diffusion and equipment-embodied technology diffusion. Disembodied technology diffusion is noted to be characterised by research spillovers and by the absorptive capacity of firms. Further, the term research spillover is defined to refer to knowledge developed by one firm becoming potentially available to other firms or industries. Depending on the methodology used, the measurement of technology flows across industries captures primarily either disembodied flows or embodied flows. Work on interindustry flows through patents is claimed to be closer to modelling disembodied diffusion flows, whereas work using interindustry transactions flows based on input-output data is closer to embodied diffusion. In practice, however, in both cases the measure of total technology level or intensity of a particular industry can reflect both embodied and disembodied diffusion (OECD, Technology and the economy, 1992, p. 47 and Papaconstantinou et al., 1996, p. 9-10).

As Mohnen (1990, p. 133) notes, technology spillovers arise since the results of R&D efforts are not entirely appropriable. Other firms, research institutes, and industries both at home and abroad benefit, to a varying extent, from the research results produced by one firm or other unit active in research. It is now widely agreed that there are spillovers of two kinds: information (or knowledge) spillovers and productivity spillovers, which often cannot be separated from each other, especially in empirical research. Information spillovers arise when a research team can obtain (at least part of) the results of others by means of various "information leakages" (from conferences, patent documents, discussions with colleagues in rival firms or institutes etc.).

Information spillovers do not necessarily require any direct input-output links between the parties involved (see Mohnen 1990 p. 133). Productivity spillovers, in turn, arise as a consequence of prices which do not fully reflect the higher user value of improved products or processes. Partly this kind of spillovers can be seen as a consequence of conventional measurement problems (see e.g. Griliches 1992 and Mohnen 1990).

These spillovers are sometimes also called rent spillovers (see, for example, Los and Verspagen 1996). Like externalities in general, also spillovers can have negative effects. Such situations are briefly discussed in Mohnen (1996; see also section 3).

As a basis for the following argumentation, I define spillovers in the following way: *spillovers are technology or information flows from one economic agent to another which are involuntary from the point of view of their source and which are not based on economic transactions.* This definition focuses on "true" or information spillovers, and takes up two essential features of spillovers. Spillovers occur basically in the form of "leakages". In order to justify this notion, spillovers should be defined to cover only such transfers of technology or knowledge, which are not as such economic transactions. A similar view is expressed by d'Aspremont and Jaquemin (1988, p. 1133): "The R&D externalities or spillovers imply that some benefits of each firm's R&D flow without payment to other firms". In other words, this knowledge flows from one economic agent to another in the form of a leakage. Secondly, this implies that the source or "sender" of spillovers should not have aimed at giving the knowledge away. In contrast, the receiver or user of the spillover may or may not have aimed at obtaining the knowledge.

Verspagen (1995) approaches the same phenomenon using the notion of appropriable and non-appropriable aspects of technology. According to him, most methods for measuring technology flows between sectors focus on the appropriable aspects of technology. For example, the method based on the sector-of-use versus sector-of-origin distinction assumes that technology flows occur only if some product is being exchanged. Such flows can, however, be accompanied by spillovers when the "full" price is not being paid (see Verspagen 1995, p. 2). In between, Verspagen speaks of "indirect" R&D, referring to embodied-kind of technology flows, apparently as equivalent to spillovers. He notes that "Knowledge is not always embodied in a good or service" and that "the many different approaches to measuring technology flows which are based on these user-producer methods should be complemented by methods which do not rely on this specific methodology to such a large extent", and proposes a "non-input-output" -method based on patent statistics to do this (see Verspagen 1995, p. 2-3 and 15). Thus, in that paper as in many others, the distinction between spillovers and other types of indirect technology (or technology diffusion), is not clear enough for drawing the right conclusions as to what kinds of technology components are more important than others.

De Bondt (1995) adds to the confusion (while in fact claiming to try to avoid it) mentioned above by speaking about spillovers as *voluntary* or involuntary leakages of knowledge or know-how: "...spillovers will here be equivalent to knowledge spillovers: involuntary leakage or voluntary exchange of useful technological information." He goes on discussing firms' taking efforts to arrange deliberate mechanisms of spillovers. However, in the cases he discusses (informal arrangements between rivals and research joint ventures), the parties involved expect to get something in exchange for the information that they give away. (De Bondt 1995, pp. 3 and 7) Thus, even when there are no fees being paid, the nature of the exchange is that of a transaction, and according to the definition above, should not be called a spillover.

2.1. Measurement of spillovers

Several methods of measuring spillovers empirically have recently been used. These methods have been surveyed, among others, by Mohnen (1990) and Nadiri (1993). Mohnen (1990) divides the studies in two main groups. A lot of the studies attempt at measuring the welfare effects of the spillover or at evaluating the social rate of return on R&D without specifying the interindustry links of the spillover, whereas another group of studies specifically looks at the links between the source and the receiving sectors. Examples of the first group of studies include Mansfield et al. (1977), Bresnahan (1986) and Griliches and Mairesse (1983).

Following Mohnen (1990), the second group of studies, where the channels of transmission of the interindustry spillover are modelled, can be further divided into six different approaches. In one of the approaches, the spillover is an unweighted sum of the R&D stocks of all other sectors in the economy or in the industry. Studies where the R&D spillover variable is a weighted sum of all the other R&D stocks can be further divided on the basis of how the weights are determined. In the studies reviewed, the weights have been proportional to the flows of intermediate input purchases, the flows of patents or the flows of innovations between the sectors, or to the correlation of the position vectors of the sectors in a technology space. In the sixth approach, the stock of each potential source of R&D spillover is entered separately into the production function.

Nadiri (1993, p. 17), in turn, divides the methodological approaches to estimate the magnitudes of R&D spillovers and their effects on productivity growth into two groups. The "technology flow" approach uses an input-output (I-O) or a technology matrix based on patent data to position the firms or industries in a matrix of technological linkages and examines the spillover effects of R&D undertaken by one firm or industry on the remaining firms or industries. The second approach is an econometric one which estimates the effects of spillover on the costs and structure of production of the receiving firms or industries. This is called the "cost function" approach by Nadiri.

Examples of studies and reviews where technology embodied in purchased intermediate and capital goods used in production are used for measuring spillovers are Nadiri 1993 (see especially pp. 19-20) and Mairesse and Mohnen 1994 (pp. 836-838 and 848). In these papers studies using the "technology flow approach" and the "cost function approach" (see Nadiri 1993) have been seen as representing the same group of studies. However, the "technology flow approach" is often based on transactions, where technology is transferred from one economic unit to another in proportion to the magnitudes of these transactions. Similarly, in the second approach of Mohnen's six approaches mentioned above, using different weighting schemes, R&D stocks of other sectors are weighted in proportion to intermediate input purchases to obtain estimates of spillovers. On the basis of the definition of spillovers above, these cases should not in fact be interpreted as measurement of spillovers. Since here actual purchases of technology are the basis for theses measures, they are closer to a measure of technology embodied in the inputs than a measure of spillovers.

Depending on the point of view of the observer, the technology flows involved can be seen as representing either actual transaction-based technology transfers (embodied technology) or as proximity measures describing somehow the ease of producing and receiving spillovers. The latter interpretation seems to be one version of the general idea that spillovers consist of other sectors' R&D weighted by some sort of "distance", or proximity measure. The weights can be interpreted as the effective fraction of knowledge in industry j borrowed by industry i (see Griliches 1992).

However, in this special case (using this kind of weights), the interpretation of what is being measured is a most confusing one. This kind of "spillover measure" leads to similar results as when technology embodied in the inputs are estimated. According to the latter view, the buyers of intermediate and capital goods receive a part of the technology produced by the producer of those goods, which is proportional to the size of their input purchases (see, for instance, Terleckyj 1980). However, as noted above, this kind of similarity in the measures of two at least in principle separate things should be avoided.

When a firm buys, for instance, a new machine which is technologically superior to the ones it already uses, it deliberately also buys the new or improved technology, not just the machine. The price it pays for it, therefore, includes a rent to the additional technological content, even if it were not high enough to reflect the full economic value of the improvement. Thus, the potential spillover should be linked, rather than to the value of that purchased technology, to the difference (if it could be measured) between the user value of the technology bought and the price actually paid for it.

It is important to keep these two technology components apart. The impossibility of the input-purchases-weighted spillover measure can be seen if thinking of an econometric model, where some performance variable (typically productivity) is explained by the distinct technology factors available to firms. What would then be the difference between the variable representing embodied technology and one representing spillovers? The variables would be much too similar (if not totally similar) for separating their effects from each other. Therefore, to avoid confusion, technology flow measures based on input purchases should be used only in the context of measuring embodied technology, and spillovers should be measured using other kinds of weighting schemes.

The measurement of technology flows which is based on technological proximity (for example, Jaffe 1986, Goto and Suzuki 1989, and Vuori 1995 and 1997), assumes that the ability to receive or absorb spillovers is dependent on whether the firm or industry is already familiar with the area in question. This is in line with the idea expressed by Cohen and Levinthal (1989) that firms invest in research and development not only to be able to generate product and process innovations, but also to develop their absorptive capacity, whereby they will be better able to use knowledge produced outside the firms. Similarly, the results of a survey which concerned Swiss firms active in R&D (Harabi 1995) showed that undertaking independent R&D was perceived as the most effective channel of R&D spillovers. The following most important spillover channels were reverse engineering for product innovations and the utilization of publications and information from technical meetings for process innovations.

3. *Domestic inter-industry and intra-industry technology flows*

A large number of empirical studies on inter-industry and intra-industry technology flows have emerged in the last couple of decades, and the growth in their number clearly accelerated in the late 1980s and early 1990s. Quite often most kinds of these flows are called spillovers, which according to the view taken in the previous section is not strictly correct. Several reviews on the measurement of domestic technology flows and their effects on some performance variable(s) have also appeared. The most recent ones include Griliches (1992), Nadiri (1993) and Mohnen (1996). Therefore, a thorough review here does not seem to be worthwhile. Instead, the main conclusions only from Mohnen (1996) will be repeated here for the sake of a brief overview of where we now stand in this research field. A somewhat more detailed review is made of international spillovers in section 4, since this area seems to be becoming increasingly important.

Mohnen (1996) reviews a considerable number of studies which estimate an R&D "spillover" effect. These studies are classified both on the basis of the methodology and of the data used. The primal approach is based on a production function, in general an extended Cobb-Douglas function. The dual approach is in general based on a flexible functional form of a variable cost function. The approaches can be further characterised by which kind of weighting schemes they use in aggregating the R&D stocks originating from outside the firm or industry. Mohnen also groups the studies in ones that deal with domestic inter-industry spillovers, domestic inter-firm spillovers, specific R&D spillovers (for example, academic R&D), and international spillovers.

For several reasons, the various studies are not easily compared. Mohnen lists the most important reasons: differences in the data, the model, the dimension of variation in the data, the weighting matrices for R&D spillovers, assumed R&D depreciation rates, the lag structures of R&D, the number of externality receivers included in the computation of the social rate of return, definitions of the rate of return, etc. The main conclusions of the studies reviewed are as follows.

First, the studies show that R&D "spillovers" exist. Secondly, the social rate of return on R&D exceeds the private rate of return by 50 to 100 per cent. Thirdly, the domestic social rate of return to R&D shows a great dispersion across industries. Fourthly, estimated spillovers are more often positive than negative. While in general technology spillovers are expected to have positive effects, in several situations also negative effects seem possible. There may be strategic reasons for taking part in an R&D race, even if no profits can be expected from this activity. Spillovers may also affect prices or the demand for old products negatively. In addition, the adjustment costs required for learning the new technologies may be high. (Mohnen 1996, pp. 51-53).

Fiftly, spillovers are present at all levels of disaggregation. Further, there are clear signs of international spillovers (see the next section for more details). The evidence of spillovers being geographically localised is somewhat mixed. In addition, there are some results regarding the effects of R&D spillovers on factor demands, and on the determinants or the endogeneity of R&D spillovers. R&D spillovers seem to have a similar ranking in magnitude as the corresponding own R&D. Further, according to several studies R&D spillovers contribute significantly to total factor productivity growth. Finally, there is mixed evidence regarding the hypothesis of a decline in the externality effects of R&D. (For further details, see Mohnen 1996).

4. *International spillovers*

In the last few years there has been a rapidly increasing interest, in the form of both theoretical and empirical papers, in the economic consequences of international technology spillovers. These papers can be seen as a natural extension to the earlier already quite substantial literature on the effects of the firms' and industries' own R&D, and more recently also of other technology inputs, such as technology embodied in purchased intermediate and capital goods, on their performance. They can also be seen as a consequence of observing the rapidly increasing globalisation and network formation among business firms. Most often, these studies deal with the U.S., Canada and/or Japan. Without trying to cover the whole literature on international spillovers, a few examples of recent empirical research representing several typical approaches in this area are presented in the following. A few other studies dealing with international spillovers are also reviewed in Mohnen (1996).

Various approaches and varying data have been used to measure international spillovers and to assess their effects. R&D stocks or flows of foreign industries or the whole business sector are the basis for measuring the spillovers. In some cases only certain high-tech sectors are looked at as potential spillover sources. Similarly as in the case of domestic spillovers, these R&D measures are in general weighted by some kind of proximity measure. This implies, as mentioned in section 2 above, that the closer the recipient is to the source of the spillover according to the measure concerned, the more it is thought to benefit from the technology created by the source. These proximity measures are based on total or high-tech imports, similarity of allocation of research funds across technology areas, patents and/or presence of foreign subsidiaries. The data used in these studies cover various periods and in the different cases one, two or several countries.

According to Bernstein and Mohnen (1994), international R&D spillovers can be transmitted in several ways: for example, through exports of goods and services, international alliances between firms, such as licensing agreements and joint ventures; foreign direct investment, international labour markets for scientists and engineers, international communications, such as conferences, and reverse engineering. Thus, spillovers may occur without international transactions taking place.

Bernstein and Mohnen develop a bilateral model of production between the U.S. and Japanese economies, where the production and R&D decisions for the U.S. and Japan are modelled simultaneously. They estimate the effects of international R&D spillovers on production cost, traditional factor demands (such as the demand for labour), the demand for R&D capital, and productivity growth rates in each country. The bilateral production model is generalized to account for adjustment costs associated with physical and research capital formation. The R&D spillover is modelled as the R&D capital of the foreign research intensive sector. The R&D capital stocks are based on cumulated deflated R&D expenditures with a 10 per cent depreciation rate. Initial stocks were calculated by grossing up initial deflated expenditures by the depreciation rate plus the growth rate of physical capital. (Bernstein and Mohnen 1994, pp. 2, 10, 30)

According to the results, short-run domestic R&D intensity is complementary to the international spillover. The complementarity persists and becomes stronger for the U.S. in the long run, and in Japan, U.S. R&D capital is substituted for Japan's own, leading to a lower R&D intensity. The Japanese R&D intensive sector substantially increases its knowledge intensity as the international spillover from the U.S. grows. Moreover, international spillovers enhance productivity growth in both countries. Spillovers from the U.S. account for about 60 per cent of Japanese productivity growth. The effect from Japan to the U.S. is smaller, 20 per cent. The social rates of return are, because of the spillovers, three and a half to four times greater than the private returns. (Bernstein and Mohnen pp. 28-29).

Coe and Helpman (1993) analyse how a country's productivity level depends on domestic and foreign R&D capital stocks. Cumulative R&D expenditures are used as a proxy for a stock of knowledge. For 22 countries (21 OECD countries and Israel) they constructed a stock of domestic knowledge, based on domestic R&D expenditures, and a foreign stock of knowledge that was based on R&D spending of its trade partners. For the construction of foreign R&D capital stocks, import weighted sums of the trade partners' cumulative R&D spending levels were used. Coe and Helpman then estimated the effects of the domestic and foreign R&D capital stocks on total factor productivity.

The productivity and R&D capital stock estimates concern the business sector in each of the 22 countries. The nominal R&D expenditures were deflated by a price index, where the implicit deflator for business sector output and an index of average business sector wages were given equal weights. The research and development capital stocks were calculated using the perpetual inventory model, using a depreciation rate of 5 per cent. The foreign R&D capital stocks used in the econometric analysis were calculated as bilateral import-share weighted averages of the domestic R&D capital stocks of each country's 21 trading partners. (Coe and Helpman, pp. 2, 28-32)

According to the results, the countries' total factor productivity is affected by both their own R&D capital stock and the R&D capital stocks of their trade partners. Foreign R&D has a stronger effect on domestic productivity, the more open an economy is to international trade. In the large countries the effect of the domestic R&D capital stock is larger than the effect of the foreign capital stock. For most of the smaller countries, the effect of the foreign stock is larger. Exceptions are Finland, Australia and Spain, where imports in relation to GDP were between 14 and 27 per cent in 1971 and 1990. In contrast, foreign R&D had the strongest impact in countries with clearly higher import ratios: Belgium, Ireland, Israel and the Netherlands. In these countries the imports/ GDP ratio was between 42 and 88 per cent in 1971 and 1990. The largest spillovers seem to originate from the United States and Japan. In addition, the rate of return on R&D capital stocks is high, both in terms of domestic output and in terms of international spillovers. (Coe and Helpman 1993, pp. 10, 20-23, 26-27).

Also Park (1995) looks at the extent to which national R&D investments affect productivity and R&D investments in other countries. The study uses a growth-accounting framework and national-level OECD data for ten countries (not Finland) in the period 1970-87. The effects of public sector funded and private sector funded R&D are looked at separately.

R&D capital stocks are derived from R&D investment flows, using the perpetual inventory method. A depreciation rate of 3 per cent is assumed for the stocks. Investments in research are assumed to add to the stock of productive knowledge capital with a lag of 3 years or more. For estimating both spillovers into production and spillovers into research, an aggregate private sector production function and a private sector R&D investment equation are specified. In each country, technical efficiency of production is assumed to be dependent on both domestic and foreign R&D capital.

In constructing foreign research capital, each foreign country's R&D capital is weighted by terms representing technological distance between the countries. Thus, knowledge inputs from different countries are not perfect substitutes from the point of view of the domestic economy. The technological distance terms are defined as the angle between the two vectors representing the functional composition on R&D (the fractions of the countries' private research budget allocated to each category of research activity) for each pair of countries. The countries are thought to be technologically close neighbours if they have a similar functional composition of R&D. The approach is related to the one used by Jaffe (1986).

On the whole, foreign private knowledge spillovers tend to dominate the effects of domestic private knowledge. This can be seen as a consequence of the fact that most of global private research capital originates in a few major countries. Domestic private research has, however, a higher rate of return than does foreign. Private sector research is a more important determinant of private sector productivity growth than is public sector research. On the other hand, public research generates cross-national spillovers into research, so as to affect productivity growth indirectly by stimulating private R&D capital accumulation. This might be a consequence of public R&D's being largely basic and thus a more probable source of spillover.

The dominant role of the United States as a producer of research capital can be seen in some of the results. There seem to be technological spillovers into production with or without the U.S. in the sample of countries. In the case of spillovers into research, no significant spillovers from foreign private research into domestic private research can be found unless the U.S. is included in the sample. In general, since a few large countries perform most of global R&D, the foreign research capital variables tend to dominate their domestic counterparts in explaining productivity and private research investment. Therefore, some countries receive more spillovers than they create and for other countries the situation is the other way round. (Park 1995 pp. 582-589).

Mohnen (1992) examines, among other things, the extent to which Canadian manufacturing benefited from R&D conducted abroad between 1964 and 1983. In constructing a measure of foreign spillovers, imports of high-tech products were used as a proximity measure in the international technology space. The R&D stocks of high-tech product groups from five sectors (electrical products, transportation equipment, chemical products, scientific instruments and non-electrical machinery) were weighted by the import share of the corresponding sector in the total imports of these sectors to obtain the spillovers. Imports from the most important R&D performing five countries were considered. Of these countries (the United States, West-Germany, Japan, France and the United Kingdom), the United States by far dominate the spillover flows: according to the measure used, 98 per cent of foreign R&D flowing into Canada originated in the U.S. The end-of-period stocks of R&D knowledge were constructed using the perpetual inventory formula with a depreciation rate of ten per cent.

In the econometric analysis of the role of foreign R&D spillovers in Canadian manufacturing, both the primal approach based on the production function and the dual approach based on the cost function were used. According to Mohnen, the effect of foreign R&D is less strong than expected, especially in view of the importance of Canadian trade with the United States, the high percentage of foreign ownership of Canadian firms and the closeness to the U.S. market. The primal approach resulted in marginal productivities around 25 to 40 per cent. In several cases the coefficients were not significant. The dual approach yielded at best a rate of return of one per cent. Canadian R&D itself did not come out very strongly. Over the period 1965 to 1983, foreign R&D contributed by only 2.5 per cent to the total factor productivity growth in Canadian manufacturing. However, foreign R&D was found to be complementary to domestic R&D. Therefore, it is important to have a domestic knowledge basis in order to benefit from outside R&D. (Mohnen 1992 pp. 25-45 and 54-56)

In another study dealing with the Canadian situation, Hanel (1995) looks at the relationship between R&D and total factor productivity in the presence of inter-industry and international technology spillovers. The study concerns the Canadian manufacturing industries in the period 1974 to 1989. A method of constructing a proxy variable for international inter-industry technology spillovers is used where the normalized distributions of inventions patented in Canada by major industrialized (G-7) countries (Canada, the United States, Japan, the United Kingdom, Germany, France and Italy) are weighted by their respective R&D expenditures. This procedure leads to estimates of R&D expenditures in other industries in Canada and abroad creating spillovers that can be used by each Canadian industry.

The proxy variable used is a function of both patenting and production by foreign owned firms in Canada. Due to a high level of foreign control and ownership in Canadian manufacturing, foreign subsidiaries are thought to be the main outside sources of new technology, progressive management and entrepreneurship. The R&D used by industry j is computed from national patent matrices for the G-7 countries. These matrices indicate the number of Canadian patents issued to business corporations according to the industries most likely to manufacture and those most likely to use the patented inventions.

The patent matrices are used to assign the R&D expenditures of each manufacturing industry i in country k to each user industry j, in proportion to the number of Canadian patents for inventions expected to be manufactured by industry i in country k. It is further assumed that the actual inflow of foreign technology is proportional to the share of industry i's sales accounted for by subsidiaries owned by country k in Canada. These shares are used in calculating a weighted sum of the R&D intensities of the seven countries to obtain the total intensity of the j'th industry's use of imported R&D.

The econometric results are based on models where total factor productivity growth is explained by the industries' own R&D intensity, the intensity of spillovers from other Canadian industries, and the intensity of foreign spillovers. According to the results, the impact of domestic and international technology spillovers does not seem to be as important as theoretically expected and as indicated by other empirical studies. The estimated effect of international spillovers of R&D on total factor productivity is mostly statistically significant. However, its magnitude varies over time and is smaller than the effect of industry's own R&D (Hanel 1995).

Eaton and Kortum (1995) have a somewhat different approach. They examine productivity growth in five leading research economies (West Germany, France, the United Kingdom, Japan, and the United States). They use a multicountry model of technological innovation and diffusion to show that, for a wide range of parameter values, countries converge to a common growth rate, with relative productivities depending on the speed with which countries adopt technologies developed at home and abroad. Moreover, they simulate how the post-war growth experience would change had technology diffusion patterns been different than they were.

The model treats capital as perfectly mobile across countries. It consists of parts describing production, ideas and the technology frontier. Productivity differences across countries arise from differences in the quality of inputs. Quality improvements result from new ideas. An idea has three dimensions: its quality, its sector of application, and the time until it diffuses to each country. A distinction is made between diffusion and adoption of ideas. Whereas diffusion from one country to another will eventually be complete, some ideas will not be adopted. The model also considers either constant or rising researcher productivity.

Eaton and Kortum (1995) conclude that technology differences, not capital accumulation, explain differences in manufacturing productivity in the major industrial countries over the last four decades. Their model examines how patterns of innovation and technology diffusion explain these differences. They find that growth is primarily the result of research performed abroad. According to the results, even the United States obtains over 40 per cent of its growth from foreign innovations.

In sum, a general result of the studies reviewed here seems to be that international spillovers exist, but they are sometimes of less importance than expected, as the two studies dealing with the Canadian situation imply. Large countries (especially the United States) which perform a dominating share of world R&D seem to be a very significant source of international spillovers. Factors which affect the size of the effect of these spillovers on the sectors receiving them are the openness of the economy concerned and the ability to absorb and adapt new technologies and product ideas to own needs (absorptive capacity). The latter is closely related to the intensity of developing competences in various ways, and obviously also to familiarity with technologies and products related to the new ones, that is, technological proximity with the leading technology suppliers is a clear advantage.

5. *Final remark*

The role of various externalities in the growth processes of firms, industries and nations has increasingly been acknowledged in recent theoretical and empirical studies. Technology spillovers seem to be an important additional technology source, complementing the firms' own research efforts and various forms of purchased technology. Clearly, we should know more of the channels, mechanisms, magnitudes and effects of spillovers. Therefore, more research is needed.

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