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Mobility of Research Workers and Knowledge Diffusion as Evidenced in Patent Data

The Case of Liquid Crystal Display Technoloy

by

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Abstract:

This paper analyses the nature of knowledge spillovers from research and development (R&D) in the field of liquid crystal display technology by estimating the impact of inventors' changing organizational and collaborative affiliations on the probability of citations in US patents filed between 1976–1995, while controlling for geographic localization effects. It is argued that technology policy towards a particular industry must take the role of inventors' mobility in facilitating the flow of ideas across space and innovating organizations into account. Policy implications for the display industry are discussed against the background of previous experiences with government-sponsored R&D collaborations.

Keywords: Patent citations, knowledge spillovers, liquid crystal displays, R&D collaboration, technology policy

JEL Classifications: L63, O31, O33, O34

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Contents

1 Introduction

Technology policy is often intermingled with regional policy and the global development of the flat panel display industry provides a case in point. When innovative activities are *ex ante* geographically localized, an uneven spatial incidence may be inevitable for any policy promoting technological development. Yet, the deliberate merger of regional and technology policy does not merely seek to perpetuate existing patterns of technological activity, it rather seeks to initiate the formation of clusters in emerging fields or to strengthen the lead of existing centers of excellence. In Germany, for example, selected biotechnology clusters have been supported through a federal government program announced in 1995 which rewarded the three winners of a national competition among regional innovation networks. Eligible for federal funding have been only projects belonging to one of the regional clusters deemed by a jury of experts to possess superior technological prowess and innovative potential in its entirety.

Policies with a similar focus on the formation of regional cooperation in research and development (R&D) have also been pursued in the case of flat panel displays, a key technology which has enabled computers and communication equipment to become mobile and increasingly lightweight since the 1980s. In Japan, the government's Ministry for International Trade and Industry (MITI) took an active part in the formation of the *Giant Electronics Technology Corporation* (GTC) in 1989, in which a diverse group of large industrial firms cooperated on R&D to improve product design and manufacturing processes for liquid crystal displays (LCDs). In the US, the Advanced Technology Program (ATP) made one of its first competitive awards in 1991 to a research joint venture managed by the American Display Consortium (ADC), in which about ten mostly small and highly specialized flat panel companies sought protection from antitrust action through registration under the National Cooperative Research and Development Act (NCRA) of 1984 (Link 1998). In Europe, finally, a pre-competitive research consortium, the *European Consortium Active Matrix* (ECAM), was started in 1993 under the auspices of the ESPRIT program and effectively operated under the industrial leadership of Philips, a multinational consumer electronics firm headquartered in the Netherlands.

In theory, technology policy can improve the efficiency of the innovation process by supporting regional cooperation and the formation of clusters when knowledge spillovers from R&D constitute true technological externalities and are geographically localized (see Grossman and Helpman 1991). Regionally targeted R&D subsidies then improve firms' incentives to generate the spillovers and so enlarge the pool of knowledge on which cluster members can draw. Patent citations are widely believed to indicate knowledge spillovers from R&D. In a pioneering large sample analysis of citations from US patents, Jaffe et al. (1993) have indeed found that not only R&D activities per se, but also the knowledge spillovers thereof tend to be geographically localized. However, while only spillovers constituting non-market or true *technological* externalities can provide a *valid* rationale for public support of *private* R&D, *pecuniary* externalities, which emanate from agents possessing pricing power and work through the price system, may be localized as well. In the context of technological innovation, such pecuniary externalities have also been termed rent spillovers (Griliches 1979).

Two distinct kinds of rent spillovers are particularly relevant for technological innovation. One of these accompanies trade in new *intermediate* (or capital) *goods* whose price does not fully reflect the marginal valuation of their innovative qualities. As Jaffe et al. (1993) observe, such trade may even induce a subcontractor in the production of a new good to make a related invention and, perhaps, an unexpected killing without having to pay any royalties. The other kind of rent spillover works its way through the *labor market* where research workers who leave a job after acquiring special skills and technical expertise in a certain area of innovative activities may subsequently offer their services to other firms at a wage which may compensate the worker only partially for his special skills and knowledge. Instead of direct subsidies for R&D, rent spillovers may call for policies that lower barriers to trade and make labor markets more flexible so that specialized human capital is readily reallocated to its most productive utilization. In a perfect labor market, the mobility of research workers cannot cause underinvestment in R&D (cf. Klette et al. 2000).

While a large body of empirical studies has estimated the economic impact of knowledge spillovers from R&D at various levels of aggregation (for a survey, see Griliches 1992), there have been few attempts to discriminate between true technological and pecuniary or rent spillover effects empirically. This issue has only begun to be addressed in a few recent econometric studies of international and intersectoral spillovers, in which a spillover channel on the basis of bilateral trade linkages or user-producer relationships has been modeled explicitly (see Mohnen 1996). However, input-output flows are available only at the level of aggregate industries, while the relevant externalities are really related to inter-firm transactions. Moreover, by ignoring direct technological linkages between source and recipient sectors, most existing studies are likely to confuse rent spillovers with pure knowledge spillovers. Verspagen (1997b) therefore uses technology flow matrices, based on distance measures derived from patent classification schemes, to quantify international spillovers at the sectoral level and finds evidence for the simultaneous presence of both types of spillovers. But even this study cannot cleanly separate the different types of spillovers because the aggregate data it uses lump many different industries and countries together. Institutional and technological differences across industries, and countries, which determine, inter alia, the relative size of knowledge spillovers and pecuniary externalities as well as the private appropriability of returns to R&D, cast doubt on the validity of existing estimates from aggregate data.

A more promising approach looks at individual industries in isolation. In a detailed study of California's biotechnology industry, Zucker et al. (1994 and 1998) have found that several performance measures of innovative firms are strongly influenced by *contractual* or ownership *links* to individual star scientists at universities in that state. They argue that the complexity of discoveries in biotechnology imposes a 'natural excludability' so that the discoverer and his or her close associates hold intellectual capital affording them a temporary monopoly in commercial applications. Interested enterprises must enter into some kind of contract in order to buy the service of these scientists. Geographic localization of knowledge spillovers may thus be consistent with a model of market exchange, although not necessarily with the model of perfect competition.

Two studies of citation patterns in the US semiconductor industry have recently raised similar doubts about the importance of true technological externalities in the form of non-market spillovers from R&D. In one of these studies, Podolny and Shepard (1998) do find evidence that geographic proximity increases the probability of technological spillovers between firms, but they reject the hypothesis that spillovers are a source of agglomeration economies, defined as a feedback mechanism creating increasing returns at the local level. In fact, Podolny and Shepard (1998) observe that local citation propensities, defined as the probability of a spillover between any pair of two proximate firms, do *not* increase with the size of an agglomeration. Moreover, new firms appear to benefit significantly *more* from spillovers than incumbent firms — in contrast to what would be expected from true technological and therefore symmetric externalities. In the other study, Almeida and Kogut (1997) have shown that the geographically confined diffusion of ideas in the semiconductor industry has largely been driven by the inter-firm mobility of key scientists.

Regional concentration and regional policies to promote innovation have also been important issues in the liquid crystal display (LCD) industry. With hindsight, the question is whether the regional focus of innovation was really warranted given the underlying dynamics of knowledge diffusion in this particular area of technology. We know that for regionally targeted R&D subsidies to be welfare-improving, the industry under consideration must feature dynamic economies of scale *external* to the individual firm, or put differently, agglomeration economies in the R&D sector must be at least partly due to true technological externalities (cf. Grosman and Helpman 1991). Other sources of agglomeration may also be relevant for the industry, but they would have different policy implications. For example, if economies of scale are static, and mainly attributable to high set up costs for individual production plants, subsidies for the *production* or for the *adoption* of new goods would be superior from a welfare point of view, provided they correct the distortion due to the monopoly power which manufacturers typically derive from the exploitation of increasing returns at the plant level.

In the case of LCDs, economies of scale at the plant level are large and widely believed to represent a significant barrier to enter the mass manufacturing of LCDs. Even so, academics and small specialized research firms continue to play an important role in the innovation process, especially in the US. Much of the relevant knowledge is sufficiently codifiable and transferable between research establishments and manufacturing firms to accommodate a diversified model of industrial organization in which incentives for individual innovators can be maintained although imperfect competition rules among large-scale manufacturers of LCDs. Moreover, the coexistence of large manufacturers and small research-oriented firms suggests that the dynamics of knowledge diffusion among R&D laboratories and the location choice for manufacturing plants are two separate issues. Only the latter is determined by plant-level economies of scale that interact with financing conditions in a country. As a policy issue in its own right, the localization of the diffusion of knowledge then revolves around two critical questions, namely first, to what extent are knowledge spillovers really localized and, second, how important are true technological externalities in explaining the localization of incremental knowledge from R&D in the LCD industry.

Historically, Japan’s strong position in the broader semiconductor industry implied that many large Japanese firms enjoyed a head start in terms of the specific manufacturing skills and experiences that were relevant to the large scale fabrication of LCDs. Indeed, many of the major players of the Japanese electronics industry, like Sharp, Toshiba, NEC, Seiko-Epson and Hitachi, have become early and leading manufacturers of LCDs. The most basic ideas behind using liquid crystals for the visual display of information have long been common knowledge, easily codified and widely communicated since their origin in academic research at US and European universities during the 1960s and

1970s. At that time, Western industrial firms with dedicated research laboratories also contributed important discoveries, like RCA of the US in the 1960s and Hoffmann-LaRoche of Switzerland in the 1970s (Schmid-Schönbein 1998). It was in the subsequent mass manufacturing of LCDs that Japan took the lead and a few of South East Asia’s newly industrializing countries made substantial inroads in the late 1990s. In the academic realm, however, the West has continued to deliver world-class research on liquid crystals and other flat panel display technologies (cf. Sigurdson 1998).

The present study takes the geographic distribution of manufacturing as given and concentrates on the nature of knowledge spillovers within the R&D sector of the LCD industry. A discrete choice model of citations, which are assumed to represent knowledge spillovers, is estimated that explicitly considers the role of inventors’ mobility in facilitating the flow of ideas across innovating organizations by including a dummy variable for observed collaboration among any of the inventors of each pair of potentially citing and cited patent. Such collaboration will be documented in patent data either by the joint filing of a third patent or by joint affiliation of inventors with the same patenting organization. Collaboration of this sort should be viewed as a channel of rent spillovers through the labor market. Scientists and engineers are likely to internalize these spillovers at least partially through lower wage demands in exchange for work at a laboratory holding, ceteris paribus, more valuable learning opportunities. Under the hypothesis that rent spillovers through the labor market are significant, inclusion of the collaboration variable should diminish the estimated impact of geographic proximity on patent citations because labor markets themselves tend to be local markets and an important source of agglomerations as was pointed out already by Marshall (1922).

2 Technology Choice and Policy Strategies in the Display Industry

Display technologies are a key element of hardware systems in the information age. Without today's advanced displays serving as an interface between man and much of his modern equipment for communication and information processing, the practical use of such equipment would be very limited indeed. Even as computers' acoustic capabilities have improved through recent advances in speech recognition and text-to-speech technology, visual interfaces have remained dominant for many purposes and are likely to remain so in the foreseeable future. After all, man's reception of acoustic information is largely restricted to one dimension and a limited variation in speed and thus cannot match his capacity to absorb visual information. Although demand for displays is really a derived demand, which depends on the overall demand for communication and computing equipment, it would be too simple to view the innovation process in display technology as one being pulled by demand only. Instead, some of the most important leaps in the development of LCDs, which significantly increased the range and usefulness of their applications, exemplify the impact of new technology pushing supply in the wider computer and communications industry. In the second half of the 1990s, the global market for flat panel displays has more than tripled in size, from 8 billion USD in 1995 to well above 24 billion USD in 2000 (Young 2001). Flat panel displays have been aptly dubbed the „face of the digital economy".

The 1990's rapidly growing demand for light, thin and energy-efficient displays was created by the advent of portable computers in the 1980s. Cathode ray tubes (CRTs), the bulky displays used in televisions and desktop PCs, were found inappropriate because of their limited potential for reducing weight, size and electric power consumption. At the end of the 1990s, LCDs appeared to have won the race to meet the demand for mobile displays against several competing flat panel designs. More than 99 percent of all 15 million notebook computers sold in 1998 were equipped with a LCD, according to data from the University of Michigan Display Technology and Manufacturing Center. Since then, notebook computer sales have jumped to 24.4 million units, or 31.5 percent of the PC market, in 2000, with revenues rising from 4.3 billion USD to 10.1 billion USD (Young 2001). Laptop computers accounted for roughly four fifth of the flat panel market in 1996 (Wong and Mathews 1998) and together with a new breed of even smaller handheld computers for still more than one half in 2000 (Stanford Resources 2001). However, LCDs are increasingly used in a variety of other office applications, mobile phones, industrial monitors, medical instruments, automotive dashboards, high-definition television, cameras and inflight entertainment, broadening the range of applications considerably since the early days of low information content displays in digital watches and electronic calculators. Overall, the demand for LCDs has been driven both by entirely new product developments and by substitution for CRTs in existing products like desktop PCs. The global market volume jumped from 10.2 billion USD in 1998 to 22.6 billion USD in 2000 when revenue for LCDs accounted for 93.5 percent of all revenue from flat panel displays (Young 2001).

Other contenders to replace CRTs as the most widely used display technology included plasma and electroluminescent displays, but due to a mixture of limited product life, high unit costs and excessive power consumption, these have been much less successful in the market place than LCDs. Plasma displays still hold the promise to build the large screens that would be required to make high definition television more popular, while electroluminescent displays excel in terms of picture resolution and viewing qualities and have been widely adopted in niche market applications like measuring instruments, information terminals and engineering workstations. But both technologies have excessive power consumption and voltage requirements for fully mobile applications. Although AMLCDs have become the dominant technological paradigm, size limits still make them unsuitable for some applications, and the difficulty of producing faultless AMLCDs has kept unit costs high, in spite of increasing returns to scale at the plant level.

Apart from being a valuable ingredient of computer hardware, LCDs are also technologically related to the wider semiconductor industry and are susceptible to similar technology-induced supply shocks. The LCD product design and fabrication process share important organizational principles and materials with mass-produced computer chips. The common technological principle of all flat panel displays is an optical material, sandwiched between two glass plates that responds to electrical signals by reflecting or emitting light. Picture elements, called pixels, are defined by the intersections of rows and columns of electrodes that can be activated separately through computer-controlled drivers. Plasma and electroluminescent displays are similar in that they contain solid phosphor to generate light in each pixel that is electrically charged. LCDs, by contrast, are non-emissive and rely on an external source of light, usually placed behind the rear plate of glass, so that the sandwiched optical material merely changes the transmission of light. Liquid crystals do the trick by rotating in response to an electric field so that they can be lined up to let light pass, but the viewing angle remains restricted and so does the rate at which pixels respond to picture changes, relative to CRTs.

During the 1990s, passive matrix LCDs, commercialized since the early 1970s, have come to be increasingly displaced by active matrix LCDs (AMLCD), also known as thin-film transistor LCDs (TFT-LCDs), which effectively blend optical and semiconductor technologies and let each pixel be controlled by its own transistor. AMLCDs achieve much higher response rates and have thus enabled video applications, like mobile TV sets and notebook computers. AMLCDs were first introduced by Japanese firms and have been mass produced since the early 1990s.

As if technological change in flat panel displays were a test case for Sahal's paradigm of innovation avenues (Sahal 1985), commercial R&D in the 1990s has been focused on scaling the characteristic parameters of panel size, picture resolution, viewing angle, color capabilities, weight, power consumption, ruggedness and manufacturing costs. The unit costs of displays remain of paramount importance since they still account for the largest portion of manufacturing value added in portable computers even after mass-production of LCDs has led to considerable declines in unit costs over the past decade.

Increasing returns, both at the plant level and at the industry level, imply that the manufacturing of LCDs is characterized not only by huge setup costs, but also by very large investment risks when a firm expands its manufacturing capacity. As in semiconductor plants, clean rooms, photo-lithography, chemical processing equipment, advanced testing facilities and other sophisticated capital inputs are required, and workers need to be trained correspondingly (Linden et al. 1998). Moreover, large teams of production engineers are needed to supervise operations and seize learning opportunities whenever something fails to work according to plan. Even at present scales, each lumpy investment to build a new LCD fabrication plant represents a noticeable addition to world capacity which has begun to outpace demand in the late 1990s. Amid soaring shipments, prices for AMLCDs in the most popular size categories fell by approximately 50 percent during 1998 alone. Since then, prices have stayed at their depressed levels and AMLCDs have won a rapidly increasing share of the market for desktop monitors, reaching almost one quarter in 2000 (Young 2001).

The construction costs for a new display fabrication facility typically run into several hundreds of millions of US dollars — Linden et al. (1998) report initial capital investments of more than 500 million USD for a state-of-the-art plant in 1998 — and this has certainly been a significant barriers to entry for small and medium-sized firms. But the huge capital requirements have not deterred some large latecomers, like the industrial conglomerates Samsung and LG of Korea, from make their debut on the learning curve. The entry of large Korean firms was probably facilitated by preferential treatment in the Korean financial system (Linden et al. 1998). Under the impact of expanding capacity, manufacturing unit costs declined so rapidly that the cost of module, cell and array material in a typical 15“ XGA LCD accounted for well over three quarters of total unit costs at the end of the 1990s, according to Young (2001), an industry consultant. Total capital spending on TFT-LCD fabrication equipment grew from 1,300 million USD in 1998 to more than 6,000 million USD in 2000 when the output of Korea and Taiwan together reached about the same level as TFT-LCD production in Japan (Young 2001). In fact, Samsung of Korea and the Dutch-Korean joint venture LG-Philips ranked at the top in terms of their share of the notebook and desktop PC market for TFT-LCDs in the second quarter of 2000, but most of the other ten largest producers were Japanese electronics firms, such as NEC, Hitachi, Sharp, Toshiba and Fujitsu (Young 2001).

In 1994, the Sharp company alone held over 40 percent of the world market for LCDs, but did manufacture some of these in the US. For most of the final quarter of the twentieth century, LCD production activity and much of the related technological development have been concentrated in Japan. This prompted Bernard and Ravenhill (1995), Borrus and Hart (1994), among others, to argue that the flat panel industry, and LCD manufacturing in particular was characterized by a complex supply architecture based on country and firm specific knowledge and capabilities that do not readily diffuse outside of Japan. The production of LCDs indeed requires the combination of sophisticated process technologies, like thin film fabrication, cell assembly, materials technologies, coloration techniques as well as lighting technologies, and the art of successfully fusing complex technologies into electronic systems has long been an important element of competitive advantage for Japan’s leading high tech conglomerates (Schmid-Schönbein 1998).

The huge plant level economies of scale might have qualified the LCD industry for targeted export subsidies in line with the ‘new’ trade theory, but historically, protectionism has played only a minor role. In 1991, the US Department of Commerce’s International Trade Administration imposed antidumping duties on Japanese imports of AMLCDs, but these were removed in March 1993 when the only US petitioner actually producing AMLCDs, OIS, requested their removal (Schmid-Schönbein 1993). The main focus of public policy throughout the triad has rather been to encourage domestic cooperation in precompetitive R&D aimed at new generic product designs and better manufacturing processes. This policy sought to internalize the industry-wide economies of scale in R&D which arise when part of the new knowledge generated by an individual firm spills over, as an external effect, into a public pool of knowledge that all firms within a given region or country can draw on. By speeding up the local generation of new knowledge when diffusion is faster to domestic players than to foreign competitors, a country can actively develop a dynamic comparative advantage, as was shown in Grossman and Helpman (1991).

In Japan, industrial R&D cooperation on LCDs was organized by the Giant Electronics Technology Corporation (GTC) which was launched by the Japan Key Technology Center (JKTC) under guidance from MITI and leading electronic firms in March 1989. The mission of the GTC was to prepare the ground for quality leaps in AMLCDs by developing generic technologies for the production of much larger sized AMLCDs of up to one square meter scheduled to start in 1996. A related technical focus was to improve display resolution through advances in patterning technology, in the mobility of polysilison circuitry and in the fabrication of polysilicon film. Since this required simultaneous improvements in fabrication processes and materials technology, the GTC actually involved firms from four quite distinct, yet equally relevant areas of technology. In electronics, the major participating firms were Hitachi, Sharp and NEC, in glass technology Asahi Glass and Nippon Sheet Glass, in printing Dai Nippon Printing and Toppan Printing, and finally in liquid crystal materials technology, they were Japan Synthetic Rubber, ULVAC, Chisso and Hoechst Japan among others (cf. Schmid-Schönbein 1998). Further project partners included specialists for TFT design, Seiko-Epson, Fujitsu, Thomson CSF, and for the relevant fabrication process technologies, e.g. Sanyo and the Semiconductor Energy Lab.

Altogether 17 firms were selected by MITI to participate in the R&D collaboration, and the inclusion of the subsidiaries of two foreign firms, namely Hoechst of Germany and Thomson CSF of France, is particularly noteworthy. The GTC operated four thematic and one central coordinating committees, but did not operate a joint laboratory, nor did it provide for an exchange of researchers between different firms on a temporary basis. While university based researchers played a role in the formation of the GTC and in its ex-post evaluation, they did not contribute any significant research of their own (Schmid-Schönbein 1998). The collaboration was terminated in 1994 with the proviso that the GTC continue to exist as a patent holding company for another 15 years, although ex ante the issue of patent ownership had been left formally undecided and most participating firms appear to have mainly patented on their own account (Schmid-Schönbein 1998). With hindsight, the GTC appears to have achieved merely incremental innovations, but failed to make the manufacturing of very large scale AMLCDs feasible and commercially viable. This is consistent with the finding of Branstetter and Sakakibara (2000) that

Japanese consortia have generally been less sucessful when product market competition among consortium members was strong and when the consortia have focused on applied rather than on basic research.

In the US, cooperation in precompetitive R&D on flat panel displays began around the same time as in Japan, but it was orchestrated against a very different background. The pertinent industrial research and manufacturing activities of the large US electronic firms that helped pioneer flat panel displays in the 1960s was abandoned during the 1970s and early 1980s when one US firm after the other decided to leave the consumer electronics market. At the same time, an increasing standardization of components in the gradually maturing computer industry relieved manufacturers from the need to make all of a computer’s components inhouse. In the late 1980s, the US flat panel display industry was hardly visible in the product market and mainly consisted of a diverse group of small and medium sized research firms which formed the American Display Consortium (ADC), a non-profit coalition seeking protection from antitrust action in order to develop and manufacture flat panel displays. All of its members were highly specialised firms, like Norden and Planar Systems in the field of EL displays, Coloray Display Co., SI Diamond Technology Inc. and Silicon Video Co. in the field of field emission displays (FEDs), Kent Display Systems, OIS Optical Imaging Systems Inc., Standish LCD, Tektronix and Three-Five Systems in LCDs as well as Electro Plasma Inc., Photonics Imaging Inc. and Plasmaco in plasma displays.

In 1993, support for the fledgling US display industry became a priority for federal technology policy and ARPA joined private industry partners, including Xerox, AT&T, Standish and OIS, to establish the United States Display Consortium (USDC) as a non-profit public/private consortium to develop US manufacturing expertise in high definition displays, with particular emphasis on a domestic supply chain for high quality materials and specialized equipment. At that time, vertical coordination of the decentralized and dispersed R&D activities of display manufacturers, materials and equipment suppliers and display users — the firms incorporating flat panel displays in their own products — was seen as critical for catching up with the Japanese. Many of the small and medium-sized firms that made up the ADC also became members of the USDC.

In terms of its genesis, strategic objectives and management practice, the USDC was very different from the GTC of Japan. Federal funding for the USDC, and for other research programs related to flat panel displays, has mostly come from the US Department of Defense which wanted to secure domestic supplies of flat panel displays for military applications under the socalled dual use strategy of technology policy. There was no participation of foreign firms, nor was there any ex ante product strategy that favored one flat panel display technology over the others. In a further contrast to Japan's GTC, the USDC never intended to patent its findings itself, leaving the private incentives for participating firms to establish their own intellectual property rights untouched (Schmid-Schönbein 1998). On the input side, it is noteworthy that university research played a much more important role in the US, a prominent example being the Phosphor Technology Center of Excellence at the Georgia Institute of Technology, established by ARPA in 1993 with the American Display Consortium as one of its members. From 1994 on, the Flat Panel Display Initiative sought to coordinate all government support programs for R&D into flat panel displays. The USDC mission to serve as an instrument to vertically integrate a diverse group of display manufacturers, display users and numerous equipment and materials suppliers was clearly inspired by the success of SEMATECH, the widely known R&D collaboration that helped the US to increase research productivity and improve manufacturing in the memory chip industry in the late 1980s.

In Europe, the flat panel industry was technologically behind the Japanese, just like its US counterpart, at the beginning of the 1990s. And likewise, industrial R&D cooperation was also to become the strategy for Europe's attempted catch up with Japan, albeit with much more focus than in the US on just one dominant technological paradigm, namely enhanced AMLCDs. But the European display industry differed in terms of its industrial organization. Instead of featuring many small specialists, European manufacturing of flat panel displays was concentrated in a small group of long established firms, most notably Philips, the leading partner in the Flat Panel Display Co., a joint venture with SAGEM SA and Thomson LCD as experts in display design as well as Merck as the supplier of liquid crystal material. It was this joint venture which assumed a central coordinating role in the precompetitive R&D collaboration *European Consortium Active Matrix* (ECAM) which was officially sponsored as part of the European Union's ESPRIT program from 1990 to 1994. In accordance with ESPRIT rules, intellectual property rights were assigned to each individual participant contributing an invention to the collaboration. ECAM itself started in 1993 and its initial phase with 19 industrial and university participants from a variety of European countries lasted until 1995. The program was twice extended until 1998, but finally ended with disappointment when the special TFT technology contributed by SAGEM and the diode technology, originally developed and pushed by Philips as a focusing device, turned out to be roadblocks on the path to larger display sizes. Philips seems to have recognized this first and started a new joint venture with the Japanese AMLCD manufacturer

Hosiden which held property rights to a more promising TFT technology. The other member firms then left the FPD Co. and collaboration on a common European technology trajectory in the field of AMLCDs effectively ceased to exist. By 1999, however, Philips had become one of the world's preeminent suppliers of AMLCDs and entered into a joint manufacturing venture with Lucky Goldstar to expand the mass manufacturing of AMLCDs in South Korea.

In retrospect, the US and European collaborative R&D initiatives have both failed to facilitate quick catch up with Japan. Japan's GTC on the other hand may have provided an organizational model of R&D cooperation that US and European firms sought to emulate, but the reality of R&D cooperation failed to live up to its promise even in Japan. This, of course, does not necessarily imply that regional cooperation was a flawed strategy from the outset since its expected net-benefits may still have been positive ex ante. Indeed, a large-sample econometric study of Japanese government sponsored research consortia by Branstetter and Sakakibara (1997) found that participation generally had a positive impact on R&D productivity at the firm level and implied that this was at least partly due to increased knowledge spillovers among the member firms of the consortia. By providing a contrast to this general finding, the actual disappointment with R&D collaboration in the LCD industry highlights the importance of assessing the empirical basis of any future public support for regional R&D subsidies. It is because only knowledge spillovers that are true technological externalities can justify regionally targeted R&D subsidies that the present study places the nature of knowledge spillovers from R&D at the center of its analysis of the LCD industry.

3 The Data

The data for this study is from US patent class 349 „Liquid Crystal Cells, Elements and Systems“ and covers 1,398 patents filed at the US patent office between 1975 and 1995. The data has been taken from a series of CD-ROMs published by Derwent Corporation, which records patents by date of application. These patents involve 2,116 different inventors and are owned by 236 different assignees. Although LCD technology has its roots in the sciences, only four patents were assigned to one Japanese and three US universities during the observation period. 969 patents register more than one inventor, but multiple assignees are rare: in fact, only 46 patents, about three percent of the total, was assigned to more than a single owner. In 1993, for example, only 46 of 161 patents registered a sole inventor while 8 had more than one assignee. International collaborations are also rare.

Based on *fractional* counts for patents with multiple inventors, the single most prolific inventor over the whole period, had *about* 17 patents. The vast majority of inventors in the field obtained only one or two patents, thus confirming the observation by Lotka (1926), which Narin and Breitzman (1995) reexamined for patent data, that research was mainly driven by a relatively small number of highly productive scientists. A similar power law seems to hold for the frequency of contributions from different research organizations. The highest ranking assignee, Sharp of Japan, owned 199 patents, discounting for shared ownership. Most assignees, however, owned fewer than 5 patents. Patents appear to be more evenly distributed among inventors than among assignees. Table 1 shows that, for example, in 1993 there were 390 active inventors sharing 161 patent grants assigned to 63 owners from 8 countries. While the best individual inventor had only 2.7 patents the most prolific assignee obtained 21.5.

However, the gini coefficient for the distribution of patents among inventors is only slightly smaller than the gini for assignees in most years and even higher in some. A higher gini coefficient indicates a more uneven distribution. It seems that, despite rapid growth in the numbers of active inventors and assignees, the distribution of patents among inventors and assignees has not become more even over time. New entrants apparently face few barriers to becoming successful inventors in the field of liquid crystal technology. By contrast, the number of active countries has risen only slightly, and the gini coefficient for countries shows an upward trend, suggesting that inventive activity in LCD technology is increasingly concentrated in a small group of leading countries.

Table 1 Descriptive Statistics on Patents Flows in US-Class 349 (Fractional Counts by Filing Dates)

Year	Number of grants	Number of active inventors	Highest number of patents for individual inventor	Gini for the distribution of patents among inventors	Number of assignees	Highest number of patents for individual assignees	Gini for the distribution of patents among assignees	Number of countries with assignees	Highest number of patents for individual country	Gini for the distribution of patents among countries
1975	12	22	1.00	0.23	11	2.00	0.08	5	5.00	0.37
1976	29	52	1.33	0.31	15	6.00	0.38	6	13.00	0.44
1977	23	34	1.50	0.24	15	4.00	0.26	6	10.00	0.43
1978	32	54	1.83	0.31	16	9.00	0.40	4	18.00	0.47
1979	28	57	1.50	0.34	16	5.00	0.24	6	11.00	0.40
1980	43	78	1.33	0.32	23	9.00	0.35	6	25.00	0.57
1981	50	92	2.50	0.44	25	12.50	0.47	4	35.00	0.51
1982	41	83	4.00	0.38	22	6.00	0.36	5	19.00	0.49
1983	44	78	2.00	0.35	24	7.00	0.34	4	24.00	0.49
1984	44	97	2.00	0.35	27	5.00	0.28	5	25.00	0.55
1985	47	104	1.25	0.34	27	6.00	0.32	4	34.00	0.58
1986	62	120	4.00	0.37	34	8.00	0.33	8	38.00	0.70
1987	48	97	3.56	0.36	27	6.00	0.38	5	28.00	0.59
1988	103	218	2.50	0.41	47	12.83	0.48	7	69.50	0.72
1989	115	269	2.50	0.43	55	15.00	0.46	7	73.75	0.71
1990	103	216	2.17	0.37	49	10.00	0.38	5	70.00	0.64
1991	128	289	2.03	0.39	57	17.00	0.44	7	85.00	0.71
1992	135	317	3.00	0.39	54	24.50	0.49	7	98.50	0.72
1993	161	390	2.70	0.38	63	21.50	0.49	8	102.00	0.73
1994	142	360	2.00	0.37	62	20.50	0.43	9	91.00	0.74
1995	38	115	1.00	0.35	22	9.00	0.39	3	28.00	0.48

Note: The decline in the number of patents in 1994 and 1995 is probably artificial, due to the fact that processing of many applications from these years had not been completed at the time of data base compilation.

Indeed, a more detailed international comparison, based on Table 2, reveals that Japan has dominated the scene almost from the beginning. Over the whole period, Japan filed 896 patents, more than 60 percent of the total. In 1993 alone, Japan filed 102 of 161 patents granted, leaving the US a distant second with 36.5 patents in 1993, and 340 over the whole period. South Korea has been a successful innovator in the 1990s, obtaining 15 patents in 1993 and a total of 45 patents over the entire period. Germany with a total of 40 patents and Switzerland with a total of 23 obtained significant patent shares in the 1970s and early 1980s, but these two countries seem to have fallen behind since then. The UK and France with 22 and 21 patents, respectively, have apparently stayed on the sidelines of liquid crystal technology throughout the observation period. Sporadic patenting originated from Belgium, Canada, China, Ecuador, Finland, Israel, Italy, the Netherlands, Norway, Russia, Sweden and Yugoslavia. However, the evidence also indicates that patenting is not a necessary precondition for the manufacturing of LCDs. Taiwan, which has become a major producer and exporter in the 1990s, obtained only 7 patents over the entire period.

In the laboratory, innovations in the field of LCD technology seem to require a considerable amount of team work. Each inventor had on average 4 collaborators over the course of the observation period. Only 246 of 2,115 inventors, 12 percent, have always patented without the help of collaborating inventors. One inventor has even worked with as many as 36 different collaborators during the observation period. Of course, even when scientists and engineers working in the same R&D laboratory patent separately are there likely to be varying degrees of collaboration and sharing of information. The 236 assignees had on average 11 contributing inventors. One assignee, Sharp of Japan, even had as many as 238.

Inventor mobility can take many different forms in practice: For example, research workers may move among different laboratories owned by one and the same firm, or they may become an employee of a new firm when their old employer is the target of a take-over. In a similar vein, inventors may meet and collaborate in temporary research joint ventures. These are examples of inventor mobility where firms either directly internalize or negotiate, in line with the 'Coase theorem', to internalize spillovers as part of a larger bilateral transaction. But, of course, there may be other cases where teams at different firms are informationally linked through inventors changing jobs and taking their accumulated experiences and tacit knowledge with them. Klette et al. (2000) argue that such mobility will not diminish the investment incentives of the firm if labor and credit markets are perfect, because research workers would then be willing to bear the full cost of acquiring human capital through doing R&D, they would accept lower wages at the beginning of their career in anticipation of steep wage increases later.

Table 2 Patent Filings from Selected Source Countries of Patents in US-Class 349 (Fractional Counts)

Year	Japan	US	Korea	Germany	UK	France	Switzer-land	Taiwan
1975	4	5	0	1	1	0	0	0
1976	13	5	0	6	1	1	3	0
1977	4	10	0	1	1	2	5	0
1978	18	8	0	0	1	0	3	0
1979	11	7	0	5	1	2	2	0
1980	25	9	0	2	1	2	2	0
1981	35	9	0	3	0	0	3	0
1982	19	15	0	5	1	1	0	0
1983	24	15	0	2	1	0	0	0
1984	25	14	0	2	0	1	2	0
1985	34	11	0	1	0	1	0	0
1986	38	12	0	1	1	2	1	0
1987	28	15	0	0	1	1	0	0
1988	69.50	23.50	0	0	4	1	1	1
1989	73.75	32	2	1	3	1.25	0	0
1990	70	27	2	2	1	0	0	0
1991	85	31	6	2	0	1	0	1
1992	98.50	21.50	6	2	0	2	0	3
1993	102	36.50	15	3	1	1	0	1
1994	91	27	12	1	2	2	1	1
1995	28	6	2	0	0	0	0	0

Note: See Table 1.

In fact, among 2,098 inventors affiliated with the 236 recorded assignees in US patent class 349, a total of 444 changes of professional affiliation occurred during the observation period, not counting first time entry and terminal exit of inventors. If all inventors had indeed been active during the entire observation period, this would suggest that an inventor will change his affiliation with a probability of 20 percent during a 20 year period. But since many inventors have presumably entered the market late, or left early, the probability of a job change would be higher. On the other hand, there is evidence that the distribution of job changes is highly skewed. 90 percent of inventors had just one, 8.6 % had two and 1.4 percent had more than two documented organizational affiliations between 1975 and 1995. This implies that the small group of the 30 organizationally most mobile inventors had on average 11 documented affiliations, although some of these may have arisen because of multiple assignees to a single patent instead of full inter-organizational mobility.

For several reasons, I have not been able to measure all potentially relevant inventor mobility in the LCD industry. Much of it may indeed have taken place without leaving any paper trail whatsoever. For example, ideas may cross organizational boundaries through informal information trading based on self-reinforcing bilateral relationships of mutual trust (Schrader 1991), and this may be interpreted as an economically relevant mobility of minds. But I also miss much of the mobility that is documented, because I do not evaluate collaborations and colleague relationships documented in patents outside US class 349 some of which probably involve inventors from within. Moreover, I also ignore collaborative relationships that may be documented in coauthored scientific publications, although many of these may well be of economic significance in a science based field of technology such as liquid crystals.

The true inventor mobility in the field of LCD technology is likely to be much larger than the one I have been able to measure. My reason for not even including all the information on inventor mobility that can potentially be found in patent documents is the high cost of sampling. Although patent databases are now readily accessible, their evaluation for the purpose of this research has required considerable manual input, in order to check and correct minor spelling inconsistencies that often affect names and addresses of patent holders from countries other than the home country of the patent office. I rely on only 65 well documented cases of collaboration or colleague relationships that are not self-citations by inventors. I therefore suggest that the impact of my incomplete measure of inventor mobility be thought of as a lower bound of the likely true impact on technology diffusion.

Table 3 summarizes descriptive statistics for the data used in the probit analysis of citation choice and in the subsequent analysis of the determinants of geographic localization in patent citations.

Table 3 Descriptive Statistics on Citations to Patents Filed from 1980 to 1984

Citable patents	178
Potentially citing patents (average number)	1216
Their total of citations of patents from all classes	9709
Percent of patents receiving citations from subsequent patents in the same class	80
Number of citations in class 349	645
Mean per citable patent	3.62
Mean per cited patent	4.51
Average citation lag in years	7.21
Crudely adjusted for the swell in patents over time	3.09
Percent of self-citations by inventors	3.7
Percent of self-citations by assignees	8.8
Percent of all self-citations	9.6

Note: Citations are from patents in US class 349 filed between 1980 and 1995.

80 percent of the 178 patents filed in US class 349 from 1980 through 1983 received citations from the 1,216 potentially citing patents that have been filed in the same class up to 1995. But these 645 citations, received with an average adjusted lag of only 3 years, represent merely 6.6 percent of all citations made to the universe of US patents. The overall rate of self-citations is defined as including cases where the citing patent is assigned to the same organization as the cited patent and and cases where the citing patent merely lists at least one of the inventors of the cited patent; this rate is below 10 percent.

True self-citations, where at least one inventor is identitical, have been removed before undertaking the empirical analysis described in the following section. True self-citations obviously do not constitute a knowledge spillover. The mere equality of assignees, by contrast, need not necessarily be incompatible with the notion of knowledge spillovers broadly defined, especially when there are multiple assignees or a substantial time lag between the filings of the cited and the citing patent. Many firms actually find it difficult to prevent stocks of knowledge, which they themselves have accumulated through inhouse R&D, from falling into oblivion even among their own research staff over time. A loss of human capital is a natural consequence of inventor mobility for firms deserted by research workers seeking a higher income or better research opportunities elsewhere.

4 Empirical Patent Citation Choices

Experimental design. In line with recent research (Jaffe et al., 1993, and Narin et al., 1997, among others), the present study assumes that patent citations are a measure of technology diffusion. Citations are likely to be correlated with actual information flows, although two types of errors have to be considered: Applicants for patent protection may have an incentive to conceal sources of their ideas in order to stake a higher claim. Patent examiners, on the other hand, are responsible for making sure all relevant prior art is cited even if the inventor was unaware of it. As a result, there may be citations where there is no spillover and there may be spillovers that do not show up as a citation. However, only if these errors were correlated with our explanatory variables, should we get a serious econometric problem.

The present study analyses *two* discrete choice models, one for the determinants of citation choice and one for the determinants of localization among patent citations. Both models are based on the same set of potentially citing and cited patent pairs, obtained through an experimental design similar to that in Jaffe et al. (1993). In a first step, all citations to the 178 original patents in US class 349 filed during the years 1980 to 1983 were culled from subsequent patents in class 349 filed up to 1995. In a second step, for each of 645 documented citations, the citing patent was randomly paired with a noncited patent from the same group of 178 original patents. This procedure generated a data set of citing and nonciting patent pairs, in approximately equal numbers and with almost identical temporal lag distribution, and we shall refer to these pairwise observations also as citations and non-citations, respectively.

Description of variables. The following probit analysis of discrete choice includes several dummy variables as explanatories, whose means among citing and nonciting patent pairs are given in Table 4. The third column gives the *t*-statistic for testing the hypothesis that the dummy means in the group of citations equal those in the sample of non-citations. *Self-cites* are understood to be pairs of patents which list at least one common inventor. Because these *self-cites* clearly do *not* constitute a spillover, they have been removed from the data set. After removing self-citations and self-noncitations, the data set includes 618 citations and 629 noncitations.

In contrast to Jaffe et al. (1993), pairs where both patents have been assigned to the same organization have been retained. These pairs are captured by the dummy variable *assignee equality.* Not surprisingly, a significantly higher proportion of citations exhibits assignee equality compared to non-citations. But at 6 percent, against 4 percent for non-citations, the proportion remains small even among citations. A fading organizational memory or a shifting research focus over time may be possible explanations for this observation.

In my search for an economically meaningful measure of geographic distance between the location of inventions, I cannot rely on the US definition of a standard metropolitan area, which was used in several previous studies of patent citations. For this measure is not applicable in Europe and Asia. I therefore define three separate distance dummy variables, and I do this first with respect to assignee location, then with respect to inventor location: The dummy *neighbouring assignees* indicates that the primary assignees of a patent pair are located in the same country and less than 100 km apart. *Distant assignees* are those that are located more than 100 km apart, yet still in the same country. *Assignees in different countries* as a dummy is self-explanatory. Comparing the group of citations and non-citations, I observe significant differences in the means of all three distance dummies whose signs are consistent with the hypothesis of geographically localized knowledge spillovers.

However, when a corporation owns several laboratories, distances calculated on the basis of assignees' headquarter location may be misleading. Hence, an analogous classification of patent pairs has been made according to the distance between inventor locations. These distances, somewhat arbitrarily, refer to the locations of the inventors listed *first* on the patent document, ignoring the many instances of multiple inventors. This failure of incorporating location information about second and third inventors may explain why only the dummy for inventors in different countries confirm our expectations.

The variable *prior cooperation* indicates that any of the inventors of the later patent is linked to any of the inventors of the earlier patent *by having been collaborators or colleagues at some third organization between the filing dates of the paired patents.* This is indeed the *key variable* in the present study. Although in line with our maintained hypothesis, the mean of prior cooperation is slightly higher among citations than among non-citations, this difference is not significant at the five percent level.

Subclass equality indicates that both patents have been assigned to the same subclass, of which there are 184 in the dataset. This variable is an indicator of technological closeness within patent pairs and will be an important control variable in the discrete choice analysis. After all, it is possible that geographic regions develop distinct patterns of specialization in subfields of LCD technology — such as the chemistry of coating glass plates, advanced drivers and their interconnections with the display panel, or automated inspection and repair or other pertinent manufacturing process technologies. In this case, localized citation patterns might merely mirror specialization and would not necessarily indicate any spillover effects at all. As a caveat, however, one reason for specialization itself may be that a localized pool of knowledge lowers the opportunity costs for firms in a given region of doing R&D in a particular technological direction. Because complementary inventions patented by other firms, including competitors, can usually be obtained through licence agreements or the purchase of patents, the individual manufacturer may find specialization of its own R&D activity on a subset of LCD technology profitable.

Examiner equality indicates that both patents of a dyad had been cleared by the same examiner. This is another control variable recognizing the crucial role of the patent examiner in the genesis of patent citations. Some critics of empirical citation studies have suggested that many actual citations may reflect the distribtion of knowledge, workload and personal preferences among the official examiners at the US patent office.

Table 4 The Means of the Dummy Variables Used to Explain Citation Choice among 216,448 patent pairs in US-class 349

Number of observations	Citations 618	Non-citations 629	H_0: $p_c = p_o$ t-statistic
Assignee equality	0.06	0.04	**2.99**
Neighbouring assignees	0.35	0.28	**3.77**
Distant assignees in one country	0.13	0.16	**– 2.13**
Assignees in different countries	0.52	0.56	**– 2.01**
Neighbouring inventors	0.11	0.09	1.67
Distant inventors in one country	0.38	0.32	3.15
Inventors in different countries	0.52	0.58	**– 3.02**
Prior cooperation	0.04	0.03	1.36
Subclass equality	0.13	0.01	**12.08**
Examiner equality	0.12	0.10	1.60

Note: The test statistic $t = (p_c^* - p_o^*) / \sqrt{\left[p_c^*\left(1-p_c^*\right) + p_o^*\left(1-p_o^*\right)\right] / n}$, where p_c^* and p_o^* are estimates of the population means, is distributed as *t*. This tests for differences between independently drawn binomial distributions, with H_a: $p_c^* > p_o^*$ or H_a: $p_c^* < p_o^*$, as appropriate.

In addition to these dummies, our probit model of citation choice includes measures of appropriability and basicness, as suggested by Jaffe et al. (1993). These are thought to capture what should be exogenous characteristics of the potentially or actually cited patent in each dyad. Appropriability simply gives the number of subsequent citations by patents in class 349 that have been assigned to the same owner as the cited patent.

Basicness gives the *total* number of citations received from all subsequent patents in class 349. Here, I assume that the overall frequency of subsequent citations in class 349 captures an exogenous characteristic of the patent cited and is not simply the endogenous aggregate of individual choices. This assumption might be violated if technological development within the field of LCD technology was path dependent. Cumulative (stochastic) citations of one particular original patent might then make subsequent citations more likely by directing the focus of R&D onto a particular avenue at the base of which the cited original patent lies.

Finally, dummy variables for different temporal lags between the two patents of each pair were included. No linear time trend was assumed because the time lag dummies better accommodate the combination of an exponential process by which knowledge diffuses and a second exponential process by which knowledge becomes obsolete, as first observed by Caballero and Jaffe (1993).

Determinants of Citation Choice. Our probit model to explain citation choice does not use the full set of data from the 216,448 possible patent pairings in class 349 that are the subject of our analysis. While all citations (excluding genuine self-cites) are included, only an equal sized sample of non-citations will be evaluated. Such *choice based sampling requires* that the likelihood function be weighted so that the probability of inclusion in the sample is taken into account. Manski and Lerman (1977) have shown that a weighted exogenous sampling maximum likelihood estimator is consistent and asymptotically normal when the weights for choice i are calculated as the ratio of the corresponding population share *Q(i)* and sample share *H(i): w(i)* = *Q(i)/H(i)*. Since only 0.5 percent of patent pairs in the population are in fact citations, they receive a much smaller weight than the randomly matched non-citations.

Table 5 reports the estimated coefficients and corresponding standard errors from weighted probit regressions for the choice of citation. Only the proposed measure of basicness and subclass equality have a highly significant positive influence on the individual citation choice. Moreover, these positive influences are robustly confirmed when the original regression equation is respecified to exclude insignificant variables, except for the time lag dummies. According to all three reported estimates, prior cooperation does not have a significant influence on citation choice. This finding suggests that the mobility of research workers is not an important channel for the diffusion of knowledge in LCD technology. This in turn could reflect the strong science base of LCD technology which implies a high share of codified knowledge which is rapidly communicated through academic publications and conferences.

Table 5 Weighted Probit Model of Patent Citations — Estimated Coefficients (Standard Errors in Parentheses)

Citing country		All countries		US	Japan
Constant	– 24.609 (1.941)	– 24.551 (1.029)	– 24.562 (1.023)	– 23.717 (2.169)	– 25.926 (1.287)
Appropriability	– .057 (.302)	—	—	– .543 (.596)	.312 (0.365)
Basicness	**.321** (.063)	**.315** (.047)	**.315** (.046)	**.298** (.115)	**.368** (.077)
Subclass Equality	**12.356** (1.198)	**12.312** (1.188)	**12.304** (1.187)	**7.324** (1.959)	**19.592** (1.701)
Examiner Equality	.275 (1.555)	—	—	—	—
Assignee Equality	.831 (2.568)	.846 (2.458)	—	**6.847** (3.701)	– .289 (2.150)
Prior Cooperation	– .962 (3.024)	– .918 (2.940)	– .260 (2.043)	—	—
Large Inventor Distance	– .065 (1.575)	—	—	—	—
Foreign Inventor Dummy	– .105 (1.571)	—	—	—	—
Lag 4 to 6 years	.182 (1.418)	.061 (1.243)	.097 (1.240)	.487 (2.409)	– .380 (1.573)
Lag 7 to 9 years	.242 (1.447)	.110 (1.203)	.134 (1.203)	.425 (2.251)	– .158 (1.561)
Lag over 9 years	– .084 (1.541)	– .226 (1.307)	– .207 (1.306)	– .469 (2.482)	.283 (1.692)
Number of observations	1247	1247	1247	433	733
Percent citations	0.5	0.5	0.5	0.5	0.5
Likelihood Ratio c^2	– 361.3	– 361.4	– 361.4	– 128.6	– 191.2
Log Likelihood for full model	– 220.8	– 220.9	– 220.9	– 78.3	– 119.1
Log Likelihood for restricted model	– 40.2	– 40.2	– 40.2	– 14.0	– 23.5
Percent correctly predicted	50.4	50.4	50.4	50.3	51.7

An interesting finding is revealed in the separate regression for citation choices documented in US patents (column 4). In contrast to Japan (column 5), assignee equality does seem to have a significant positive influence on the choice of citations in US patents. This suggests that new technological knowledge diffuses less rapidly across the boundaries of firms in the US than it does in Japan, the main source country of LCD-related patents. Part of the explanation for these country-specific findings is likely to be the fact that Japanese firms have been more focused on upgrading the quality of just one dominant design, AMLCDs, while the mostly small independent research firms in the US have pursued a more diverse variety of approaches to designing flat panel displays.

Surprisingly, dummies for geographical distance between inventors and for the temporal distance between filings of patent pairs are not significant. Nor is the influence of appropriability significant.

Determinants of Spillover Localization. Our second discrete choice model follows Jaffe et al. (1993) and asks what determines localization among observed citations. The dependent variable is the dummy for neighbouring inventors, and the regression includes a dummy for the corresponding observation in the control sample of non-citations. In addition, the regression includes the full set of explanatory variables, apart from the distance dummies.

Table 6 reports the results from probit estimations with four different dependent variables. Of interest here is primarily the first column of Table 6. The estimated coefficients of this equation suggest that a geographic match in the control sample, appropriability, subclass equality, assignee equality and prior cooperation have a significant positive influence on the geographic localization of citation choices, while basicness and examiner equality exert a significant negative influence. This finding supports our hypothesis that the geographic localization of patent citations can be partly explained by cooperation and colleague relationships among inventors.

Moreover, also the positive impact of the control sample match and of appropriability are in line with expectations. Appropriability seems to be effective in preventing knowledge from spilling out to unrelated inventors so that localized citations become more likely. The negative impact of basicness is consistent with our prior belief that more basic ideas spread more quickly across spatial boundaries. The positive impact of subclass equality suggests that different regions may actually have developed unique patterns of technological specialization within LCD technology as defined by US patent class 349. The negative impact of examiner equality is consistent with the notion that they may often add citations where there are no real knowledge spillovers because an inventor was actually unaware of prior art relevant to his own work. Finally, the strong positive impact of assignee equality suggests that most firms do not spread their inventors around the world, but rather concentrate them in one or a few laboratories only.

How do these findings compare with those Jaffe et al. (1993) obtained for a much larger set of data covering the entire universe of US patents across all patent classes? It turns out that our findings confirm the findings of Jaffe et al. (1993) with respect to the positive influence of the control sample match, appropriability and basicness, although their definition of basicness was much broader, taking into account the generality of patent's impact across many different patent classes. The present study, by contrast, has deliberately focused on just one patent class in order to avoid the heterogeneity which different patterns of knowledge diffusion in unrelated fields of technology have presumably imposed on the data used by Jaffe et al. (1993).

Table 6 Geographic Probit Results — Estimated Coefficients (Standard Errors in Parentheses)

Dependent Variable	Local matches among inventors	Foreign matches among inventors	Local matches among assignees	Foreign matches among assignees
Constant	– 1.418 (.276)	.015 (.181)	– .991 (.192)	.024 (.180)
Dummy for control sample match	**0.641** (.225)	**.490** (.106)	**1.037** (.122)	**.472** (.105)
Appropriability	.094 (.066)	**– .145** (.040)	**.196** (.041)	**– .143** (.039)
Basicness	**–.029** (.015)	– .007 (.008)	– .007 (.009)	– .004 (.008)
Subclass Equality	**0.448** (.201)	**– .270** (.156)	**.374** (.162)	**– .251** (.156)
Examiner Equality	**–.880** (.392)	– .179 (.198)	.209 (.207)	– .184 (.198)
Assignee Equality	**1.484** (.335)	—	—	—
Prior Cooperation	**1.275** (.438)	—	—	—
Lag 4 to 6 years	– .065 (.297)	– .059 (.182)	.107 (.193)	– .057 (.182)
Lag 7 to 9 years	.013 (.294)	.001 (.187)	.126 (.198)	.006 (.187)
Lag over 9 years	.110 (.310)	.033 (.199)	.114 (.212)	– .007 (.199)
Number of observations	618	618	618	618
Percent matches	10.8	51.6	34.8	52.1
Likelihood Ratio c^2	118.2	57.5	116.2	52.6
Log Likelihood for full model	– 153.0	– 399.3	– 341.2	– 401.5
Log Likelihood for restricted model	– 212.1	– 428.0	– 399.3	– 427.8
Percent correctly predicted	92.2	59.1	73.8	60.4

5 Conclusions

The findings of this study can be summarized as follows: Patent citations in LCD technology and the knowledge spillovers they indicate are *not* random. The study thus confirms that there is an opportunity to use patent information in order to explore the changing nature of the diffusion of knowledge and ideas in innovating economies. By contrast, the adoption of new technology, which may ultimately be more important for the geographic distribution of manufacturing capacity and for the growth of total factor productivity, is a separate, if not entirely unrelated issue.

It is doubtful whether localization of the LCD industry can be attributed to R&D spillovers at all, be they true technological externalities or mere rent spillovers. Instead, economies of scale at the manufacturing plant level and their interaction with inherited firm-specific manufacturing skills and countries' financial market conditions appear to have been more important determinants of the observed location of LCD plants than any temporary lead in R&D. In particular, the striking geographic concentration of LCD manufacturing capacity in Japan, Korea and Taiwan must be seen in this light since Taiwan has had only a weak patenting record in LCD technology.

The most important determinant of citation choice seems to have been the technological closeness of two inventions as captured by the dummy for equality of patent subclass assignment. This suggests that subclasses effectively define fields of technology in which progress is cumulative. Moreover, the observation that subclass equality also helps to explain geographic localization of citations suggests that regions may have developed distinct patterns of technological specialization even within the narrow field of LCD technology. This finding, incidentally, casts some doubt on the common assumption that localized citation patterns are straightforward evidence of geographically localized knowledge spillovers.

In general, the diffusion of knowledge among inventors in the field of liquid crystal technology does not appear to exhibit localization effects. The probability of citation does not depend on the distance within a country, nor on the presence of international borders between inventors' locations. With respect to the central theme of this paper, our (admittedly incomplete) measure of documented prior cooperation among citing and potentially cited inventors does not help to explain citation choice. However, prior cooperation is a significant determinant of the geographic localization of citations. This suggests that rent spillovers transmitted through the labor market for research scientists and engineers do play a role in explaining localization effects in the R&D sector of the LCD industry.

With regard to technology policy, this study raises doubts whether targeted R&D subsidies can or should be employed to confer an artificial comparative advantage in LCD technology onto lagging regions or countries. The innovation process seems to be accessible by large and small firms from all advanced countries. This is not to deny that inter-firm cooperation in R&D can in principle be efficient when it either helps to coordinate complementary research efforts on the path to a dominant design or when it helps to avoid wasteful parallel R&D by competitors in the product market. In future research, it will therefore be interesting to combine patent data with company financial data and to compare findings from the LCD industry with other fields of technology.

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