SPRU Science and Technology Policy Research

Electronic Working Paper Series

Paper No. 73

Does Proximity Matter for Knowledge Transfer from Public Institutes and Universities to Firms?

Author Anthony Arundel [+]
MERIT, University of Maastricht
&
Aldo Geuna [*]
SPRU, University of Sussex

First Draft: May 2000
This Draft: October, 2001

The authors wish to thank Cristiano Antonelli, Ben Martin, Martin Meyer, Keith Pavitt, Jacky Senker and Ed Steinmueller for helpful comments and suggestions on earlier drafts. An earlier version of this paper was presented at the 8th Schumpeter conference, in Manchester. Financial support from two programmes of the European Commission is acknowledged. The analyses of the PACE data were supported by the KNOW project of the TSER Programme, while analyses of the 1997 CIS data were conducted as part of EIMS project 98/180 under DG Enterprise.

+: MERIT,
Maastricht University,
PO BOX 616,
6200 MD Maastricht, NL.
Tel. +31 43 3883702,
Fax. +31 43 3884905,
e-mail: a.arundel@merit.unimaas.nl

*** Corresponding author:**
SPRU,
University of Sussex,
Mantell Building,
Brighton, BN1 9RF, UK.
Tel. +44 1273 877139,
Fax. +44 1273 685865,
e-mail: a.geuna@sussex.ac.uk

Abstract

'National Innovation Systems' theories are built upon the assumption that linkages among organisations matter to innovation. Specifically, proximity is a crucial factor in most of the explanations of regional innovation systems. Yet several things, such as the rapid growth of the internet and email, suggest that the role of proximity could be breaking down, particularly for large firms with the financial resources to seek out knowledge anywhere in the world. However, the need to access tacit knowledge in rapidly evolving science-based technologies could counter the centrifugal features of modern communication technologies. This study examines the effect of proximity on the sourcing of knowledge by firms from suppliers, customers, joint ventures, competitors (via reverse engineering) and publicly-funded research organisations (PROs). The focus is on PROs, since they are an essential component of National Innovation Systems. Relevant data for up to 615 firms are available from the 1993 PACE survey of Europe's largest industrial firms. Descriptive results show that compared to four other information sources proximity effects are greatest for PROs. The factors that influence the importance of proximity to the use of information from PROs are explored through an ordered logit model. The dependent variable is the relative importance of domestic and foreign PROs. The independent variables include firm size, activity in foreign markets, R&D intensity, a proxy for codified knowledge, and two proxies for the quantity and quality of the scientific base of a country. The ordered logit model results show that proximity effects decline with an increase in the firm's R&D expenditures, the importance attached to basic research results in publications, and activity in the North American market, but increase with the quality and availability of outputs from domestic PROs.

Keywords: Public research, localisation, knowledge flows, knowledge spillovers, process of innovation.

JEL Subject Classification: H4, L3, O3,

1. Introduction

Both the recent theories of National Innovation Systems (Nelson, 1993; Lundvall, 1992) and interactive and chain-link models of innovation stress the importance of flows of knowledge and information to the ability of firms to innovate (Kline and Rosenberg, 1986; Freeman, 1987). Within this framework, economic theory and empirical research have focused on two types of knowledge flows: between firms, through inter-firm research collaborations (Hagedoorn *et al.*, 2001), user-producer networks (Lundvall, 1992), or linkages between competing firms (von Hippel, 1988); and between firms and public research organisations (PROs) such as universities, government laboratories, and publicly-funded technical institutes (Mansfield, 1991; Mansfield and Lee, 1996; Pavitt, 1991). The empirical evidence shows that both types of knowledge flows, including unintentional spillovers, make a substantial contribution to innovation and, consequently, to public welfare. Estimates of the rate of return to publicly funded research, for example, range between 20% and 60% (Salter and Martin, 2001). These rates of return are dependent on firms acquiring knowledge and information produced by public research organisations PROs (universities, public research institutes and government laboratories) and successfully applying this information to their innovative activities.

In recent years, empirical research on the localisation of innovative activity, partly inspired by National Innovation Systems theories, has examined whether and how the proximity of knowledge production (for instance by both universities and firms) and innovative activities favours information exchange.[1] With a few exceptions (Henderson *et al.*, 1994), this research has found that knowledge production and innovative activities tend to agglomerate geographically. The literature focuses on the concept of knowledge spillovers (positive external knowledge economies due to the value of received knowledge exceeding its cost) and provides statistical evidence for their localisation. There are two main drawbacks to much of this literature, which we partly address in this study. First, many of the available studies lack direct evidence of the knowledge flow from the producer of knowledge to the user, and second, none of the research to date directly investigates why proximity might matter, although the most common explanation is that some of the knowledge needed by firms to innovate

[1] For a recent analysis of the geography of innovation, see the special issue of Economics of Innovation and New Technology (Vol. 8., 1999). For a critical review see Breschi and Lissoni, 2001.

is tacit and, therefore, requires direct, personal contact between the scientists and engineers in different organisations.

We use the results of the PACE survey of Europe's largest industrial firms to empirically determine whether proximity matters to the flow of technical knowledge from a range of external sources to innovative firms. We define both 'knowledge flows' and 'proximity' in broad terms. The former includes all types of knowledge flows, including knowledge that is transferred via market mechanisms and true knowledge spillovers. Proximity is defined at the level of the European nation, which means that it combines geographical, cultural, and linguistic proximity. The cultural and linguistic aspects could be particularly important if the value of proximity is due to the need to access tacit knowledge (Maskell and Malmberg, 1999; Leamer and Storper, 2001). These two components also assume that the concept of a national system of innovation is a useful analytical tool for explaining the innovative activities of firms. The use of the nation rather than smaller geographical units is further justified by the focus on Europe's largest industrial firms. The nation state should be a useful unit of reference for these firms, given their size and involvement on both domestic and international markets.

Although we evaluate the value to firms of several knowledge sources, the primary focus of this study is on knowledge flows from PROs.[2] First, we examine the general importance of PROs as a source of knowledge for the firm's innovative activities and compare the importance of PROs to other knowledge sources. Second, we determine whether the effect of proximity on the transfer of technical knowledge from PROs differs in importance compared to other external sources of knowledge. Third, we explore the methods that firms use to obtain information from PROs. These include methods for acquiring tacit and codified knowledge.

In addition, we develop an ordered logit model to evaluate the effect of several factors on the importance of proximity for the flow of knowledge from PROs to firms. The independent variables at the firm level include firm size (measured by R&D expenditures), nationality, a measure of familiarity with foreign countries, R&D intensity, and different measures of the methods that the firm uses to obtain information from PROs and the degree of codification of the desired knowledge. We assume that proximity will be less important when the firm obtains information using highly codified methods such as publications, whereas proximity will be more important when the firm employs 'tacit' methods such as informal contacts or hiring new scientists. Similarly, generic or basic research results could be more codified, since they are usually disseminated through publications.[3] Another important aspect of the model is that it includes a variable for the amount of relevant research output produced by PROs in the same country as the firm. This is measured by the number of domestic papers of relevance to the firm's sector of activity and published in the five years before the survey. Lastly, to account for both the availability and quality of public research in each country, we examine the effect of the share of higher education R&D expenditures in national GDP.

The remainder of the paper is organised in five sections. The theoretical and empirical background is presented in Section 2. Section 3 describes the data sources, while descriptive results for the relevance of public research to the innovative activities of firms are presented in Section 4. Section 5 provides the econometric model of the importance of localisation for the transfer of knowledge from PROs to firms. Conclusions and policy implications are presented in Section 6.

2. Theoretical and empirical background

In the last 15 years, a large body of literature has analysed the role of public research in the process of industrial innovation. This section briefly reviews the literature in relation to three questions of relevance to the effect of proximity on knowledge flows from PROs to firms. First, how important is the knowledge produced by PROs, compared to other sources of technical knowledge outside the firm, to the innovative activities of firms? Second how does proximity mediate the importance of knowledge obtained from PROs and other sources? And third, what methods are used by firms to access the results of research produced by PROs?

2.1 Knowledge flows from PROs to firms

[2] Although we are aware of the differences within PROs, especially between universities and other organisations, we have to subsume all types of PROs under one class because of data limitations.

[3] This distinction is a modelling simplification of the reality where companies use publications and informal contacts in an interrelated way (see Section 2.3 for further discussion).

Four different methods have been used to evaluate the flow of knowledge and information from PROs to industrial innovation: production function models using patents or product announcements as the dependent variable, citations of scientific papers, detailed case studies of specific innovations, and surveys of the subjective importance of PROs to firms as a source of knowledge. Several of the relevant studies have evaluated knowledge flows in order to estimate spillovers in a geographical context. This is discussed in the following section on geographical proximity.

Jaffe (1989) uses a modified version of the production function model, originally developed by Griliches (1979), to estimate spillovers from university research to commercial innovation in the United States. The dependent variable is the number of patented inventions registered by the US patent office (a proxy for innovative output), while private corporate expenditures and university research expenditures are used as explanatory variables. The model estimations provide evidence that expenditures by universities positively influence corporate patenting activity. Acts *et al.* (1992) use a similar method, but replace the number of patents with the number of announcements of product innovations in newspapers and trade journals. Their estimations report increased elasticity for university research expenditures, confirming the importance of public research to industrial innovation. The disadvantage of the production function approach is that there is no information on how the knowledge produced by PROs reaches the firms, or on the type of knowledge that is used.

Several studies on patent citations provide a more direct method of tracing knowledge flows from PROs to firms. A patent citation of a scientific paper is assumed to represent the flow of knowledge from scientific research to the firm that patented the invention (Narin and Olivastro, 1992). Jaffe *et al.* (1993) report that patents granted to US universities received more citations than patents granted to corporations. Narin *et al.* (1997) find that 73% of the papers cited by US industry patents were produced by PROs. Malo and Geuna (2000) adopted the same methodology to study science-technology links in combinatorial chemistry and biology using the European Patent Office database. They found that 81% of patent citations to the literature are to universities and other research institutions. At a more micro level, Verspagen (1999) studied the citation record for patents taken out by Philips Electronic. Half of the literature citations are to papers from PROs.

There are three disadvantages to using patent citations for tracing knowledge flows from PROs to firms. First, some of the citations have been added by the patent examiner, so we cannot be sure that the firm actually used the cited literature.[4] Second, the literature can be cited to build the patent claim, without having actually contributed to the invention. And third, literature citations will not necessarily capture the many other methods that firms can use to source information from PROs, such as direct interpersonal contacts or contract research.

The next two methods, case studies and surveys, enable direct evaluation of the contribution of PROs to innovation. The case study approach was used by the National Science Foundation's Technology in Retrospect and Critical Events in Science (TRACES) project, carried out in 1968. The study traced the contribution of basic research knowledge to four major industrial innovations, showing that the agriculture and medical research sectors benefited the most from investment in public research (Steinmueller, 1996).

Mansfield used a method that lies somewhere between the case study and survey methods (Mansfield, 1991; Mansfield, 1995; Mansfield and Lee, 1996). He gathered data from a sample of 76 large R&D performing firms in seven manufacturing industries for the period 1975-1985. According to the R&D managers, about 10% of the new products and processes could not have been developed in the absence of recent academic research (occurring within 15 years of the commercialisation). These results were confirmed in an update covering 1986 to 1994 (Mansfield, 1998). Again, we do not know how the firms acquired the results of academic research.

The final method, also used in this paper, is to survey firms and ask respondents directly about the contribution of PROs to their innovative activities. The Yale survey of large R&D performing firms in the United States in the early 1980s looked at the value of university-based research compared to the overall body of science in those areas of value to the firm (Klevorick *et al.*, 1995). This survey that university-based research was less important than other sources of scientific output and, surprisingly, that applied knowledge produced by universities was of greater value than basic

[4] Current empirical research overcomes this shortcoming focusing on citations from the inventor.

science. One problem with these conclusions is that the Yale survey asked respondents about the importance of science to their line of business, rather than focusing on its importance to the firm itself. This introduces errors in requiring respondents to estimate conditions outside their immediate area of expertise. The possibility for error is further magnified by the fact that the Yale survey had only one respondent from 55 out of 130 business lines.

Later surveys, based on the OECD Oslo Manual, corrected this drawback to the Yale survey by asking respondents about the importance of different information sources to the firms innovative activities. The results of the first European Community Innovation Survey (CIS) in 1993 show that public research is one of the least important sources of information for firms with less than 500 employees (Arundel and Steinmueller, 1998). The second CIS in 1997 confirmed these results. In contrast, initial results from the 1993 PACE survey of Europe's largest industrial firms found that PROs were one of the most important information sources for large firms (Arundel *et al*., 1995).

2.2 Geographical proximity

In recent years, academic research has revisited some of the issues raised by Marshall (1920) on the geographic localisation of economic activity, including knowledge flows between PROs and firms. A large body of literature, from both a neoclassical and a heterodox perspective, has tried to explain the geographical agglomeration of industrial and research activities and, specifically, if and why the contribution of PROs to industrial innovation is localised. The four methodologies identified above for the study of the importance of public research have also been adopted (often in the same work) for the analysis of localisation. Below we present a selective review of the main findings.[5]

In his 1989 production function analysis of university spillovers, Jaffe concludes that there are important and strongly bounded in space (at the state level) knowledge spillovers from academic research. Following this seminal study, a large number of studies applying the production function framework have provided statistical evidence

[5] For detailed, although partial, surveys of this literature see, among others, Baptista (1998), Breschi and Lisson (2001) and Feldman (1999).

for the existence of localised knowledge spillovers from PROs.[6] These studies developed the original analysis, including smaller units of observation, more tightly-defined technological areas, and different proxies for the innovation output of firms. As already pointed out, the main limitation of the production function approach is that it does not model or trace local knowledge flows. No specific evidence of the flow of knowledge from the local producer to the local user is provided.

The analysis of patent citations attempts to provide a method to trace knowledge flows. The studies discussed above, specifically the one by Jaffe *et al.* (1993), provide strong evidence that knowledge flows from universities to firms are highly localised at the regional or state level.

Current work in economic geography (also defined as the new industrial geography) implements detailed case studies of the importance of proximity between private and public R&D activities for the economic development of cities, regions and nations. Most of this literature focuses on the development of high-technology clusters in the US. As an example, Saxenian's (1994) study of Silicon Valley and Route 128 underlines the impact of the research infrastructure on the development of the innovative capacity of these regions.

The localisation of knowledge flows has also been evaluated in surveys on the importance of PROs to industrial innovation. Mansfield's various studies (Mansfield, 1991; Mansfield, 1995; Mansfield and Lee, 1996) find evidence supporting the importance of proximity in the transfer of knowledge from universities to firms. For example, he reports that firms prefer to work with local university researchers, within 100 miles of the firm's R&D laboratory, and that firms are more reluctant to support university research at institutions 1000 or more miles away than the local one. Beise and Stahl (1999) use a similar methodology to survey the contribution of public research to innovation among 2300 German firms. Their main result, discordant with most of the literature, is that firms located near universities or polytechnics do not have a higher probability of using the results of publicly-funded research. They recognise that a central issue is the geographical unit of analysis. Indeed, they point

[6] See, among others, Acts *et al.* (1992), Anselin *et al.* (1997) and Audretsch and Feldman (1996).

out that the largest distance in Germany is 600 miles, which is well under the 1000 miles used in the Mansfield and Lee study.

Adams (2001) uses the results of a 1997 survey of 208 private R&D laboratories in the United States to investigate the relative importance of proximity for acquiring knowledge from PROs and from other firms. The survey provides data on the amount spent by each lab to learn about academic and private R&D located within 200 miles and further than 200 miles away. He finds that proximity is more important for academic R&D than for research conducted by other firms.

In summary, studies using different research designs have stressed the importance of proximity in the transfer of knowledge from PROs to firms. However, there are several drawbacks: the definition of proximity in terms of geographical distance is often - though not always - unclear, most of the evidence is from the United States, and, most importantly, information is rarely provided on how the firms acquired the results of academic research.

2.3 How firms access PRO results

In contrast to most of the available research, Adams (2001) is able to explore the effect of four methods for obtaining knowledge from academic and private research and the relationship between each method and proximity. The four methods for academic research are outsourcing research, faculty consulting, licensing university patents, and hiring engineering graduates; the four methods for private research are outsourcing research, joint research, publications, and patents. The importance of each method is correlated with a localisation indicator, which is the ratio between the log of the amount spent on learning about local (less than 200 miles) versus distant results of academic or private research. Two of the four methods for learning about private research, publications and patents, are negatively correlated with the localisation indicator, while all four methods for learning about academic research are correlated with the localisation indicator. Adams concludes that firm-university interactions tend to be more localised than interactions with other private firms.

The empirical evidence in support of localised knowledge flows, either between firms and PROs or between firms and other firms, requires an explanation for why such flows are encouraged by geographical, cultural, or linguistic proximity. Adams (2001) suggests that the reason for the proximity effect for PROs could be a trend towards supporting industry-university cooperation as part of a system of knowledge dissemination. However, this explanation is unsatisfactory because it does not provide a reason for why proximity should be of value. The explanation offered in most of the literature focuses on the value of direct, inter-personal contacts between PROs and firms, primarily in order to acquire tacit knowledge (Quintas, 1992; Faulkner *et al.*, 1995; von Hippel, 1987; Maskell and Malmberg, 1999). Therefore, the value of proximity should depend on the degree to which knowledge is in a codified form, such as in patents and publications, or in tacit form, requiring inter-personal contacts. Though distinct, these two forms of accessing knowledge do not completely substitute for one other. Some degree of inter-personal contact might be necessary even when information is available in publications and patents since both these sources might omit information that is crucial to the full understanding of research results. However, for someone 'skilled in the art', it may not matter if a sizeable portion of the necessary knowledge is not codified, since the codified information may provide enough information for the research to be pursued.

Imai (1991), Antonelli (1999), and Roberts (2000) argue that modern information and communication technologies, lower costs for codifying knowledge, and stronger intellectual property rights, are reducing the need for proximity while simultaneously increasing the ability of firms to obtain knowledge from outside the firm. These developments suggest that knowledge production and use are becoming increasingly globalised, resulting in a decline in the importance of proximity to access tacit knowledge. Perhaps the best example of innovation via completely codified knowledge is the collective development of Linux software, where problems, software code and information are shared almost entirely by email (Cowan and Jonard, 2000). Conversely, Senker (1995) proposes that most rapidly developing technologies that are characterised by complexity will always be dependent on tacit knowledge and, consequently, on inter-personal mechanisms for knowledge flows. This proposal is supported by Saviotti (1998), who develops a model in which the extent of knowledge codification is inversely correlated with the distance from the technological frontier. High technology firms active on the frontier are able to create temporary monopolies due to the low rate of dissemination of tacit knowledge to other firms. The economic benefits that flow from the appropriation of tacit knowledge - by firms that are capable of innovating at the frontier - should ensure that these firms invest in knowledge gathering methods that permit the transfer of tacit knowledge.

There are two main criticisms of the 'tacit' knowledge explanation for proximity effects. Breschi and Lissoni (2001), in a review of the literature on the localisation of knowledge, comment that other factors, such as the economics of knowledge codification, labour markets, and appropriation strategies (as in Saviotti's model) could explain the phenomenon of localisation. This argument is particularly compelling given the paucity of direct evidence for the effect of proximity on knowledge flows. The second criticism comes from Cowan, David and Foray's (2000) theoretical evaluation of 'tacit' versus codified knowledge. They suggest that very little knowledge is intrinsically tacit in the sense that it is impossible to codify. Instead, much of what is believed to be 'tacit' could be codified if economically worthwhile, while other knowledge appears to be tacit only to the uninitiated. However, the latter criticism, although raising doubts about the role of tacit knowledge *per se*, does not counter a need for direct, personal contact in order to effectively transfer knowledge. This is because it is not just when knowledge is intrinsically tacit that proximity will confer advantages. The real issue for firms might simply be whether or not the knowledge is codified *and* publicly available. When knowledge is neither codified nor publicly accessible to firm's researchers, it becomes crucial to understand who knows what –i.e. where the new knowledge is. In this context, proximity matters because direct, personal contacts allow a company faster and more successful access to knowledge gatekeepers to discover where and how to access the new knowledge. At the same time, codified research outputs, such as papers and patents, can 'signal' the location of academics conducting research of value to firms.

The preceding discussion highlights the need for empirical analysis of the relative importance of public research to the innovative activity of firms, compared to other external sources of knowledge, the effect of proximity on the use of public research, and the methods that firms use to access public research results, including methods based on codified and tacit (or non-codified) knowledge. These three issues are explored through analysis of the PACE survey results. Specifically, descriptive results are presented in Section 4 while in Section 5 a model showing the factors that affect the importance of proximity to the acquisition of knowledge from PROs is developed and tested. The way in which a firm judges the relevance of proximity to PROs depends upon: the methods used to acquire knowledge; firm specific factors, such as its size and overseas activities; and structure and intensity of its R&D. Sector and country level factors are also included to account for technological diversity and availability and quality of PROs.

3. Data Sources

The 1993 PACE survey of Europe's largest R&D performing industrial firms, excluding firms based in France, covers innovative activities between 1990 and 1992. The response rate was 55.6%, with a total from both industrial and manufacturing firms of 615 useable responses. Most of the results presented here are based on the 473 firms responding to the question on R&D expenditures that were active in manufacturing sectors (ISIC 15 to 36 inclusive) or utilities (ISIC 40).[7] Some of the PACE results refer to low, medium and high technology classes. The definition of each technology class largely follows the OECD's definition.[8]

[7] The French section of the PACE survey was conducted by SESSI. Unfortunately, differences in the design of the French questions on knowledge sources means that the results for France are not comparable to those for other European countries, and are therefore excluded.

[8] The technology class definitions are as follows, with the ISIC (3rd revision) classification code given in parentheses. The low technology class includes Food & Beverages (15), Tobacco (16), Textiles and Leather (17 - 19), Wood products (20), Paper and Printing (21), Petroleum products (23), Ferrous metals (27), Fabricated metal products (28), other manufacturing (36) and utilities (40). The medium technology class includes Automobiles (34), Chemicals other than pharmaceuticals (24), Plastic and Rubber products (25), Non-ferrous mineral products (26), and Machinery (29). The high technology class includes Pharmaceuticals (2423), Office Equipment and Computers (30), Electrical Equipment (31), Telecoms Equipment (32), Precision Instruments (33), Aerospace (35.3), and Trains (35.2). (In Europe, train manufacturers more closely resemble high technology than medium technology firms.)

Almost all responses were from R&D managers, who were asked to complete the questionnaire for their ‘area of responsibility’. For firms active in more than one product area, PACE sampled at the business line level, but in some cases an R&D manager’s area of responsibility covered more than one business line. The results were carefully checked to ensure that the responses referred only to the respondent’s area of responsibility. This resulted in 30 firms, where the respondent gave results for the entire firm rather than for his area of responsibility, being excluded. For simplicity, we refer to each ‘business unit’, ‘division’, or ‘area of responsibility’ as a firm. Further details on the PACE survey are available in Arundel *et al.* (1995).

The PACE survey includes some questions on public research from the 1994 Carnegie Mellon Survey (CMS) of R&D performing firms in the United States (Cohen *et al*., forthcoming), although subtle differences in the PACE and CMS questions prevent direct comparison. Some general comparisons with the CMS results are given below.

Several PACE questions refer to knowledge flows between firms and between firms and PROs. The first PACE question of interest concerns the general importance to the firms’ innovative activities of technical knowledge obtained from PROs, affiliated firms, joint or cooperative ventures, suppliers, and customers, as well as ‘technical analysis’ (reverse engineering) of their competitor’s products. The second relevant question asks about the importance of technical knowledge obtained from each source in four locations: the European country in which the firm is located (the ‘domestic’ country), other European countries, North America, and Japan[9]. Furthermore, PACE asks a series of in-depth questions on the use of knowledge obtained from PROs, including the importance of four different outputs of public research and seven different methods for learning about public research results[10].

Responses to all four of these question groups are measured on a five-point ordinal scale, ranging from 1 or ‘not important’ to 5 or ‘extremely important’. The statistic used to evaluate the results is the percentage of firms that give their *highest* score to

[9] Firms can also source information from countries outside of these four regions, such as South-East Asia or Latin America, but the CIS results show that less than 2% of firms are involved in research cooperation outside of the four main areas covered by PACE, suggesting that their exclusion from PACE should not affect the results.
[10] The full PACE questionnaire is available in Arundel *et al.* (1995) or from the authors.

each variable. The distribution of the highest scores is preferred to the means or the percentage of firms that rate each source as 'very' or 'extremely' important because the highest score avoids problems of inter-rater differences in the meaning of the ordinal importance scale. Instead, we make a reasonable assumption that respondents give internally consistent responses. For instance, we assume that a respondent that gives a score of 4 to public research and a score of 3 to the five other knowledge sources finds public research to be the most important of these six sources. Tied high scores are equally distributed among the relevant sources, so that the percentages across all questions in a group sum to 100%.

The descriptive results are weighted by the R&D expenditures of each firm, in order to adjust the results by a proxy for innovative output, assuming a positive correlation between the number of innovations developed by a firm and the absolute amount of its R&D expenditures. For example, R&D weighting gives a firm that spends 20 million Euros on R&D twice as much weight in the calculation of the distribution of the highest scores as a firm that spends 10 million Euros on R&D.

Some results from the 1997 European Community Innovation Survey (CIS) are also used. Although more recent than PACE, and covering a much larger number of firms, the CIS is less useful for analysis of knowledge flows because it does not include questions on the methods used to source the outputs of PROs and it only investigates proximity effects for cooperative R&D projects between firms and PROs. However, the CIS results are used to replicate the PACE estimates of the general importance of public research as a source of knowledge for the firm's innovative activities.

4. Descriptive results

4.1 The relative importance of PROs

Figure 1 shows the distribution of the highest scores, by technology class, for PROs plus five other external sources of technical knowledge. The pattern of the results is similar when not weighted by R&D, although the value of public research compared to several other sources decreases.

[Insert Figure 1 here]

The results depicted in Figure 1 show that 24.2% of the R&D weighted firms give their highest score to PROs, with all other sources cited less frequently. The value of PROs is particularly marked among high technology firms, with 37% of these firms giving their highest score to PROs. Surprisingly, 30% of low technology firms give their highest score to PROs. Public research is of less importance to firms in medium technology sectors - all other external information sources, except joint ventures, account for a larger share of these firms' highest scores.

These results contrast sharply with several of the conclusions of the European CIS surveys, which find that PROs are a comparatively unimportant knowledge source for most firms, with less than 5% of respondents to the second CIS, covering innovative activities between 1994 and 1996, giving their highest score to PROs (Arundel *et al.*, 2000). The results of the CIS, and similar innovation surveys, have been widely cited to show that PROs are of little importance to the innovative activities of firms. For example, the 1998 OECD report, *The university in transition*, notes that "firms…rely little on university (and public) laboratories as a source of information and stimulus for their innovative efforts". Similar conclusions are drawn in a report sponsored by the European Commission on industry-science relations (EC, 2001). The report suggests that the output of PROs is of little value to most firms because it is largely relevant only to the early stages of the innovation cycle. Therefore, the research is of little relevance to firms in mature sectors or for most innovative activities involving minor improvements.

Both the PACE results and the findings of the CMS survey for the United States contradict the assumption that public research is of less value to firms in mature sectors. As shown in Figure 1, low technology sectors give a higher rating to public research than firms in medium technology sectors. Cohen *et al.*'s (forthcoming) results for the United States are given for individual sectors, but similarly show that firms in several low technology sectors such as food, paper, glass, and concrete rate public research of greater importance than firms in medium technology sectors such as chemicals, machinery, and automobiles.

There are two main explanations for the large differences between the importance of PROs in PACE and the published research based on the CIS. First, PACE is limited to

Europe's largest firms, which are more likely than smaller firms to use knowledge obtained from PROs. Second, the published results from the CIS are not weighted by a proxy for innovation outputs, which means that the results largely measure the importance of PROs to smaller and less innovative firms, which make up the vast majority of CIS respondents. We investigated the differences in the PACE and CIS results by limiting the analyses to a comparable group of R&D performing firms with over 500 employees and from three sectors, food, chemicals, and machinery; for which there are more than 50 PACE responses.[11] All results were weighted by R&D expenditures. With the exception of the food sector, PROs score highest for a *greater* percentage of the CIS than the PACE respondents: 68% of chemical firms in the CIS compared to 57% of chemical firms in PACE, and 48% of machinery firms in the CIS compared to 34% of machinery firms in PACE. These results show that analytical methods that do not take account of firm size effects and which do not weight by a proxy for innovative output can substantially underestimate the contribution of PROs to innovation.

We also evaluated the importance of external information sources to the innovative activity of firms according to their R&D expenditures (<2.5m, 2.5 - 10m, 10-40m, > 40m) and R&D intensity (< 1%, 1 - 3%, 3 - 7%, > 7%). Firms in the highest R&D expenditures class rank public research in first place (25.2%) followed by affiliated firms (21.7%). For all other R&D classes, suppliers and technical analysis are in first and second place, with public research in fourth place. Public research is in second place for the most R&D intensive firms, close behind joint ventures (24.1% versus 24.3%). Public research ranks second for the least R&D intensive firms, at 21.6%, after technical analysis at 24.1%. For the medium intensive R&D groups, it ranks 4th and 5th. These results are similar to those by sector, with public research being most important to low and high tech firms.

[11] The CIS results are based on 179 food, 238 chemical, and 329 machinery firms. Access to the 1997 CIS data was only available for six countries: Germany, France, Italy, Ireland, Norway and Sweden. The PACE results are derived from the full data set of 615 firms, of which 56 are in the food sector, 134 in chemicals, and 54 in machinery. The CIS also asked about 10 different external sources. In order to maintain comparability, the analyses were limited to four sources that were included in both surveys: affiliated firms, suppliers, customers, and PROs. The latter group includes both the CIS question on 'universities' and 'government laboratories'. Since the CIS used a three point scale versus PACE's five point scale, we also assumed that a score of either 4 (very important) or 5 (extremely important) in PACE was equal to the CIS score of 3 (very important).

4.2 Proximity and the use of knowledge from PROs

For each of five external knowledge sources, we constructed a proximity variable that measures the relative importance of domestic sources of technical knowledge over foreign sources. For example, in the case of the importance of proximity to public research, the variable PROXPR is defined as follows:

> **PROXPR = 0 if** the importance of public research in the domestic country is *lower* than its importance in *at least* one foreign location.
>
> **PROXPR = 1 if** the importance of public research in *any* other country is *equal* to its importance in the domestic country but never exceeds the domestic score.
>
> **PROXPR = 2 if** the importance of public research in the domestic country is *greater* than its importance in *any* other country.

Figure 2 shows the distribution of the equivalent of each of these three categories of PROXPR for the five external sources of technical knowledge (weighted by R&D expenditures). The results show that the sourcing of technical knowledge from PROs is most affected by localisation of the knowledge source. 47% of firms rate domestic public research as more important than foreign, while only 5% consider domestic public research to be less important than foreign research. Proximity to the source of technical knowledge affects the importance of other sources, but to a lesser degree. Only 4% of the firms give greater importance to domestic sources for the technical analysis of competitors products. This result is reassuring, as this mechanism for acquiring new knowledge should be largely unaffected by geographical or cultural distance.

[Insert Figure 2 here]

An analysis of the effect of proximity on the use of PROs by technology class, using the highest score method depicted in Figure 1, shows that high technology firms are less likely than other firms to give their highest score to domestic PROs (49% versus 65%) and more likely to give their highest score to PROs located in North America (25% versus 14%). This result points to the importance of sector specific effects on the localisation of knowledge flows.

4.3 Methods of accessing PRO research results

The PACE questionnaire asks firms about the importance to their innovative activities of four outputs of public research and about the importance of seven methods for learning about public research. The most important output is 'specialised or applied knowledge', ranked highest by 44.8% of the firms, followed by 'general knowledge obtained from basic research' (25.5%), 'new instrumentation and techniques' (20.4%), and lastly 'early versions of prototypes of new product designs' (9.3%).[12] The high value attributed to applied knowledge confirms the results of the Yale survey covering the early 1980s (Klevorick *et al*., 1995). There are few differences in the importance given by firms active in low, medium and high technology sectors to each type of output , but the importance of basic research increases with total R&D expenditures, while prototypes are more important to firms with low R&D expenditures.

The seven questions on different methods for learning about the results of public research include both codified sources, such as reading publications and technical reports and attending public conferences and meetings, and methods based on direct contacts, which would permit access to non-codified knowledge. The latter include hiring trained scientists and engineers, informal personal contacts, and personnel exchange programmes. Two additional questions enquire about contract research - where the PRO conducts the research - and joint research projects. Both of these methods would allow the exchange of non-codified information, although joint research would conceivably be more productive in this respect.

Very few firms give their highest score to personnel exchanges. The most important methods are regarded as hiring (given the highest score by 30.4% of all firms), informal contacts (23.4%), and contracted out research (15.6%). As shown in Figure 3, there are notable differences by technology class, with firms active in high technology sectors preferring informal personal contacts and hiring, while low technology firms are more likely than other firms to give their highest scores to contract research and to the two codified sources of conferences/meetings and

[12] R&D weighted results, although the unweighted results are very similar.

publications.[13] The importance of informal contacts to high technology firms is also noted by Oliver and Liebeskind (1998) in a study of the biotechnology sector.

[Insert Figure 3 here]

These results partially support Senker's (1995) conclusion that firms in high technology sectors are more likely than low technology firms to need to access non-codified knowledge (in her view the 'tacit' component) held by PROs, since high technology firms give greater importance than low technology firms to methods that offer the possibility of the exchange of non-codified knowledge.

The CMS survey also investigated the importance of different methods of obtaining the results of public research, although it differs from PACE in asking about three additional methods, using a four-point scale, and limiting the responses to a 'recent major' innovation project. Cohen *et al.* (forthcoming) give unweighted CMS results for the percentage of American R&D lab managers that scored each method 'moderately important' or 'very important'. For comparison, a similar method was applied to the PACE data.[14] Although it is not possible to make a direct comparison, the rank order of the importance of each method can be compared between PACE and CMS. In both surveys, publications and technical reports are in first place (most frequently cited as important), informal contacts are ranked second, public conferences and meetings are ranked third, and temporary personnel exchanges are in last place. The rank order for hiring, contract research, and joint research differs between the two surveys. Cohen *et al.* conclude that the first, second and third place results for longstanding methods of information exchange point to the importance of 'open science', in contrast to the current policy emphasis on more formalised methods. The PACE results concur with this conclusion.

The PACE results for each method of accessing information on PRO results were also correlated with PROXPR, or the importance given by the firm to knowledge obtained

[13] The unweighted results are similar, except that publications become much more important. This is because a higher percentage of smaller firms (based on R&D spending) give their highest score to this method. For example, 26.8% of firms with less than 2.5 million Euros in R&D expenditures give their highest score to publications, compared to 8.3% of firms with R&D spending over 40 million Euros. Conversely, the respective results for hiring are 16.2% for the smaller firms and 31.4% for the larger firms.

[14] The closest match is between the percentage of PACE respondents that gave a score of 'very important' or 'extremely important' to each method.

from domestic and foreign PROs. Informal personal contacts are preferred by more firms that find domestic PROs of greater value than foreign PROs (25.5% versus 19.0%). However, the reverse pattern applies to hiring scientists and engineers, with comparable results of 25.8% and 37.1%. Other methods that provide access to non-codified knowledge (joint research projects and contract research) are preferred by firms that value domestic over foreign PROs, while publications are preferred by firms that give greater importance to foreign PROs. The relationship between the methods for sourcing non-codified knowledge from PROs and the importance of proximity is clearly complex, since firms can use one method to provide access to non-codified knowledge close to home and another method to provide access to culturally or geographically ‘distant’ expertise.

5. Econometric model of knowledge localisation

Given the ongoing debate on the contribution of public research to the economic development of a country, it is important to understand which factors affect the importance of proximity to the acquisition of knowledge from PROs. In this section, we use an ordered logit model to evaluate the effect of firm-specific, sector-specific and country-specific factors on the relevance of proximity for the transfer of knowledge from PROs. The dependent variable is PROXPR, as defined above.

5.1 Firm-specific independent variables

We expect larger firms to find it easier than smaller firms to access information from abroad, due to their greater financial resources. We capture this effect through the natural log of the firm’s R&D expenditures (LNR&D). In addition, familiarity with foreign countries could both increase awareness of the output of foreign PROs and decrease the costs of accessing these outputs. Two groups of variables have been designed to capture this effect. First, a dummy variable HOMEOFF identifies foreign-owned firms. The variable is equal to 1 if the firm’s head office is located in the domestic country and equal to 0 if it is located in another country. Second, firms that sell products in foreign markets are assumed to be more familiar with local conditions. Three dummy variables account for presence in the North American (AMERICA), Other European (EUROPE) or Japanese (JAPAN) markets. They are equal to 1 when the firm is active in the foreign market and 0 otherwise.

It is possible that R&D intensive firms might be more likely to go abroad for information because they are active at the technological frontier and must seek out expertise wherever it is available. Examples include firms active in pharmaceuticals, optics, and information technology. To test for this effect, we include a variable for the R&D intensity of the firm (RDINT), based on the ratio between R&D expenditures and sales.

Several attempts were made to construct a variable to measure the importance to the firm of accessing public research results via codified sources, such as publications, versus 'tacit' methods, such as informal contacts, hiring, or temporary exchanges of personnel. None of these relative measures of codified versus tacit sources had any effect in a series of preliminary analyses. We suspect that the explanation for this is that firms use different methods to access non-codified knowledge from distant versus proximal PROs, as noted above. As an alternative, we constructed a variable, CODIFY, that equals the product of the importance to the firm of publications as a method for accessing public research results multiplied by the importance of basic research carried out by PROs. Since both variables are measured on a five-point scale, CODIFY can vary from 1 to 25. Firms with a high value of CODIFY will attach a high level of importance to published basic research results.

5.2 Sector and country level variables

The descriptive results show that there are large differences by technology class in the influence of proximity on the importance of PROs as a knowledge source and in the methods used to access this knowledge. One of the models. therefore. includes dummy variables for the firm's sector of activity at either a two-digit or four digit ISIC level (DISIC), with pharmaceuticals as the reference category. Sectors with very few representative firms (less than 10) are excluded, which results in the loss of 40 firms, leaving up to 433 firms in 16 sectors[15].

[15] The 16 sectors are telecoms equipment (32), Aerospace (35.3), pharmaceuticals (2423), office machinery and equipment (30), instruments (33), electrical equipment (31), automobiles (34), chemicals excluding pharmaceuticals (24), plastics and rubber products (25), machinery (29), non-ferrous mineral products (26), food (15), petroleum products (23), ferrous metals (27), fabricated metals (28), and utilities (40).

We would expect that the quantity and quality of the scientific "competencies" of a country's research output should positively affect the importance of domestic versus foreign PROs. Two variables, PUBSHARE and HERDGDP, capture these effects.

PUBSHARE is based on the Institute for Scientific Information (ISI) National Science Indicators (NSI) database of the number of science publications by field and country. The main problem is to limit PUBSHARE to papers of relevance to the firm's innovative activities. This problem was solved by creating a concordance table between the NSI's classification of papers into 102 scientific fields, corresponding to the ISI's *Current Contents* categories, and the 16 industrial sectors. Of the 102 scientific fields, 67 were considered relevant to these sectors. Several scientific fields were relevant to more than one of the 16 industrial sectors.[16] PUBSHARE equals the total number of relevant ISI-SCI papers between 1986-1990 by country and of relevance to the firm's industrial sector, divided by the total number of relevant papers in the world.

PUBSHARE measures the overall quantity of scientific research in each country that is of relevance to the firm's sector. Of course, the number of publications is also a proxy measure of the supply of domestic scientists and engineers that can provide access to non-published knowledge. Traditional bibliometric indicators, such as the total number of citations and citations per paper, are indicators of academic impact and the internationalisation of the academic system, and are less relevant for an analysis of the effect of proximity on knowledge flows from PROs to firms.

A country level variable, HERDGDP, is a proxy for both the availability and quality of a country's public research base. HERDGDP equals the ratio between the total amount of higher education R&D expenditure (5 year average for the period 1986-1990) and the country GDP. Countries with a high value for HERDGDP invest a relatively bigger amount of resources in public research. Therefore, the quality of domestic public research should be higher than in countries with a low value for HERDGDP, positively affecting the importance of proximity.

[16] The concordance table has been built on the basis of expert opinion. It is available from Dr Geuna of SPRU. Another concordance table, built on the basis of the publication output of firms included in the BESST database (see Larsen and Salter, 2001 for the description of the concordance table), was used and similar regression estimations obtained.

5.3 The ordered logit model

We model the determinants of the effect of proximity on the use of public research using an ordered logit. The ordered logit model can be employed to examine the impact of a range of exogeneous variables on a dependent variable which takes a finite set of ordered values (1,2 .. n) (Liao, 1994). The method of estimation is maximum likelihood. The model assumes that the dependent variable y is generated by a continuous latent variable y* whose values are unobserved, in our case the value of proximity. The model assumes that there is a set of ordered values (μ_1, μ_2, .. μ_{n-1}) and a variable y* such that:

(1) $y = 1$ if $y^* < \mu_1$
$y = k$ if $\mu_{k-1} < y^* < \mu_k$ for $1<k<n$
$y = n$ if $\mu_{n-1} < y^*$

The unobserved variable y* is modelled as a linear function of the (N,k) vector of exogenous variable X:

(2) $y^*_i = \beta X_i + \varepsilon_i \quad i = 1,...N$

where ε_i has a distribution function f derived from the logistic cumulative distribution function:

(3) $F(x) = 1/(1+ e^{-x})$

Given the characteristics X_i of individual i, the probability that y_i is found in category k is:

(4) $\text{Prob } (Y_i = 1/Xi) = F(\mu_1-\beta X_i)$
$\text{Prob } (Y_i = k/Xi) = F(\mu_k-\beta X_i) - F(\mu_{k-1} -\beta X_i)$
$\text{Prob } (Y_i = n/Xi) = 1- F(\mu_{n-1} -\beta X_i)$

with n number of categories. In our case, the dependent variable PROXPR has three categories 0, 1 and 2 with increasing importance of proximity. As noted above, most of the characteristics X_i of individual i refer to specific attributes of the firm that affect the relevance of proximity for the transfer of knowledge from PROs. In addition, a few country and sector specific characteristics are included in the model.

The model estimates the effect of several firm and sector specific characteristics on the importance to the firm of proximity for sourcing knowledge from PROs. The

model does not explain the importance to the firm of the knowledge obtained from PROs. For this reason, the estimation is not affected by problems of endogeneity.
The ordered logit equation is estimated for the following three forms:[17]

(5) $PROXPR = 1- F(\mu-\beta_1 LNR\&D-\beta_2 AMERICA-\beta_3 CODIFY -\beta_4 PUBSHARE-\beta_5 HERDGDP)$

(6) $PROXPR = 1- F(\mu-\beta_1 LNR\&D-\beta_2 AMERICA-\beta_3 CODIFY -\beta_4 PUBSHARE-\beta_5 HERDGDP-\beta_6 RDINT-\beta_7 HOMEOFF- \beta_8 EUROPE-\beta_9 JAPAN)$

(7) $PROXPR = 1- F(\mu-\beta_1 LNR\&D-\beta_2 AMERICA-\beta_3 EUROPE -\beta_4 JAPAN - \beta_5 CODIFY-\beta_6 PUBSHARE-\beta_7 HERDGDP-\beta_8 HOMEOFF-\Sigma_j\beta_j DISIC_j)$

There is only one μ estimate because for three categories n-2 = 3-2 = 1, with the first μ normalised to be zero and j=1…15, given 15 sector dummies (DISIC).

5.4 Model results

Table 1 gives the three ordered logit results. The first model correctly predicts the dependent variable for 56% of the firms, while the third model correctly predicts 60%. The highly significant, positive μ (M) estimate indicates that the three categories in the responses are indeed ordered.

[Insert Table 1 here]

In all three models, the importance of proximity declines with R&D expenditure (LNR&D), showing that firms with large financial resources for R&D are less constrained by proximity than other firms. Conversely, neither R&D intensity (RDINT) nor the location of the home office (HOMEOFF) influences the importance of proximity. R&D intensity was also included in a version of the third model with sector dummies, but it did not have a statistically significant effect.[18] Activity in the European (EUROPE) or Japanese (JAPAN) markets also does not influence the probability that the firm will find proximity of importance, but activity in the North American market (AMERICA) significantly reduces proximity effects. One

[17] We also estimated different versions of the model that included country dummies (only included in the model when country specific information such as HERDGDP are excluded).

possibility is that the results for AMERICA are distorted by UK firms, which are culturally and linguistically closer to North America than firms based in other countries, or by pharmaceuticals firms, which are more likely than other firms to go to the United States for new knowledge, particularly in biotechnology.[19] To check for these possibilities, the regressions were rerun both after 1) excluding the pharmaceutical sector and 2) excluding the UK. In both of these regressions the coefficient for AMERICA was statistically significant and negative, showing that activity in the North American market has a robust effect in reducing the importance of proximity.

The measure of the importance to the firm of codified outputs of public research (CODIFY) is negative and statistically significant in the first model. This indicates that firms that seek codified basic research outputs are less likely to find proximity of importance. One explanation for this effect is the lower costs of accessing codified versus non-codified knowledge, particularly in the Internet age. Given these lower costs for codified knowledge, firms will face few financial constraints in accessing it from wherever it may be available. Of interest is that the effect of CODIFY is no longer statistically significant once sector dummies are included, suggesting that the importance of codified outputs from PROs varies by sector. This should not come as a surprise, since the importance of basic research to firms and the availability of useful results in publications should vary by sector. For example, the highest mean value of CODIFY (which can vary from 1 to 25) is 18.1for the pharmaceuticals sector, while the lowest mean values are 8.5 in fabricated metals and 8.9 in aerospace.

Both PUBSHARE and HERDGDP have a positive and significant effect on the importance given to proximity confirming that the quantity and quality of the scientific "competencies" of a country’s research output affects the way in which managers of large R&D intensive companies assess the relative importance of domestic sources of technical knowledge compared to foreign sources. It is important to notice that PUBSHARE partially reflects the size of the country insofar as larger countries produce more publications.

[18] R&D intensity is not included in the final version of model 3 because its inclusion results in a loss of 53 firms, due to missing sales data.

An alternative version of each model replaced the country level variable HERDGDP with the geographical size (in hectares) of each country. Country size could influence the importance of proximity if firms based in small countries find it less costly to go abroad because the average distance from domestic firms to foreign PROs is lower than for large countries. Or, firms based in small countries might need to go abroad because small countries might lack the funds to support public research in all fields. However, country size had no effect in any of the models. There are two possible explanations for this; either the measure is too crude to adequately capture the effect of geographical distance or cultural or social effects are more important than geographical distance.

Table 2 presents the marginal effects at mean values for the first model estimation. A one unit change in LNR&D, equal to 16.7 million Euros, results in a 2.6% decrease in the proximity effect (the probability that the firm finds domestic public research to be more important than public research in any other location). Firms that are active in the North American market are 14.8% less likely than other firms to find domestic PROs to be of greater value than PROs in other countries.

[Insert Table 2 here]

The two variables for output and investment in domestic PROs have a comparatively large impact on the proximity effect. For instance, a relatively small increase of about 70 million Euros in national expenditures on higher education R&D (equal to a 1% change in the average HERD for all countries in the regression) results in an increase of 1.1% in the probability that the firm finds domestic public research to be more important than public research in any other location. An analysis of the marginal effects for the variable PUBSHARE for the food sector shows that an increase of about 5,000 papers over the five years preceding the survey increases the proximity effect by 3.2%.

6. Conclusions and policy implications

[19] The pharmaceuticals sector has the highest level of internationalisation in R&D, thus the use of US subsidiaries by EU firms to tap into the local knowledge (Senker *et al.* 1996, Patel and Pavitt, 2000)

Two essential questions for innovation policy are first, whether proximity matters to knowledge flows, and if yes, how these knowledge flows occur and the what are the conditions necessary for their success. Answers to these two questions are of relevance to an assessment of a range of policies that have been introduced by governments, particularly in Europe, to support close linkages between firms and between firms and PROs. These policies include subsidies to encourage the regional development of clusters of innovative firms, subsidies for firms to collaborate with PROs, and the establishment of science parks close to universities - with poor results in a large number of cases (Quintas, 1992; Cesaroni and Gambardella, 1999).

The descriptive results presented above provide direct evidence, although based on the subjective judgement of R&D managers, that PROs are not only an important source of technical knowledge for the innovative activities of Europe's largest industrial firms, but are the most important of five external knowledge sources, after adjusting for a proxy measure of innovative output. Other sources of knowledge, such as suppliers and customers, are of less importance overall, although suppliers are a more important source of knowledge for firms active in medium technology sectors.

These results on the general importance of PROs are relevant to science and technology policy, particularly when the effect of proximity is taken into consideration. Not only are PROs the most important external source of knowledge for innovation, but proximity effects are more pronounced for PROs than for four other external knowledge sources. Only about 5% of R&D weighted firms find knowledge obtained from foreign PROs to be of greater value to their innovative activities than knowledge from domestic PROs, while almost half find the output of domestic PROs to be more valuable than the output of foreign PROs. The ordered logit model results show that proximity effects decline with an increase in R&D expenditures and with experience in the North American market, but increase with the quality and availability of outputs from PROs in the firm's domestic country.

The results of both the descriptive and econometric analyses provide useful insights into the current policy debate on the role of PROs in a national system of innovation. Firms find PROs to be a valuable knowledge source and benefit more from domestic than foreign public research outputs. The positive impact in the econometric analyses of both PUBSHARE and HERDGDP on the proximity effect points to the need for a well-funded national public research base, particularly for firms with smaller R&D budgets that could lack the financial resources or capabilities to source knowledge abroad.

The most frequently cited explanation for proximity effects is the need to acquire tacit knowledge, or at least knowledge that is not yet codified. Firms use a variety of methods to acquire different types of knowledge from PROs, including some that provide access to codified knowledge, such as reading publications or attending conferences, and methods that provide the opportunity to access non-codified knowledge, such as informal personal contacts, joint research, and hiring trained scientists and engineers. In general, firms prefer methods that provide the opportunity for accessing non-codified knowledge, although we do not know whether informal contacts are used for this purpose. However, exploratory econometric analyses did not find that the relative importance of methods that provide access to codified versus non-codified knowledge had any impact on the proximity effect. In part, this is due to the complexity of the methods available to firms for accessing non-codified research. Firms can use one method for foreign PROs and a separate method for domestic PROs. In contrast, firms that attach a high importance to basic research results in publications (CODIFY) are less likely than other firms to give a higher importance to knowledge sourced from domestic versus foreign PROs. This is partly due to sectoral differences in the importance to firms of this type of codified knowledge. Nevertheless, the role of proximity declines when useful knowledge is available in a codified form. This suggests that new technologies that increase the amount of codified knowledge produced by PROs, and decrease the time between discovery and codification, could reduce the importance of proximity.

References

Acts, Z. J., D. B. Audretsch and M. P. Feldman. 1992. Real Effects of Academic Research. *American Economic Review,* 82: 363-67.

Adams JD. Comparative localization of academic and industrial spillovers. NBER working paper series 8292, NBER Cambridge, 2001.

Antonelli C. 1999. 'Industrial Organisation and the Production of Knowledge'. *Cambridge Journal of Economics* 23: 243-60.

Arundel, A., J. N. Cobbenhagen N. Schall. 2000. *The Acquisition and Protection of Competencies by Enterprises*. Final Report for EIMS Project 98/180**,** DG Research, Luxembourg.

Arundel, A. and W.E. Steinmueller. 1998. The Use of Patent Databases by European Small and Medium-sized Enterprises. *Technology Analysis and Strategic Management,* 10: 157-173.

Arundel, A., G. van de Paal and L. Soete. 1995. *Innovation Strategies of Europe's Largest Firms. Results of the PACE Survey*. European Innovation Monitoring System, Report No.23. Bruxelles: European Commission.

Audretsch, D. B. and M. Feldman. 1996. 'R&D Spillovers and the Geography of Innovation and Production'. *American Economic Review,* 86: 630-42.

Baptista, R. 1999. 'Clusters, Innovation, and Growth: A Survey of the Literature'. In G.M.P. Swann, M.Prevezer and D. Stout (eds). *The Dynamics of Industrial Clustering*, Oxford: Oxford University Press.

Beise, M., and H. Stahl. 1999. 'Public Research and Industrial Innovations in Germany'. *Research Policy*, 28: 397-422.

Breschi, S. and F. Lissoni. 2001 (forthcoming). Knowledge Spillovers and Local Innovation Systems: A Critical Survey. *Industrial and Corporate Change*.

Cesaroni, F. and A. Gambardella. 1999. 'Dai "Contenitori" ai "Contenuti":I parchi Scientifici e Technologici in Italia'. In C. Antonelli (ed) *Conoscenza Tecnologica. Nuovi Paradigmi dell'Innovazione e Specificità Italiana*, Torino: Fondazione Giovanni Agnelli, pp.

Cohen, W.M., Nelson, R.R., and J.P. Walsh. (forthcoming) Links and impacts: The influence of public research on industrial R&D, Management Science.

Cowan, R., P.A. David, and D. Foray. 2000. 'The Explicit Economics of Knowledge Codification and Tacitness', *Industrial and Corporate Change*, 9: 211-54.

Cowan, R. and N. Jonard. 2000. 'The Dynamics of Collective Invention', MERIT Memorandum 2/20-018, MERIT, Maastricht.

EC (European Commission). June 2001. Benchmarking Industry-Science Relations- The Role of Framework Conditions. Final Report, commissioned by DG Enterprise and the Federal Ministry of Economy and Labour, Austria.

Faulkner, W., J. Senker and L. Velho. 1995. Knowledge Frontiers. *Public Sector Research and Industrial Innovation in Biotechnology, Engineering Ceramics and Parallel Computing*. Clarendon Press, Oxford.

Feldman, M. P. 1999. 'The New Economics of Innovation, Spillovers and Agglomeration: A Review of Empirical Studies'. *Economics of Innovation and New Technologies*, 8: 5-25.

Freeman, C. 1987. *Technology Policy and Economic Performance: Lessons from Japan*. London: Pinter.

Griliches, Z. 1979. 'Issues in Assessing the Contribution of R&D to Productivity Growth'. *Bell Journal of Economics,* 10: 92-116.

Hagedoorn, J., A.N. Link and N. Vonortas. 2000. 'Research Partnerships'. *Research Policy,* 29: 567-86.

Henderson R, Jaffe AB, Tratjenberg M. Numbers up, quality down? Trends in University patenting 1965-1992. Presentation to CEPR/AAAS conference "University goals, institutional mechanisms and the Industrial transferability of research', Stanford University, March 18-20, 1994.

Hippel, E. von. 1987. 'Cooperation between Rivals: Informal Know-how Trading'. *Research Policy* 16: 291-302.

Jaffe, A. 1989. 'Real Effects of Academic Research'. *American Economic Review,* 79: 957-70.

Jaffe, A., M. Trajtenberg, and R. Henderson. 1993. Geographic Localization of Knowledge Spillovers as Evidenced by Patents Citations. *Quarterly Journal of Economics,* 63: 577-98.

Klevorick, A.K., R.C. Levin, R.R. Nelson and S.G. Winter. 1995. On the Sources of Significance of Interindustry Differences in Technological Opportunities. *Research Policy*, 24: 185-205.

Kline, S. and N. Rosenberg. 1986. 'An Overview of Innovation'. In Landau, R., (ed.), *The Positive Sum Strategy*. National Academic Press, Washington, DC.

Larsen K. and A. Salter, 2001. The Fruits of Intellectual Production: Economic and Scientific Specialisation Among OECD Countries. Available at: http://www.researchineurope.org/newkind/documents/index.htm on 25/10/2001.

Leamer E.E., Storper M. 2001. The economic geography of the Internet age. NBER Working Paper 8450, NBER, Cambridge MASS.

Liao, T. F. 1994. *Interpreting Probability Models. Quantitative Applications in the Social Sciences*. Thousand Oaks: Sage Publications.

Lundvall, B. (ed.) 1992. *National Systems of Innovation*. London: Pinter.

Malo, S. and A. Geuna. 2000. 'Science-Technology Linkages in an Emerging Research Platform: The Case of Combinatorial Chemistry and Biology'. *Scientometrics,* 47: 303-21.

Mansfield, E. 1991. 'Academic Research and Industrial Innovation'. *Research Policy,* 20: 1-12.

Mansfield, E. 1995. 'Academic Research Underlying Industrial Innovations: Sources, Characteristics, and Finance'. *The Review of Economics and Statistics,* 77: 55-65.

Mansfield, E. 1998. 'Academic Research and Industrial Innovation: An Update of Empirical Findings'. *Research Policy,* 26: 773-76.

Mansfield, E. and J.-Y. Lee. 1996. 'The Modern University: Contributor to Industrial Innovation and Recipient of Industrial R&D Support'. *Research Policy,* 25: 1047-58.

Marshall, A. 1920. *Principles of Economics.* Reprinted 1997. New York: Prometheus Books.

Maskell P and A. Malmberg. 1999. 'Localised Learning and Industrial Competitiveness'. *Cambridge Journal of Economics,* 23: 167-75.

Narin, F., K. S. Hamilton, and D. Olivastro. 1997. 'The Increasing Linkage between U.S. Technology and Public Science'. *Research Policy,* 26: 317-20.

Narin, F. and D. Olivastro. 1992. 'Status Report: Linkage between Technology and Science'. *Research Policy,* 21: 237-49.

Nelson, R. (ed.) 1993. *National Innovation Systems: A Comparative Study*. New York: Oxford University Press.

Oliver AL, Liebeskind JP. 1998. Three levels of networking for sourcing intellectual capital in biotechnology. International Studies of Management and Organisation 27:76-103, 1998.

Patel P. and K. Pavitt. 2000. 'National systems of Innovation under Strain: the Internationalisation of Corporate R&D' in R. Barrell, G. Mason and M. O'Mahoney (eds.) *Productivity, Innovation and Economic Performance*, Cambridge University press, pp. 217-235.

Pavitt, K. 1991. 'What Makes Basic Research Economically Useful?' *Research Policy*, 20: 109-119.

Quintas P. 1992. 'Academic-Industry Links and Innovation: Questioning the Science Park Model'. *Technovation,* 12: 161-75.

Roberts, J. 2000. From Know-how to Show-how? Questioning the Role of Information and Communication Technologies in Knowledge Transfer. *Technology Analysis and Strategic Management*, 12: 429-43.

Saxenian, A. 1994. *Regional Advantage: Industrial Adaptation in Silicon Valley and Route 128*. Cambridge: Harvard University Press.

Salter, A.J. and B.R. Martin. 2001. he Economic Benefits of Publicly Funded Basic Research: A Critical Review *Research Policy* 30: 509-32.

Saviotti PP. On the Dynamics of Appropriability, of Tacit and of Codified Knowledge. *Research Policy* 26:843-856, 1998.

Senker J. 1995. 'Tacit Knowledge and Models of Innovation'. *Industrial and Corporate Change* 2: 425-47.

Senker J., P.B. Joly and M. Reinhard, 1996. Overseas Biotechnology Research by Europe's Chemical/Pharmaceuticals Multinationals: Rationale and Implications. STEEP Working Paper N.33, Brighton: SPRU.

Steinmueller, W.E. 1996. 'Basic Research and Industrial Innovation'. In M. Dodgson and R. Rothwell (eds). *The Handbook of Industrial Innovation*, Cheltenham: Edward Elgar.

Verspagen, B. 1999. 'Large Firms and Knowledge Flows in the Dutch R&D System: A case Study of Philips Electronics'. *Technology Analysis & Strategic Management,* 11: 211-33.

Table 1. Ordered Logit Model Estimates

X variables	First Estimation β (t ratio)	Second Estimation β (t ratio)	Third Estimation β (t ratio)
LNR&D	-0.106 (-2.284)**	-0.153 (-2.792)***	-0.108 (-2.008)**
RDINT		-0.004 (-1.550)	
AMERICA	-0.596 (-2.837)***	-0.768 (-2.599)***	-0.740 (-2.430)**
EUROPE		-0.063 (-0.171)	0.100 (.291)
JAPAN		0.384 (1.493)	0.359 (1.333)
CODIFY	-0.033 (-2.148)**	-0.027 (-1.659)*	-0.024 (-1.398)
PUBSHARE	0.130 (3.933)***	0.133 (3.797)***	0.164 (4.538)***
HERDGDP	0.046 (3.642)***	0.048 (3.521)***	0.051 (3.542)***
HOMEOFF		0.400 (1.097)	0.250 (.679)
SECTOR DUMMIES[1]	No	No	Yes
Constant	1.779 (3.251)***	1.746 (2.173)**	0.065 (0.072)
M	2.594 (14.179)***	2.639 (12.940)***	2.771 (13.937)***
LL	-389.83	-339.61	-370.64
Model significance	P < .000	P < .000	P < .000
No. of firms	443	390	443

*** statistically significant at p. <.01;
** statistically significant at p. <.05;
* statistically significant at p. <.10.
1: Pharmaceuticals is the reference category.

Table 2. Marginal Effects for the first model estimation

	Foreign > domestic (PROXPR=0)	Domestic = foreign (PROXPR=1)	Domestic > foreign (PROXPR=2)
LNR&D	0.0078	0.0187	-0.0264
AMERICA	0.0436	0.1048	-0.1484
CODIFY	0.0024	0.0058	-0.0083
PUBSHARE	-0.0095	-0.0229	0.0324
HERDGDP	-0.0034	-0.0082	0.0116
CONST	-0.1300	-0.3127	0.4427

FIGURE 1: Importance of external information sources to the innovative activities of low, medium and high tech firms

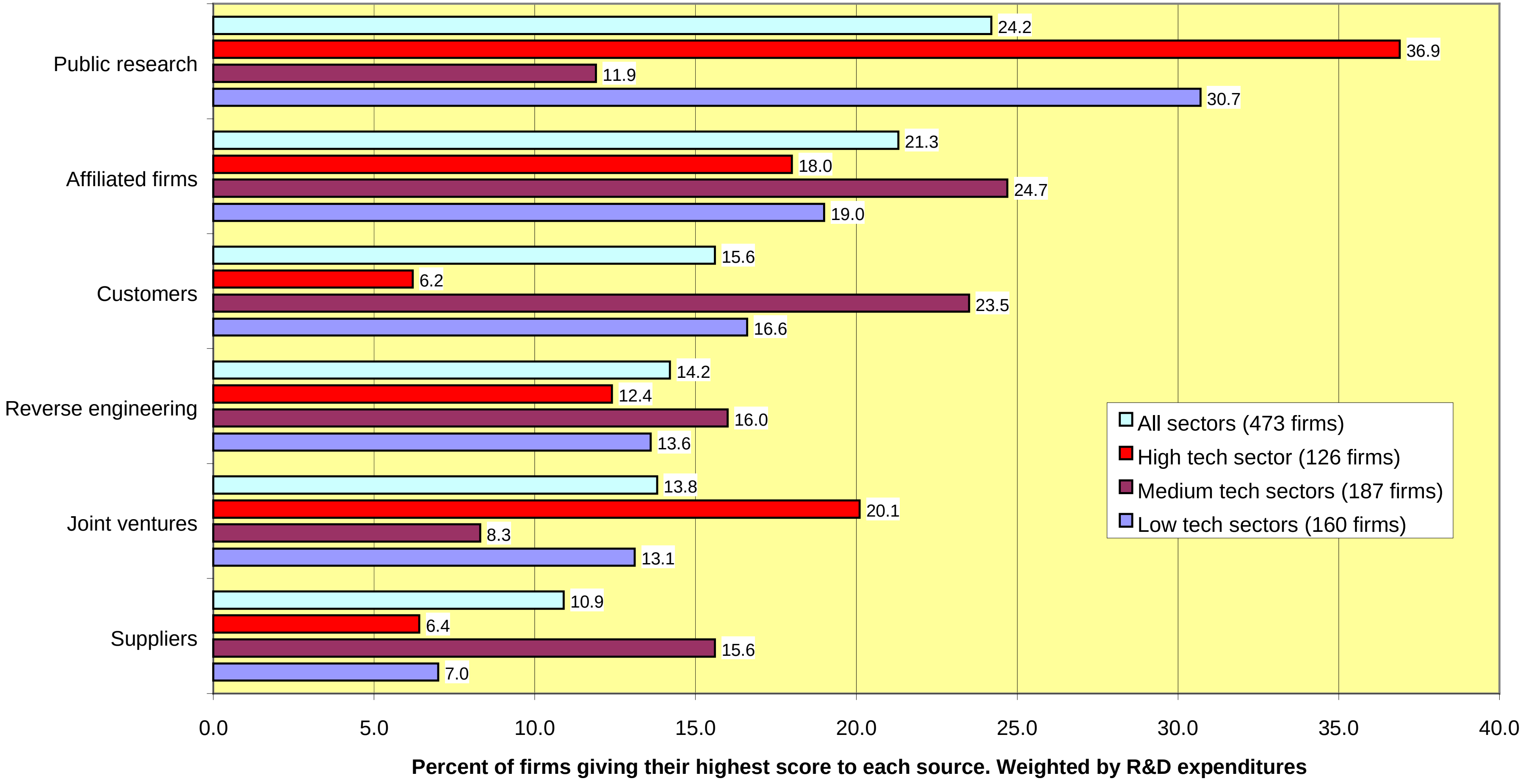
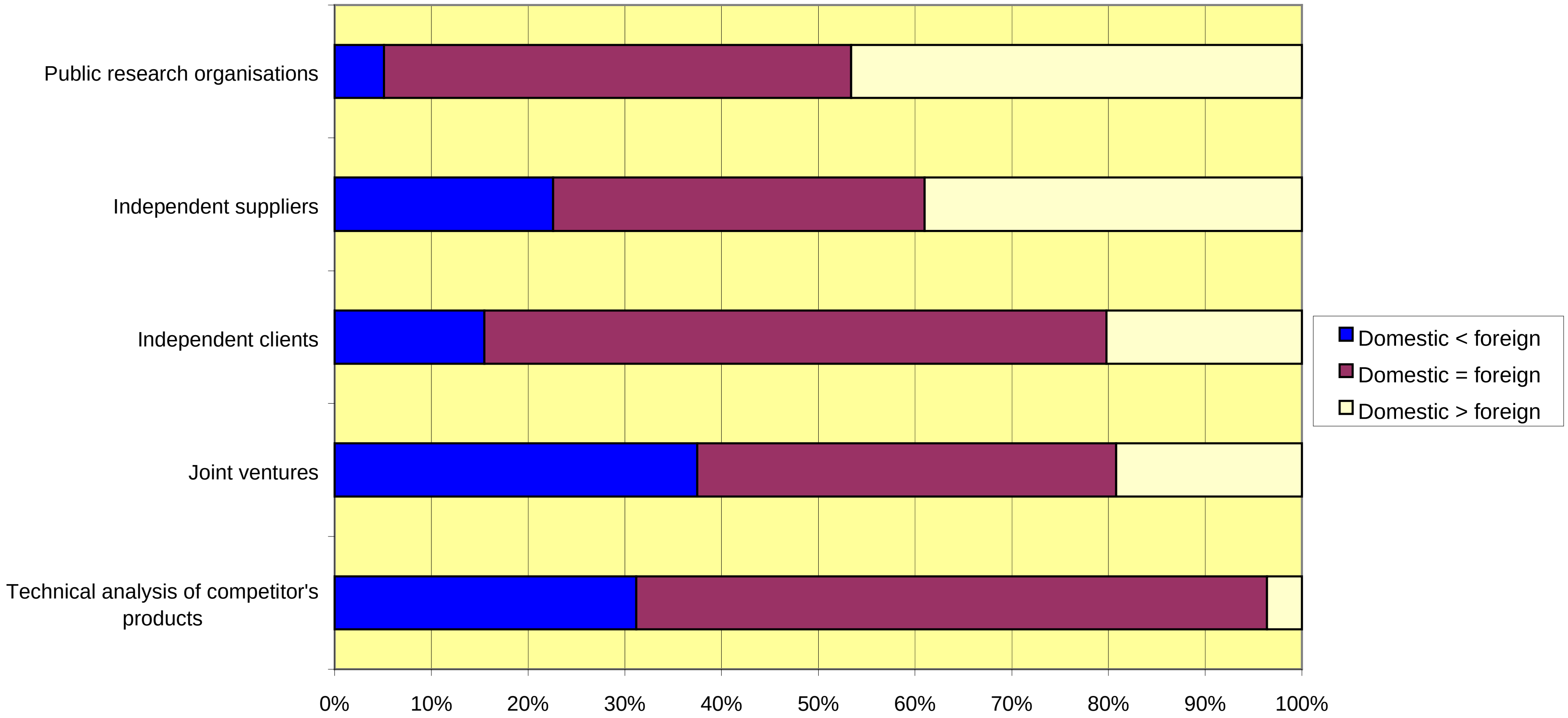


FIGURE 2: Importance of proximity for five external sources of technical knowledge (Weighted by R&D expenditures)



Percentage of firms rating domestic sources of technical knowledge as less important than all other foreign sources, of equal importance, and of more importance

FIGURE 3: Importance of methods for learning about public research results