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The Impact and Organization of Publicly-Funded Research and Development in the European Community

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ABSTRACT. – This paper examines R&D activities in the European Community using several Community R&D Information Service (CORDIS) databases. We find that a country's private companies tend to be specialized in the same scientific fields as its universities and public organizations. In addition, we construct indicators of the degree of R&D tacitness and find that greater expected ability to communicate research outcomes encourages less centralized R&D programs. Programs that yield tangible results are less geographically and administratively centralized. The more that research leads to codifiable knowledge, the less centralized R&D activity needs to be.

Impact et organisation de la recherche et développement sur fonds publics dans la communauté européenne

RÉSUMÉ. – L'article analyse les activités de R&D au sein de la Communauté Européenne à partir des données collectées par le CORDIS, service d'information spécialisé sur la recherche de la Communauté. Nous observons que les entreprises privées dans un pays tendent à être spécialisées dans les mêmes domaines scientifiques que les universités et organismes publics de ce pays. Nous construisons aussi des indicateurs du caractère plus ou moins tacite ou codifié de la R&D. Nous trouvons que les programmes de R&D sont d'autant moins centralisés qu'il paraît plus aisé de communiquer les résultats des recherches, et que ceux qui génèrent des résultats tangibles sont moins centralisés géographiquement et administrativement. Les activités de R&D ont ainsi d'autant moins besoin d'être centralisées qu'elles conduisent à des connaissances codifiables.

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1 Introduction

Innovation, rather than the result of the efforts of an individual inventor, is most likely predicated on the orchestration of different and complementary streams of knowledge. A substantial share of this knowledge is the product of publicly-funded research and development (R&D). For example, the fraction of R&D expenditure that is governement-funded is 32% in the United Kingdom, 37% in Germany, and about 45% in both France and Italy [1]. In recent years, a significant amount of publicly-funded R&D in Europe has been coordinated by the Commission of the European Community (CEC). For example, the CEC created the Community R&D Information Service (CORDIS), to "assist interactions and cooperation among individual ...participants; and help promote co-ordination with similar RTD [research and technological development] activities in Member States". A principal objective of publically funded R&D is the overall "advancement of knowledge"; "industrial development" is an important secondary objective [2].

In this paper we examine some important aspects of the impact and organization of publicly-supported R&D activities in the European Community, using several of the large and rich CORDIS databases. We analyze the relationship between public and private R&D-performing organizations, and test the hypothesis of *complementarity* of the research efforts of these two sectors [3]. In particular, we determine whether a country's private organizations tend to be specialized in the same technologies as its public organizations.

We also propose and test a theory of the (geographic and administrative) *organization* of R&D programs. A number of recent studies have suggested that R&D investment has a strong geographic component [4]. Organizations that use similar knowledge tend to locate near one another, presumably because the cost of transmitting and acquiring knowledge increases with distance. (Language differences and political boundaries also further increase these costs). We hypothesize that the extent of geographic and administrative decentralization of R&D activities is greater, the less tacit (or more codifiable) the knowledge generated by the R&D is expected to

1. Source: Science and Engineering Indicators 1996, Appendix Table 4-35.
2. The fraction of government R&D budget appropriations devoted to the "socioeconomic objective" of "advancement of knowledge" ranges from 22% in the U.K. to 51% in Germany. In contrast, only 4% of U.S. public R&D is devoted to this objective. (In the U.S., defense and health account for 55% and 17% of public R&D, respectively.) The fraction of European public R&D devoted to industrial development ranges from 7% in France to 16% in Italy; less than 1% of U.S. public R&D is devoted to this objective. (Source: Science and Engineering Indicators 1996, Appendix Table 4-32.)
3. In previous research, LICHTENBERG [1984, 1987, 1988] investigated the issue of complementary (or its opposite, "crowding out") between privately- and government-funded (defense) R&D expenditure in the U.S.
4. See, for example, ACS, AUDRETSCH and FELDMAN [1992, 1994], ZUCKER, L., DARBY, M. and ARMSTRONG, J. [1994], FELDMAN and FLORIDA [1994], JAFFE [1989], and PORTER [1990].

be. We construct several indicators of the degree of R&D decentralization and tacitness of European Community RTD programs from data contained in the CORDIS databases to test this hypothesis.

The remainder of this paper is organized as follows. In the next section, we provide some descriptive statistics about R&D activity in the European Community as reflected in the CORDIS data, including distributions of organizations by type, country, and technological field. Since we can determine, for example, the number of German manufacturing firms and universities engaged in R&D in the area of genetic engineering, we can identify each country's areas of technological specialization. In Section 3, we analyze the relationship between the extent of R&D activity by universities and other public organizations within a given region and field of science and the extent of R&D undertaken by private firms in the same region and scientific field. In Section 4, we advance and test the hypothesis that research programs that produce more tacit results are more geographically concentrated than programs that produce more articulable results. Section 5 concludes.

2 The Degree of Specialization in Country Knowledge Resources

Just as countries specialize in the production of physical goods and services we expect that there will be specialization in the production of knowledge. The data contained in the CORDIS RTD-Partners database – in particular, the technology and industry classification codes-allow us to construct the distribution of each country's knowledge base by scientific field and type of organization [5]. Table 1 provides an accounting of the types of organizations represented in the data. The most prominent type of organization lised is universities and educational organizations (4413). Manufacturers accounted for 2692 organizations [6]. Public, non-university research centers, such as the Commissariat a l'Énergie Atomique (France), Fraunhofer-Institut fuer Materialfluss und Logistik (Germany), and Institutop de Linguistica Teorica e Caomputacional (ILTEC) (Portugal), accounted for

5. The RTD-Partners database includes information about all organizations that have registered with the Community R&D Information Service in order to try to establish R&D partnerships with other organizations in the European Community. (International partnership is a necessary but far from sufficient condition to be eligible for EC support.) "Organizations" may be university *departments* or *divisions* of companies. These organizations have not necessarily received any public R&D funding-most probably have not. This reduces the probability that this sample misrepresents the aggregate distribution of private-sector research. The other CORDIS databases (RTD-Programmes, -Projects, and -Results) analyzed later in this paper describe R&D activities that have received some public support.
6. Some private firms may be university spin-offs, but these are not systematically identified in the database.

TABLE 1

Number of Organizations, by Type.

Organization Type	Number of Organizations
Universities and Educational Organizations	4413
Manufacturer	2692
Public Research Center (Non-University)	2167
Service Company	2001
Consultancy	1725
Public Organization (National)	423
Technology Transfer Organization	859

2167 organizations. Technology transfer organizations, such as Zentrum Mikroelektronik Dresden (Germany), Transcend Technology LTD (United Kingdom), Impetus Consultants (Greece) accounted for 859 entries. National public organizations, such as Technicatome (France), Empresa Nacional Adaro (Spain), Ente per le Nuove Tecnologie (Italy), accounted for 423 of the organizations.

The distribution of organizations, by country, is shown in Table 2 [7]. For example, there were 3054 R&D organizations in the United Kingdom and 2502 located in Germany. The relative ranking among countries is consistent with ARCHIBUGI and PIANTA's [1992] analysis based on patent registration and bibliometric indicators. To normalize for population, the last column of Table 2 presents the number of organizations per 1 million population. While the United Kingdom and Germany have the greatest number of R&D organizations, Ireland, with a small population and a high degree of foreign investment, has the highest number of R&D organizations on a per capita basis.

All of the R&D organizations in the CORDIS database report the technological fields in which they are currently working. Since organizations typically work with different technologies, each organization may report up to five unique fields of technological expertise [8]. There are 400 distinct technological fields and the 15,491 organizations report 42,862 fields of technological expertise. Table 3 provides a listing of the most prominent scientific disciplines, which are more aggregate groupings of technological

7. This table does not provide data for those countries with fewer than 100 organizations reporting. Other countries and their number of organizations include Luxembourg (39 organizations), Romania (29), Slovenia (20), Czech republic (18), Latvia (18), Poland (17), Israel (14), Estonia (8), and Croatia (3).
8. The mean number of technological fields per organization is 2.77, and the modal number is the maximum number allowed, 5. This suggests that there may be a significant amount of truncation in the reporting of technological fields.

TABLE 2

Number of Organizations, by Country.

Country	Number of Organizations	Population	Organizations per million population
United Kingdom	3054	58,295,119	52.4
Germany	2502	81,337,541	30.8
Italy	2205	58,261,971	37.8
France	1740	58,109,160	29.9
Spain	1163	39,404,348	29.5
Greece	911	10,647,511	85.6
Belgium	859	10,081,880	85.2
Netherlands	831	15,452,903	53.8
Ireland	511	3,550,448	143.9
Denmark	395	5,199,437	76.0
Portugal	355	10,562,388	33.6
Finland	278	5,085,206	54.7
Sweden	251	8,821,759	28.5
Austria	165	7,986,664	20.7
Switzerland	146	7,084,984	2.06
Norway	125	4,330,951	28.9
Source for population data: http://www.odci.gov/cia/publication/95fact			

fields [9]. For example, there were 3995 organizations engaged in computer science, the most prominent of the disciplines. This represented 9.32% of all the capabilities mentioned by the organizations.

The assessment of national capabilities and performance in technological fields is important from a policy perspective for both government and private firms. Table 4 identifies the scientific disciplines in which countries have a specialization or weakness relative to that country's overall R&D activity. To test for the degree of specialization we use a non-parametric

9. The technological fields are hierarchically organized within scientific domains. The data presented in Table 2 and Table 3 are for scientific domains that are the larger categories of expertise. For example, all of the medical subfields and specialities are aggregated in the scientific domain of medicine.

TABLE 3

Number of Organizations, by Scientific Discipline.

Scientific Discipline	Organizations Reporting	Share of all Technologies (%)
Computer science	3995	9.32
Material technology	3546	8.27
Construction technology	3538	8.25
Biochemistry	2475	5.77
Chemistry	2409	5.62
Environmental engineering	2244	5.24
Electronics and related fields	1953	4.56
Mechanical engineering	1880	4.39
Production technology	1873	4.37
Medicine	1784	4.16
Transportation technology	1629	3.80
Physics	1495	3.49
Telecommunications	1065	2.48
Geology	956	2.23
Composite materials and related fields	920	2.15
Biomedical and related sciences	878	2.05
Coatings and surface materials engineering	848	1.98
Electrical engineering	683	1.59
Energy research	662	1.54
Ceramic materials and related fields	628	1.47
Nuclear engineering	524	1.22
Ecology	432	1.01
Microelectronics	417	0.97
Laser technology	366	0.85
Zoology	355	0.83
Thermal engineering	246	0.57

TABLE 4

Country Specialization in Scientific Disciplines: Countries and Scientific Fields with "Unexpectedly" High or Low Numbers of Organizations.

Technology	Country	Count	Percent	Chi-Sq
Computer Science	Germany	682	16.98	23.68
Electronics	Italy	52	– 62.50	12.50
	United Kingdom	216	24.86	17.77
Material Technology	Spain	150	– 75.53	48.75
	Greece	147	– 74.22	46.48
	Germany	618	18.67	26.50
	Italy	619	29.13	74.10
Construction Technology	Ireland	60	– 81.67	22.03
	United Kingdom	746	– 12.68	10.65
	Netherlands	237	19.83	11.63
	Denmark	155	31.74	22.88
	Bulgaria	12	86.67	67.60
Biochemistry	Germany	67	– 85.67	26.49
	France	116	28.19	12.84
	Spain	100	34.80	18.57
	Sweden	25	49.60	12.20
	Portugal	51	58.04	40.94
Chemistry	Italy	185	– 61.08	42.85
	Denmark	108	33.24	17.88
	Sweden	54	36.11	11.02
Environmental Engineering	Germany	173	– 102.78	90.12
	United Kingdom	472	– 24.60	22.92
	Italy	566	45.90	220.43
Electronics and Related Fields	Italy	146	– 65.48	37.83
	France	150	23.53	10.86
	Austria	59	56.95	44.45
	Luxembourg	14	85.71	72.00
	Solvenia	14	88.57	96.10

TABLE 4 (continued)

Technology	Country	Count	Percent	Chi-Sq
Mechanical Engineering	Greece	39	– 103.08	20.40
	Italy	92	– 47.39	14.02
	Germany	253	38.62	61.46
Production Technology	United Kingdom	283	– 57.10	58.74
	Greece	90	– 50.11	15.06
	Germany	324	18.15	13.04
	Italy	438	47.15	184.20
Medicine	Germany	122	–107.30	67.75
	Italy	115	– 91.91	50.62
	Netherlands	60	– 59.67	13.38
	Belgium	120	29.42	14.71
	France	286	40.84	80.63
	Spain	249	46.79	102.43
Transport Technology	Portugal	16	– 148.13	14.15
	United Kingdom	522	25.84	47.01
Physics	Italy	77	– 140.13	62.97
	Netherlands	46	– 74.57	14.65
	United Kingdom	422	15.83	12.56
	Germany	261	18.81	11.38
	Austria	34	42.94	10.99
Telecommunication	Italy	93	– 41.72	11.42
	Spain	81	32.84	13.01
	Finland	50	53.20	30.24
Geology	Belgium	14	– 224.29	21.72
Biomedical Sciences	Netherlands	39	42.82	12.51
Coatings and Surface	Spain	29	– 117.24	18.35
	Greece	31	– 97.74	14.98
	Italy	60	– 74.83	19.22

TABLE 4 (continued)

Technology	Country	Count	Percent	Chi-Sq
Coatings and Surface (cont.)	Germany	199	39.60	51.66
Electrical Engineering	Italy	97	30.83	13.32
Energy Research	Greece	79	39.49	20.36
	Denmark	35	43.43	11.67
	Switzerland	20	64.00	22.76
Laser Technology	Germany	104	50.10	52.30
Electronics	Italy	101	30.10	13.09
	Finland	34	63.24	36.98
Ceramic Materials	Italy	42	– 85.00	16.40
Nuclear Engineering	Italy	31	– 109.03	17.63
	United Kingdom	183	31.97	27.49
	France	91	45.39	34.32
Microelectronics	Germany	88	32.84	14.13
Zoology	Germany	22	– 128.64	15.92
	Spain	54	51.11	28.85
Thermal Engineering	Portugal	14	57.14	10.67

chi-square test of association based on the share of all organizations with the various scientific expertise for a given country relative to the European total [10] . Within each country we identify those scientific disciplines which make a statistically significant contribution to the overall chi-squared value. Column 3 provides the total number of organizations in a country involved with a scientific discipline. Column 4 presents the percentage by which

10. The data for all countries are pooled to perform the test. The following simple example illustrates the test procedure. Suppose that there are only two countries and two fields. The following table represents the number of organizations in each country and field

	Country 1	Country 2
Field 1	N_{11}	N_{12}
Field 2	N_{21}	N_{22}

The test we performed is simply a standard chi-square test of the independence of field and country. (The CORDIS data contain a few R&D organizations that are non-European; these were excluded from our sample.)

the actual number of organizations is different than the expected number of organizations under the null hypothesis of no national technological specialization. This provides evidence on the extent to which a scientific discipline is over- or under-represented in a given country. A negative number indicates that the actual number of organizations is less than the expected number of organizations for that country. Column 5 provides the country-discipline contribution to the chi-square and provides an index of the degree of scientific specialization of each country [11]. If a country has no scientific specialization, that is, the same percentage distribution in a scientific discipline as the rest of the European Community, the chi-squared value would be zero. The larger the absolute value of the chi-square, the greater the evidence of scientific strength or weakness.

There is evidence of a high degree of specialization in scientific disciplines among countries. The highest degree of specialization observed is for Environmental Engineering in Italy. There are 566 organizations in this scientific discipline in Italy; this was 45.9% greater than expected. Based on the overall chi-square value, we conclude that the observed patterns of distribution of scientific disciplines among countries are not random. The configuration of knowledge among industries and countries appear to represent distinct competencies.

Table 5 provides the distribution of organizations among a representative sample of the different technological fields. On average, for all fields, universities accounted for 32.2 percent of all organizations. The highest percentage of universities and educational organizations, 65.8%, were reported for technologies involving condensed matter. As this table demonstrates, there is a great degree of heterogeneity in the prominence of different organizational types among technological fields.

3 Complementary Between Public and Private Technological Orientation

Previous studies have suggested that public and private R&D organizations may complement one another. For example, Part 3 of LEVIN *et al*'s [1987, 790] survey of 650 American R&D managers explored the links between an industry's technology and other sources of scientific expertise. The survey asked about the importance of scientific research in general and university-based research in particular, and found a strong association between private firm R&D and external sources of knowledge. Other research has found a strong geographic association between university research and private firm R&D (JAFFE [1989]; ACS, AUDRETSCH and FELDMAN [1992] and MANSFIELD

11. A value greater than 10.5 is statistically significant at the 5% level.

TABLE 5

How Important are Different Organizations for Each Technology?

Technology (Ranked by University Share of all Organizations)	Number of Orga-nizations	Percent of Organizations Reported as					
		Univer-sity	Manufac-turer	Public Research Center	Service Company	Consul-tancy	Tech Transfer
Condensed Matter, Electronic Structure	237	65.8	5.1	12.7	4.2	4.6	4.6
Physical Chemistry	157	59.2	4.5	20.4	4.5	6.4	5.1
Semiconductors Physics	108	56.5	8.3	7.4	4.6	13.0	8.3
Condensed Matter Physics	243	56.4	3.7	22.2	4.9	2.9	6.2
Mathematics	186	52.7	6.5	10.2	13.4	10.8	3.2
Hydrobiology, Marine Biology	509	52.3	4.9	11.2	2.9	15.9	2.8
Aquaculture, Pisciculture	518	51.2	5.6	9.5	3.7	16.4	4.1
General Biomedical Sciences	119	50.4	9.2	15.1	8.4	9.2	7.6
Statistics, Operations Research	329	44.1	2.4	8.5	17.0	21.6	4.6
Chemistry	889	42.4	10.8	19.6	16.9	5.2	2.9
Proteins, Enzymology	250	41.2	8.8	28.8	7.6	6.0	5.2
Microbiology, Bacte-riology, Virology	388	36.3	8.2	30.9	6.7	9.5	4.9
Mechanical Engineering	1096	36.2	20.3	12.5	14.2	9.2	5.1
Material Technology	3549	34.9	24.9	14.5	12.2	6.4	5.7
Computer Science	1027	34.9	9.9	10.0	19.4	17.8	6.0
Analytical Chemistry	294	34.7	2.7	36.4	6.8	7.5	6.5
Ceramic Mate-rials and Powders	628	34.6	15.1	21.5	9.6	8.3	8.8
Biochemistry	253	34.4	5.5	32.0	11.5	5.5	7.5

TABLE 5 (continued)

Technology (Ranked by University Share of all Organizations)	Number of Orga-nizations	Percent of Organizations Reported as					
		Univer-sity	Manufac-turer	Public Research Center	Service Company	Consul-tancy	Tech Transfer
Composite Materials	920	34.3	18.2	18.7	11.3	7.7	7.7
Artificial Intelligence	386	33.7	8.0	10.1	15.3	21.8	9.8
Coatings and Surface Treatment	848	32.9	16.3	20.3	11.9	8.5	8.4
Soil Science, Agricultural Hydrology	208	32.7	3.8	28.8	12.0	10.1	5.8
ALL FIELDS	42862	32.3	16.0	16.6	13.2	11.9	6.8
Zootechnics, Animal Husbandry, Breeding	134	32.1	6.7	32.1	3.7	8.2	9.7
Laser Technology	366	32.0	13.9	19.7	10.4	9.3	10.7
Thermal Engineering, Thermodynamics	248	31.9	8.9	12.1	13.3	20.2	10.9
Environmental Chemistry	1277	31.6	7.0	24.5	18.2	9.7	5.2
Air Transport Technology	274	31.4	19.7	13.9	10.6	14.2	7.3
Medical Technology	366	29.5	22.4	11.2	13.9	11.5	9.0
Horticulture	296	29.1	7.8	35.1	5.4	7.8	8.1
Civil Engineering	514	29.0	14.4	11.9	16.5	20.2	5.6
Informatics, Systems Theory	477	27.7	7.3	10.5	18.0	24.9	10.1
Environmental Technology	2138	27.5	10.9	17.9	18.3	14.8	7.1
Imaging, Image Processing	744	26.7	16.0	15.2	15.5	14.9	9.1
Instrumentation Technology	773	26.4	21.0	18.0	14.2	8.7	8.3

TABLE 5 (continued)

Technology (Ranked by University Share of all Organizations)	Number of Orga-nizations	Percent of Organizations Reported as					
		University	Manufacturer	Public Research Center	Service Company	Consultancy	Tech Transfer
Computer Systems Technology	2018	26.1	14.5	10.5	22.1	17.8	7.3
Electronics & Electrical Technology	472	26.1	24.6	10.8	16.7	10.0	8.9
Electrical Engineering	393	25.7	34.1	6.6	13.0	12.2	6.1
Metrology, Physical Instrumentation	228	25.4	14.9	23.7	11.0	9.6	7.9
Automation & Robotics	1585	24.9	23.2	11.9	16.0	11.9	9.0
Energy Research	664	24.8	11.3	18.5	13.1	17.8	10.8
Road Transport Technology	438	23.3	20.3	11.6	13.5	21.0	7.5
Microelectronics	418	22.5	27.3	12.4	10.3	12.7	11.2
Production Technology	1873	22.4	34.9	10.4	14.1	9.3	7.6
Transport Technology	498	20.5	18.1	14.5	17.9	21.7	6.0
Telecommunication Engineering	628	19.6	16.7	9.9	19.6	21.5	9.6

[1995]). Similarly, ADAMS [1990] used the distribution of an industry's scientists by academic discipline (e.g., physics, chemistry) to examine the relationship between fundamental stocks of knowledge and industry productivity growth. Public organizations other than universities, such as technology-transfer agencies, may also contribute to knowledge accumulation in private enterprises. Indeed, their RTD activities may have a stronger or more immediate effect on private knowledge than those of university research, which is more basic in nature.

In this section we explore the relationship between private and public knowledge within the same country, by estimating regressions of the number of consultancies, manufacturers, and service companies – which are predominantly private-sector organizations – on the number of public organizations – public research centers, technology transfer organizations, and universities – which are predominantly public-sector organizations – by country and scientific field. The distribution of organizations by type and sector (private vs. public) is shown in Table 6. Table 7 reports the mean number of fields of science, by organization type, and indicates that there is significant heterogeneity in the degree of scientific specialization. In general, private sector organizations – consultancies, manufacturers and

TABLE 6

Number of Organizations, by Type* and Sector**.

	Private	Public	Total
Consultancy	55	4	194
Manufacturer	65	12	290
R&D Organization	136	254	80
Service Company	44	7	155
Technology Transfer Organization	3	4	10
University	2	687	1129
Total	254	948	

*Source: RTD-Results database. * An organization could be classified as more than one type. ** Sector was not reported for many organizations.*

TABLE 7

Mean Number of Fields, by Organization Type.

Organization Type	Mean	Standard Deviation	t-statistic for testing H_0: difference from mean for other org. types = 0
Consultancy	2.96	1.62	7.37*
Manufacturer	2.55	1.30	29.32*
Public Organization (National)	3.22	1.37	0.0
Public Research Center (Non-University)	3.28	1.32	– 2.09*
Service Company	2.68	1.46	18.81*
Technology Transfer Organization	3.42	1.52	– 3.90*
University and Educational Organizations	3.14	1.30	4.75*

** Statistically significant at the 5% level.*

service companies – are involved in fewer fields of science. The t-statistics for testing the null hypothesis of equality of means across the different types of organizations are shown in the last column of Table 7. The only organizational type for which the mean number of technologies is not statistically significantly different from the others is national laboratories.

The regressions include complete sets of technology field and country dummies, so the coefficients indicate the degree of complementarity between different pairs of public and private organizational types. The country dummies control for all country characteristics that do not vary across fields, such as country size, national R&D budget, public sector employment, and engineering school graduation rates. The regressions are of the form

$$\text{(1)} \qquad \begin{aligned} \mathrm{N\_PRIV}_{ij} &= \beta_1\,\mathrm{N\_PubOrg}_{ij} + \beta_2\,\mathrm{N\_PubRes}_{ij} \\ &\quad + \beta_3\,\mathrm{N\_TechTrans}_{ij} + \beta_4\,\mathrm{N\_Univers}_{ij} + \delta_i + \gamma_j + u_{ij} \end{aligned}$$

where $\mathrm{N\_PRIV}_{ij}$ denotes the number of private organizations (consultancies, manufacturers, or service companies) in country i ($i = 1, ..., 38$) active in scientific field j ($j = 1, ..., 198$); N_PubOrg is the number of national public organizations; N_PubRes is the number of public research centers; N_TechTrans is the number of technology transfer organizations; and N_Univers is the number of universities. Significant positive $\beta_k\,(k = 1,\ 2,\ 3,\ 4)$ coefficients indicate that if a country has an unexpectedly large number of public organizations active in a scientific field (given the size of the country and the field), it also tends to have an unexpectedly large number of private organizations in the field. Stated differently, positive coefficients signify that a country's private organizations tend to be concentrated (specialized) in the same scientific fields as its public organizations. Within each field, private and public organizations tend to be distributed across countries in similar ways.

Some of the coefficients are likely to be biased upwards due to the fact that multiple organization types are reported for some organizations. For example, 40 organizations described themselves as both consultancies and public organizations; one-sixth of public organizations also described themselves as consultancies. When we calculated the number of organizations by country, type, and field to compute the regressions, we "double-counted" organizations: an organization that was listed as both a consultancy and a public organization would be counted twice (in a given field), once as each type. Consultancy and Technology Transfer Organization are the two organization types most frequently involved when there are mutliple organization types, so the β_3 coefficient in the number-of-consultancies regression is most likely to be biased upwards. In contrast, manufacturers, service companies, public organizations, and universities are very infrequently "double counted", so we expect little, if any, bias in the corresponding coefficients.

Estimates of the parameters of eq. (1) are shown in Table 8. The coefficients on public organizations and universities in the manufacturers and service companies regressions are all positive and statistically significant. This indicates that a country's manufacturers and service companies tend to be specialized in the same scientific fields as its universities and public organizations. For example, if few or none of a nation's universities are active in a particular field of science, few or none of its firms are also likely to be active in that field.

TABLE 8

Complementarity Model – Regression Results.

Independent Variables	Dependent Variables		
	Consultancies	Manufacturers	Service Companies
Public Organizations	.093 (1.81)	.873 (3.79)	.333 (4.04)
Public Research Centers	–.046 (3.21)	.122 (1.90)	.220 (9.59)
Technology Transfer Organizations	1.21 (47.5)	1.23 (10.8)	.930 (22.7)
Universities	.071 (10.2)	.058 (1.85)	.050 (4.43)
R-squared	0.8320	0.3660	0.7030

Note: t-statistics in parentheses. All regressions include 198 technical field dummies and 38 country dummies and are based on a sample of 2401 observations.

The coefficients on public organizations are much larger than the coefficients on universities. This might mean that private-sector technological activity is more sensitive to activity in other public organizations than it is to university activity, which is expected to be more basic in orientation. On the other hand, the number of public organizations may be determined, in part, by the number of firms in the same country and scientific field. The might indicate that governments may be inclined to establish public organizations in technical fields in which their private sectors are already specialized. This argument could also apply, albeit perhaps not as strongly, to the establishment of university departments. Thus the data are highly consistent with the hypothesis of complementarity between a country's public and private technological orientation, but the causal mechanism underlying this is difficult to determine. Also, we would like to be able to test whether countries that have the "best matched" input combinations (*i.e.*, in which the distributions of public and private R&D across fields are most similar) are the most productive in terms of innovation. Data limitations make this infeasible, however: although we have indicators of innovative output (numbers of publications and research results), by country, we lack the corresponding country-level data on research inputs or expenditure necessary to make productivity comparisons.

4 Codifiability of R&D Outcomes and the Organization of R&D Programs

The endeavor to create useful knowledge is often uncertain and there are questions about how to best organize research programs to best advance scientific and commercial interests. Knowledge, rather than being a homogenous good, appears to vary in terms of tacitness or codifiability across different technologies and this affects the organization of the R&D program (Von HIPPLE [1994]). Knowledge with a low degree of tacitness may be easily standardized and codified and such knowledge may be easily transmitted via journal articles, project reports and prototypes and other tangible mediums. In contrast, tacit knowledge has a higher degree of uncertainty and the precise meaning is more interpretative and is not easily conveyed in a standardized medium. As a consequence, when the knowledge used in an R&D program is more tacit in nature, face to face interaction and communication are important, and we may expect that R&D programs are likely to be centralized both in terms of their administrative and geographic organization. That is, the more easily codified and articulated the knowledge is expected to be, the greater the degree of decentralization both in administrative and geographic organization.

Previous authors have argued that geographic centralization or localization facilitates the communication of knowledge in the invention process. HENDERSON [1994] suggested that centralized multi-disciplinary teams are an efficient means for individual companies to organize R&D programs when technology is not standardized. JAFFE, HENDERSON and TRAJTENBERG [1993] find that patent citations are more frequently attributed to the state where the patent originated. Similarly, AUDRETSCH and FELDMAN [1994] find a higher propensity for innovation to cluster geographically in industries where new knowledge plays a more important role. ZUCKER, DARBY and ARMSTRONG [1994] reported that biotechnology firms tend to locate near the “star” researchers that generate new and rapidly evolving commercially relevant knowledge. The consensus is that tacit knowledge that is not codified and easily transferable creates incentives for organizations to locate near one another. Indeed, if knowledge is published or easily licensed it may be disseminated at great distance. In contrast, the more tacit the knowledge produced by R&D programs, the greater the tendency for geographic concentration.

Although previous investigators have hypothesized that tacitness encourages geographic and administrative concentration, there have been few attempts in the literature to measure tacitness. Fortunately, several indicators of the degree of tacitness of European Community RTD programs can be derived from the CORDIS databases. Some projects result in prototypes that might be easily transferred while others result in know-how that is novel and less able to be transmitted. Other outcomes, such as technical reports or new processes, move along the tacitness continuum by being more easily transferred but still requiring some face-to-face collaboration before the results may be adopted.

In this section, we characterize technologies as to their degree of codifiability and then analyze the relationship of this attribute to the degree of administrative and geographic centralization. We expect that programs that rely on tacit knowledge will be more administratively centralized and encompass fewer unique and separate projects. We also expect that, the more difficult knowledge is to codify, the greater the degree of geographic concentration.

It may be worth emphasizing that the unit of observation that we will analyze below – an R&D *program* (which is pursued in a number of coordinated but distinct R&D *projects*, often conducted in a number of *countries*) – is not the same as the unit of observation in the preceding analysis (e.g., a particular field of science in a particular country). In principle, it might be desirable to include scientific "field effects" in the models of R&D program decentralization that we estimate below. There may be much greater scale economies (e.g., due to indivisibilities of research equipment) in certain fields of research (nuclear engineering) than in other fields (artificial intelligence), encouraging more centralized research in the former. Unfortunately, the number of programs for which we have sufficient data is small relative to the number of scientific fields, rendering inclusion of field effects impractical [12]. However, provided that research scale economies (or other unobserved determinants of centralization) are uncorrelated with our measures of tacitness, which does not seem unreasonable, the absence of field effects does not undermine the validity of our hypothesis tests.

To test the effect of the articulability of research outcomes on the organization of R&D programs, we will use data from several related (European) Community Research and Development Information Service (CORDIS) databases: the RTD-Programmes, -Projects, -Publications, and -Results databases. Below we describe key aspects of these databases and the measures that we constructed from them.

The RTD-Programmes Database is fundamental to the CORDIS service and to our analysis. The program is the major instrument through which the European Commission pursues and finances Community policy on Research and Technological Development, fulfilling the objectives of the Single European Act. (The term "program" is used in a broad sense to designate Community initiatives and actions under which individual projects or activities are carried out, usually through contractual agreements placed with outside organizations.)

This database provides a starting point to relate information from the other databases. It contains details of Community RTD-Programmes and provides references to additional sources where the user can obtain further information if required. Each record includes various descriptive fields that

12. It is also infeasible to perform the analysis with the *project* as the unit of analysis, since we cannot construct meaningful measures of either decentralization or tacitness at the project level.

give the program objectives, its internal structure and key references. Much of this information is derived from the Official Journal of the European Communities.

We obtained information on two program attributes from the RTD-Programs database: Program Funding (in millions of European Currency Units (ECUs)), and Number of Projects – the number of projects under the program listed in the RTD-Projects Database (described below). Using these two variables (denoted FUND and N_PROJ, respectively), we can judge how administratively decentralized an R&D program is: holding program funding constant, the greater the number of projects, the more decentralized the program. Average funding per project is an inverse indicator of the degree of decentralization.

The data contained in the RTD-Projects Database also enable us to determine how geographically decentralized each program is. This database contains details of individual RTD projects financed wholly or partly from the budget of the European Communities. These projects are normally implemented through contractual agreements placed by the European Commission with commercial organizations, research institutes, universities, or other bodies. Such projects operate within the structure of a specific Commission programme, details of which are contained in the RTD-Programmes Database. The record for each project contains a country code for the prime contractor's country. For each program, we calculated the distribution of projects, by country. We computed two summary indicators of program decentralization from this distribution: the number of countries in which (any) prime contractors were located, and an inverse Herfindahl index (INV_HERF) of geographic concentration. INV_HERF was constructed as follows:

(2) $$\mathrm{INV\_HERF}_j = [\Sigma_i \, (N_{ij}/N_{.j})^2]^{-1}$$

where $N_{ij} =$ the number of program j's projects located in country i and $N_{.j} = \Sigma_i \, N_{ij} =$ the total number of projects in program j. The more geographically decentralized a program, the larger the value for both of these indicators.

The last two databases provide information about published or announced outcomes of R&D programs. We use these data to derive indicators of the degree of articulability of the knowledge the program yielded. The RTD-Publications Database provides references containing bibliographic details and abstracts of publications and other documents resulting from EC RTD. Cited publications are: (1) EUR reports, which include: scientific and technical studies; monographs; proceedings of conferences; workshops and contractors' meetings organized by the European Commission; and various reports resulting from the research; (2) other reports and documents produced by the Commission relating to Community RTD activities; and (3) articles and conference papers relevant to the Commission's research activities. If the publication exists in more than one Community language, the citation is usually given for the English language version. The availability of the publication in other Community languages is also indicated. The database contains records dating from 1962. From 1990 onwards, record contents are consistent with other CORDIS databases. Entries made after 1990 enable a publication to be related to a given program via the program acronym. We calculated the number of publications (N_PUB) associated with each program.

The RTD-Results Database contains information about the results of R&D in science, technology and medicine. The information comes from public and private sector organizations, regardless of the funding sources. Entries in this database are comprehensive, providing information about the research result, the contributing organization, type of collaboration sought, the availability of a prototype, the commercial potential, the contact point information, and other details. Records can be identified by program acronym, the type and location of the contributing organization and other details. Each result is classified into one of the following two type categories: (1) process, prototype; or (2) methodology, skill, know-how. For each program we calculated the number of type-1 (process, prototype) results (N_RSLT1), the number of type-2 (methodology, skill, know-how) results (N_RSLT2), the total number of results (N_RSLT=N_RSLT1+N_RSLT2). We also calculate the share of type-1 results in total results (SHR_RSLT1=N_RSLT1/N_RSLT).

We believe that the number of publications and the number and type of announced results of a program are reasonable indicators of the degree of articulability of the knowledge it generated. Holding constant program funding, the greater the number of publications or the number of announced results, the greater the degree of articulability of the knowledge. Since we hypothesize that programs that are expected to generate knowledge that is easier to articulate and communicate will be more decentralized (geographically and administratively), this suggests that, holding funding constant, programs that yield more publications or announced results will be more decentralized. We can test this by estimating models of the form

$$\ln Y = \Pi_0 + \Pi_1 \ln \mathrm{FUND} + \Pi_2 \ln X + \varepsilon \tag{3}$$

where Y is a measure of program decentralization (N_CTY,INV_HERF, or N_PROJ), X is the number of results or the number of publications, and ε is a disturbance. Positive and statistically significant estimates of Π_2 would be consistent with our hypothesis.

We believe that, conditional on funding, a larger number of results signals that the knowledge generated by a program is more articulable, but certain types of results may indicate more articulability than others. In particular, we hypothesize that type-1 results, which announce the existence of a process or prototype, indicate a higher degree of articulability than type-2 results, which merely announce the acquisition of “skill, methodology, or know-how”. We can test for this by generalizing the above model as follows:

$$\ln Y = \Pi_0 + \Pi_1 \ln \mathrm{FUND} + \Pi_2 \ln\left[(1+\theta)\,\mathrm{N\_RSLT1} + \mathrm{N\_RSLT2}\right] + \varepsilon \tag{4}$$

This model allows changes in N_RSLT1 and N_RSLT2 to have different marginal effects on Y. Positive and significant estimates of θ would be consistent with the hypothesis that type-1 results indicate a higher degree of articulability. (In the preceding model, θ was implicitly constrained to equal zero.) This equation is nonlinear in the parameters, but it can be approximated by the linear equation

$$(5)\ \ln Y = \Pi_0 + \Pi_1 \ln \mathrm{FUND} + \Pi_2 \ln \mathrm{N\_RSLT} + (\theta\,\Pi_2)\,\mathrm{SHR\_RSLT1} + \varepsilon$$
$$= \Pi_0 + \Pi_1 \ln \mathrm{FUND} + \Pi_2 \ln \mathrm{N\_RSLT} + \theta'\,\mathrm{SHR\_RSLT1} + \varepsilon$$

where $\theta' = (\theta\Pi_2)$. We expect program decentralization to be increasing with respect to both the total number of announced results and the fraction of those results that are type-1 results, controlling for funding.

An equivalent way of expressing the last equation is

$$(6)\quad \ln Y = \Pi_0 + (\Pi_1 + \Pi_2) \ln \mathrm{FUND} + \Pi_2 \ln (\mathrm{N\_RSLT}/\mathrm{FUND}) + \theta'\,\mathrm{SHR\_RSLT1} + \varepsilon$$

Only the coefficient on ln FUND is affected by this transformation, not the coefficients on the other regressors, which are of primary interest. The coefficient on ln FUND captures the "pure" effect (if any) of program "scale" on decentralization, since FUND and N_RSLT may be regarded as alternative possible measures of program scale. The other coefficients capture the effects of articulability on decentralization, given scale. We estimate equations of this form.

Estimates of eq. (6) are presented in Table 9. In the regression shown in the first column, the measure of decentralization (the dependent variable) is the log of the number of countries in which prime contractors are located. The coefficients on both indicators of articulability – the log of the number of announced results per unit of funding and the fraction of those results that were type-1 results – are positive and significantly different from zero. The coefficient on the program scale variable, the log of funding, is positive but only marginally significant. R&D programs that generated above-average numbers of results per unit of funding tended to be more geographically decentralized; this is consistent with our hypothesis that greater (expected) ability to communicate research outcomes encourages less centralized R&D programs. We can obtain a point estimate of the "excess" impact on decentralization of type-1 results relative to type-2 results by dividing the coefficient on SHR_RSLT1 ($\theta' = \theta\,\Pi_2$) by the coefficient on ln (N_RSLT/FUND) (Π_2). This implies that $\theta = .554/.124 = 4.47$, and $(1 + \theta) = 5.47$: one additional type-1 result is associated with 5.5 times as great an increase in decentralization as one additional type-2 result. Programs that yield processes and prototypes are much less centralized than programs that yield the less-well articulated "methodology, skill, and know-how".

Col. (2) presents estimates of an equation with the same regressors but with our alternative measure of geographic decentralization – the inverse Herfindahl index – as the dependent variable. The estimates are somewhat smaller in magnitude and somewhat less significant, but qualitatively very similar.

Col. (3) presents estimates where we replace one of the measures of the degree of knowledge articulation – results reported in the RTD-Results

TABLE 9

Tacitness Model Regression Results (t-statistics in parentheses).

Dependent Variable:	*In* N_CTY	*In* (Inv-Herf)	*In* (Inv-Herf)	*In* N_PROJ
In $\frac{(N\_RSLTS)}{(FUND)}$	0.124 (3.54)	0.093 (3.23)		0.174 (2.35)
In $\frac{(N\_PUBS)}{(FUND)}$			0.81 (2.39)	
Shr (Results 1)	0.554 (2.66)	0.313 (1.83)	0.405 (2.14)	0.662 (1.50)
In (FUND)	0.090 (1.65)	0.061 (1.37)	0.038 (0.83)	0.488 (4.24)
Intercept	1.806 (7.87)	1.450 (7.65)	1.470 (7.33)	2.515 (5.21)
N	77	77	73	79
R^2	.2075	.1545	.1088	.2302

Note: t-statistics in parentheses.

database per unit of funding – with an alternative measure: publications reported in the RTD-Publications database per unit of funding. The coefficients of the publications variable and the result-share variable are both positive and significant, again consistent with the notion that articulability promotes geographic decentralization.

The dependent variable in the last equation, shown in col. 4, is the log of the number of projects comprising the program, which we have argued is an indicator of the degree of administrative decentralization. Like the geographic decentralization measures, it is highly positively correlated with log (N_RSLT/FUND); unlike them, it is also highly correlated with program funding, and its partial correlation with the results share variable is only marginally significant.

5 Summary and Conclusion

Some previous studies have suggested that public and private R&D organizations may complement one another. We explored the relationship between private and public research investment within the same country and technological areas, by estimating regressions of the number of consultancies, manufacturers, and service companies (which are predominantly private-sector organizations) on the number of public research centers, technology transfer organizations, and universities, by country and scientific field. The estimates indicate that a country's manufacturers and service companies tend to be specialized in the same scientific fields as its universities and public organizations. The data are also consistent with the hypothesis that private-sector technological activity is more sensitive to activity in non-university public organizations than it is to university activity. The causal mechanism underlying the observed correlations between public and private research is, however, difficult to determine.

Previous investigators have hypothesized that the extent of geographic and administrative decentralization of R&D activities is greater, the less tacit (or more codifiable) the knowledge generated by the R&D is expected to be. But this hypothesis has not been tested formally due to inability to measure tacitness (or codifiability). We constructed several indicators of the degree of R&D decentralization and tacitness of European Community RTD programs from data contained in the CORDIS databases. The number of countries in which an R&D program is conducted – controlling for total program funding – is an indicator of geographic decentralization, and the number of distinct projects into which a program is subdivided is an indicator of administrative decentralization. The number of publications and the number and type of announced results of a program – again controlling for program funding – are reasonable indicators of the degree of codifiability (or articulability) of the knowledge it generated. The estimates are consistent with the hypothesis that greater (expected) ability to communicate research outcomes encourages less centralized R&D programs. R&D programs that generated above-average numbers of results per unit of funding tended to be more geographically decentralized. Moreover, programs that yield (relatively tangible) processes and prototypes are much less centralized than programs that yield the less-well articulated "methodology, skill, and know-how".

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