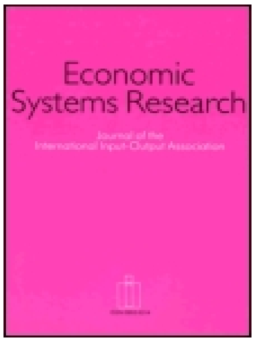

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A New Indicator of European Integration and an Application to Collaboration in Scientific Research

KOEN FRENKEN

ABSTRACT *The goal of this study is to develop a comprehensive indicator of integration among countries within a supranational system. Integration is not analysed in terms of the growth in interactions among countries, but in terms of the matrix distribution of interactions among countries. Integration can then be indicated in terms of interaction biases among countries measured by the difference between the observed matrix distribution and the hypothetical random distribution. The indicator is applied to data on research collaborations among European research institutions (1993–2000). Evidence is found that the European science system has indeed become more integrated. The higher level of integration has resulted exclusively from a more evenly distributed pattern of European collaborations, while the strong bias towards intra-national collaborations persisted. The results point to the persistence of national science systems. A future research agenda and science policy implications are discussed.*

KEYWORDS: *European integration; mutual information; research collaboration; network externalities*

1. Introduction

The goal of this study is to develop a comprehensive indicator of integration among countries within a supranational system. The main novelty incorporated in the indicator proposed here is that an integration process among countries is not analysed in terms of the *growth* in interactions among countries, but in terms of the *matrix distribution of relative frequencies* of interactions among countries. The degree of integration of a supranational system can then be indicated in terms of interaction biases among participating countries as measured by the difference between the observed distribution of interactions and the hypothetical distribution of random interactions. We will derive interaction biases by means of computing the mutual information of the yearly country-country distributions in a way similar to Theil (1967) who computed the mutual information of input-output tables to derive their information contents.[1]

In this study, the indicator of integration is applied to yearly data on collabo-

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rations among European research institutions as listed in the *Science Citation Index* during the period 1993-2000. Collaborations are counted by publications containing multiple institutional addresses, and each co-occurrence of two institutional addresses counts as an interaction. In this way, a matrix can be constructed of intra-national and international collaborations. The application of the indicator provides one with a comprehensive measurement of integration of the European science system and its development over time. Other social and economic systems can be analysed in the same way. We will elaborate on other applications in the final discussion section.

2. International Collaboration in Science

International collaboration in research is expected to generate important benefits in many ways. The rationales for collaboration can be divided into economic benefits and intellectual benefits. Collaboration provides economic opportunities to realize economies of scale, for example with regard to costs of training and research infrastructures (Katz & Martin, 1997). European examples of such large research infrastructures that have emerged through intergovernmental collaboration, are the European Space Agency (ESA) and the European Centre for Nuclear Research (CERN). Collaboration is also expected to generate intellectual benefits from the cross-fertilization of ideas that previously were unconnected and from a better quality control through internal refereeing. More generally, collaboration is intellectually required when specialized knowledge and skills are distributed among different persons (Gibbons *et al.*, 1994; Ziman, 1994). Given the increasing level of specialization within disciplines and sub-disciplines resulting from an increasing division-of-labour among scientists, research would benefit from international rather than national recruitment of scientists to participate in particular projects.

The growing internationalization in scientific research may appear, at first sight, contradictory to the recent literature on the geography of innovation. This literature tends to emphasize the increasing localized nature of knowledge production at the sub-national scale (Arthur, 1990; Boschma & Lambooy, 1999; Caniëls, 2000; Feldman, 1999; Van Oort, 2002). A number of theoretical arguments support this thesis. Most importantly, localization economies of various sorts arise when people and firms engaged in knowledge production are geographically concentrated. These externalities range from labour market pooling, informal networking and knowledge spillovers. In particular, tacit components of knowledge production typically develop and diffuse through close interaction with suppliers and clients. Furthermore, tacit knowledge is often reproduced in spin-off firms that typically locate in the region of the parent company. Another important reason for localized innovation concerns the difficulties of governance of collaborative industrial R&D. As the modalities of collaboration are hard to encode in contracts, collaboration often relies on informal contacts, reciprocity and trust between partners, which is facilitated when participants share local ties and a similar institutional environment. If one accepts that the economy has become rapidly more knowledge-intensive, economic activity can be expected to have become more localized in recent times.

From these theoretical rationales for localized industrial innovation however, one cannot conclude that one should expect scientific research to develop into a more localized activity as well. Scientific research is qualitatively different from industrial innovation. Although, in some disciplines, the distinction between science and innovation has become less relevant, such as in biotechnology and informatics, scientific knowledge production generally differs from industrial knowledge production in a number of ways. First, the tacit component is expected to be much smaller in scientific knowledge production, which renders communication and collaboration at a distance much easier. Second, the specificity of knowledge ('appliedness') is expected to be much smaller in scientific research compared with industrial R&D. Consequently, problem definitions are, to a lesser extent, determined by the local context, but emerge from a global *discourse*. Third, the incentive structure in scientific knowledge production is explicitly oriented towards (international) diffusion, while investors in industrial R&D have an incentive to appropriate the results (whatever the mechanism used to achieve this). For these reasons, one should expect scientific knowledge production to be less localized than industrial innovation.

A number of studies have addressed the characteristics of tacitness, specificity and appropriability of knowledge as variables that explain the degree of geographical localization of knowledge production (Feldman, 1999). For example, a US patent citation study has found that specificity and appropriability of knowledge as documented in patents contributed significantly to the extent that citation originated from the same region (Jaffe *et al.*, 1993). If one accepts that scientific knowledge production is typically characterized by a low degree of specificity and appropriability, this finding suggests that the degree of localization of scientific knowledge production is indeed lower compared with industrial R&D. In conclusion, both theory and evidence suggest that scientific knowledge production differs from industrial knowledge production in that the latter may primarily be accumulating at a regional scale, while the latter is expected to internationalize over time.

The recent rise in international collaborations in scientific research can relatively easily be indicated by computing the share of international co-authorships in all publications. It has been estimated that the share of international collaborations has doubled during the period 1987-97 to account for 15% of world publications (Wagner, 2002). To assess the benefits of international collaboration is a somewhat more difficult exercise. Empirical studies that addressed the benefits of international collaboration have focused on the effects of collaboration on scientific impact and productivity (Katz & Martin, 1997). A number of effects have been found. The impact of scientific output resulting from collaboration as measured by citation rates is substantially higher than average. The difference in citation impact is even higher for international collaboration. Furthermore, it has been found that the productivity of scientists is positively dependent on the frequency of collaboration. Collaboration tends to increase the level of personal productivity as measured by the number of publications produced per year.

A large part of European science policy can be considered as an attempt to capitalize on the potential of scientific collaboration among member states. Not surprisingly, research collaboration and the mobility of researchers are at the core of the European science policy. Given the evidence on the positive effects of research collaboration, and the policy importance attached to it, an important question is whether empirical data show that the European science system has indeed become more integrated or not. Within the European context, the number of European collaborations has undeniably increased over the last few decades. However, the number of collaborations is, in itself, no indication of integration (Leydesdorff, 1992). For example, the number of collaborations can double in a period, but at the same time the distribution of collaborations may fragment in a number of islands of collaborating countries. The question is whether the increase in collaborations, as a general phenomenon, also contributed to a more integrated pattern of collaborations.

The hypothesis holds that European science indeed evolved towards a more integrated system. However, in an empirical research design, the hypothesis of increasing integration requires further specification. What does it mean that a set of countries becomes more integrated? Below, I address this hypothesis using data on both national and European collaborations as indicated by publications with multiple addresses. European integration, then, can be analysed by comparing the propensities of countries to collaborate nationally with the propensity to collaborate with other European member states. It is crucial to distinguish intra-national from international collaboration, because, other things equal, larger countries are expected to collaborate relatively more often nationally than internationally, simply because there exist more potential national partners in larger countries than in smaller countries. Controlling for differences in size of countries leads us to specify two hypotheses:

H_1: European integration increases over time as indicated by a declining bias to collaborate nationally, controlling for differences in size of countries.

H_2: European integration increases over time as indicated by a convergence in the bias of each pair of countries to collaborate, controlling for differences in size of each of the countries.

3. A New Measure of Integration

An inter-institutional collaboration is defined here as a pair of different institutional addresses occurring in a publication record contained in the *Science Citation Index*. Note that this definition is not restricted to co-authorship, as one person can be associated with more than one institution.[2]

The number of inter-institutional collaborations between two European member states i $(i = 1, \ldots, 15)$ and j $(j = 1, \ldots, 15)$ as a share of the total number of collaborations is denoted as q_{ij}, which results in a 15×15 matrix of 225 q_{ij} values. National collaborations are present on the diagonal for which $i = j$ holds, while all other cells refer to country-country collaborations for which $i \neq j$ holds. A co-occurrence of two addresses in different countries is attributed to both cells that refer to a pair of countries so we get a symmetric matrix $(q_{ij} = q_{ji})$.[3] The share of each country in the total number of collaborations is then given by:

$$q_{i.} = \sum_{j=1}^{15} q_{ij} \tag{1}$$

and, because of symmetry in the matrix, $q_{.j}$ is equal to $q_{i.}$ for $i = j$. In other words, to derive the marginal totals for each country one can either sum over the rows or over the columns.

3.1. *Mutual Information*

The degree of integration of country i with respect to country j is measured here as the difference between the observed share of collaborations q_{ij} and what would be expected from the product of the individual shares $q_{i.}$ and $q_{.j}$ (i.e. Random interaction). The difference between the observed share and the expected share is measured by the natural logarithm of the division of q_{ij} by the products of $q_{i.}$ and $q_{.j}$:

$$T_{ij} = \ln \frac{q_{ij}}{q_{i.} \times q_{.j}} \quad (2)$$

The T_{ij}-value is a measure *of bias*. The value is positive when country i is collaborating with country j more than is expected from the product of the individual country shares in all outputs. The T_{ij}-measure takes on a negative sign when country i is collaborating with country j less than is expected from their shares. Put another way, a positive value indicates a positive bias in the propensity of country i to collaborate with country j and vice versa while a negative value indicates a negative bias in the propensity of country i to collaborate with country j and vice versa.

The use of a logarithm renders this measure symmetric with regard to whether a country collaborates x times more than expected or x times less than expected with another country. For example, when two countries collaborate two times more than expected, the T_{ij}-measure equals $\ln 2 = 0.693$ and when two countries collaborate two times less than expected, the T_{ij}-measure equals $\ln\frac{1}{2} = -0.693$.

The degree of integration of the network of 15 member states as a whole is measured by T, which is the sum of the values for T_{ij} weighted for the share in the total number of collaborations q_{ij}. In information theory, the measure T is known as the 'mutual information' value, which measures dependence in a frequency matrix (Frenken, 2000, 2001; Langton, 1990; Leydesdorff, 1991; Theil, 1967, 1972):

$$T = \sum_{i=1}^{15} \sum_{j=1}^{15} q_{ij} \ln \frac{q_{ij}}{q_{i.} \times q_{.j}} \quad (3)$$ [4]

It has been shown that mutual information is non-negative for any frequency distribution (Theil, 1972). When all pairs of countries would collaborate exactly as much as expected from their individual shares, we have $q_{ij} = q_{i.} \times q_{.j}$. In this case, all pair wise bias values T_{ij} equal zero, and the T-value consequently also equals zero (total independence). In the context of research collaboration, a zero T-value indicates perfect integration of all 15 member states within the European science system. When any bias exists in the propensity to collaborate, mutual information will be positive. The higher the T-value, the less countries are integrated in a system (higher dependence).

Theil (1967, chapter 9) initially used the mutual information measure to characterize the amount of information contained in input-output tables. In this application, the values of q_{ij} stand for the inter-industry flows as fractions of the total of inter-industry flows. Total independence of the matrix ($T = 0$) would mean that the input-output table would not contain any information at all, since the inter-industry flows q_{ij} can readily be derived from the product of the marginal totals $q_{i.}$ and $q_{.j}$. Any other input-output table would yield a positive mutual information. The higher the value of the mutual information, the more structure is present in the input-output-table, and the higher its information content.[5,6]

In the context of research collaboration addressed here, it is important to note that the indicator takes into account both intra-national ($i = j$) and international ($i \neq j$) interactions. In this way, the degree of integration is adjusted for differences in the size of countries as measured by the number of collaborations in which a country participates, as a fraction of the total number of collaborations. Collaboration patterns are assessed by means of comparing the observed frequency of collaboration (q_{ij}) to what is expected from the individual shares of countries ($q_{i.} \times q_{.j}$). What follows is that a large country should be expected to collaborate more intensively at the national level than a small country, because there are more researchers available in larger countries to interact with at the national level. In this, the indicator proposed above differs from other measures that indicate internationalization either by looking at international collaboration only (Katz, 2000) or by taking the ratio between national and international activity (Kearney Inc., 2001). The latter types of indicators typically show high integration values for smaller countries compared with larger countries as these indicators do not control for the size of countries.

3.2. Analysing Subsets

As explained above, the integration measure is a weighted sum of all intra-national and international T_{ij}-values weighted for their share in the population. For the European Union, there are $15^2 = 225$ T_{ij}-values. By summing non-overlapping subsets of the 225 T_{ij}-values, and dividing the sum by the share of the subset in the population, one can focus on the degree of integration of a subset of the matrix.

In the case of the European Union, one can think of two ways of splitting the matrix into subsets. First, one can compare the T_{ij}-values for national ($i = j$) and international ($i \neq j$) collaborations to analyse to what extent integration is due to intra-national biases versus international biases. We get, respectively:

$$T_{i=j} = \frac{1}{\sum_{i=1}^{15} \sum_{j=1}^{15} q_{ij}} \left(\sum_{i=1}^{15} \sum_{j=1}^{15} q_{ij} \ln \frac{q_{ij}}{q_{i.} \times q_{.j}} \right) \qquad (i = j) \tag{4}$$

and

$$T_{i \neq j} = \frac{1}{\sum_{i=1}^{15} \sum_{j=1}^{15} q_{ij}} \left(\sum_{i=1}^{15} \sum_{j=1}^{15} q_{ij} \ln \frac{q_{ij}}{q_{i.} \times q_{.j}} \right) \qquad (i \neq j) \tag{5}$$

A second way to split the matrix into subsets is to sum the subset of 15 T_{ij}-values belonging to a country i. In this way, one obtains the level of integration for each individual country labelled as T_i. We get:

$$T_i = \frac{1}{q_{i.}} \sum_{j=1}^{15} q_{ij} \ln \frac{q_{ij}}{q_{i.} \times q_{.j}} \tag{6}$$

for each of the 15 member states ($i = 1, \ldots, 15$). Table 1 provides a numerical example of the application of all integration measures described above, using imaginary data on collaboration patterns of three countries.

Note that the application of this measure is by no means restricted to the analysis of country-country collaborations. The indicator can be applied to the level of regions in a country (or in the European union) and to the level of cities in a region (or in a country or in the European union). Similarly, the indicator can be applied to supranational blocks within the world system.

Table 1. Example of application of integration indicators

Example (for three countries)

Co-occurrences in the *Science Citation Index*:

FRANCE-FRANCE:	250	UK-FRANCE:	120	GERMANY-FRANCE:	140
FRANCE-UK:	80	UK-UK:	800	GERMANY-UK:	90
FRANCE-GERMANY:	160	UK-GERMANY:	110	GERMANY-GERMANY:	750

Collaboration matrix:[17]

	FRANCE	UK	GERMANY	SUM
FRANCE	250	100	150	500
UK	100	800	100	1000
GERMANY	150	100	750	1000
SUM	500	1000	1000	2500

Frequency matrix:

	FRANCE	UK	GERMANY	
FRANCE	$q_{11} = 0.10$	$q_{21} = 0.04$	$q_{31} = 0.06$	$(q_{.1} = 0.20)$
UK	$q_{12} = 0.04$	$q_{22} = 0.32$	$q_{32} = 0.04$	$(q_{.2} = 0.40)$
GERMANY	$q_{13} = 0.06$	$q_{23} = 0.04$	$q_{33} = 0.30$	$(q_{.3} = 0.40)$
	$(q_{1.} = 0.20)$	$(q_{2.} = 0.40)$	$(q_{3.} = 0.40)$	$(q_{..} = 1.00)$

T_{ij}-values:

	FRANCE	UK	GERMANY
FRANCE	$T_{11} = \ln(0.10/0.04) = 0.92$	$T_{21} = \ln(0.04/0.08) = -0.69$	$T_{31} = \ln(0.06/0.08) = -0.29$
UK	$T_{12} = \ln(0.04/0.08) = -0.69$	$T_{22} = \ln(0.32/0.16) = 0.69$	$T_{32} = \ln(0.04/0.16) = -1.39$
GERMANY	$T_{13} = \ln(0.06/0.08) = -0.29$	$T_{23} = \ln(0.04/0.16) = -1.39$	$T_{33} = \ln(0.30/0.16) = 0.63$

Integration indicators:

$$T = (0.10 \cdot 0.92) + (0.04 \cdot -0.69) + (0.06 \cdot -0.29) + (0.04 \cdot -0.69) + (0.32 \cdot 0.69) + (0.04 \cdot -1.39) + (0.06 \cdot -0.29) + (0.04 \cdot -1.39) + (0.30 \cdot 0.63) = 0.30$$

$$T_{i=j} = (1/0.72) \cdot ((0.10 \cdot 0.92) + (0.32 \cdot 0.69) + (0.30 \cdot 0.63)) = 0.70$$

$$T_{i \neq j} = (1/0.28) \cdot ((0.04 \cdot -0.69) + (0.06 \cdot -0.29) + (0.04 \cdot -0.69) + (0.04 \cdot -1.39) + (0.06 \cdot -0.29) + (0.04 \cdot -1.39)) = -0.72$$

$$T_1 = (1/0.2) \cdot ((0.10 \cdot 0.92) + (0.04 \cdot -0.69) + (0.06 \cdot -0.29)) = 0.23$$
$$T_2 = (1/0.4) \cdot ((0.04 \cdot -0.69) + (0.32 \cdot 0.69) + (0.04 \cdot -1.39)) = 0.35$$
$$T_3 = (1/0.4) \cdot ((0.06 \cdot -0.29) + (0.04 \cdot -1.39) + (0.30 \cdot 0.63)) = 0.29$$

4. Results

Data were collected from the *Science Citation Index* for the period 1993-2000 covering the large majority of publications of natural and life sciences. I first selected for each year all records containing at least one address located in an EU member state.[7] I further reduced the size of the dataset by excluding records containing the most common inter-institutional collaborations with the major countries outside the EU.[8] The resulting number of records amounts to over 200 000 on average each year, with the number increasing from 183 020 in 1993 to 230 561 in 2000.

To sample the number of inter-institutional collaborations within and between European member states, I used only the first three listings of addresses. Each first and second address, each first and third address, and each second and third address were counted as one collaboration. Thus, a single-address record yields no collaboration, a double-address record yields at most one collaboration between a pair European countries, and a record containing three (or more) addresses yields at most three collaborations between pairs of European countries.[9]

4.1. Collaboration in the European Union as a Whole

Figure 1 shows the values of mutual information T as computed from equation (3) for each year during the period 1993-2000. As explained above, a lower T-value indicates lower levels of biases in the choice of partners, and thus a higher level of integration between the EU member states. The trend of T-values indicates a gradual integration process suggesting that EU member states indeed, on average, have become less biased with regard to the country of origin of their research collaboration partners.

The integration process, however, is very slow as the integration indicator only decreased from 1.526 to 1.461. Put another way, the level of integration in 2000 is 95.7% of the level in 1993. This seemingly slow process of European integration, however, should not be judged from the reference level of full integration (no bias at all as indicated by $T = 0$), but from an (unknown) reference level of bias that would occur when institutional and language barriers between countries were to be fully removed.[10] This reference level of bias, which is expected to remain in homogeneous geographical territories, is expected to be substantial following from the theory of geography of innovation as discussed in Section 2. Even if scientific knowledge does not share the characteristics of industrial innovation for what concerns its degree of specificity, tacitness, and appropriability, some degree of spatial concentration is expected to remain.

4.2. Intra-national versus international collaboration

The next question regarding the integration process at the EU level holds whether the integration process is an effect of a decreasing bias of countries to collaborate

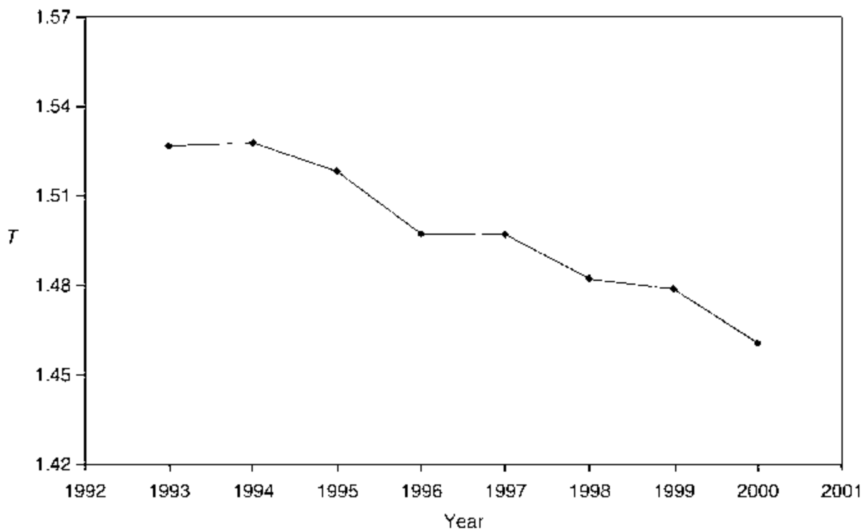

Figure 1. *T*-values indicating the level of integration of all EU countries for both intra-national and international collaborations.

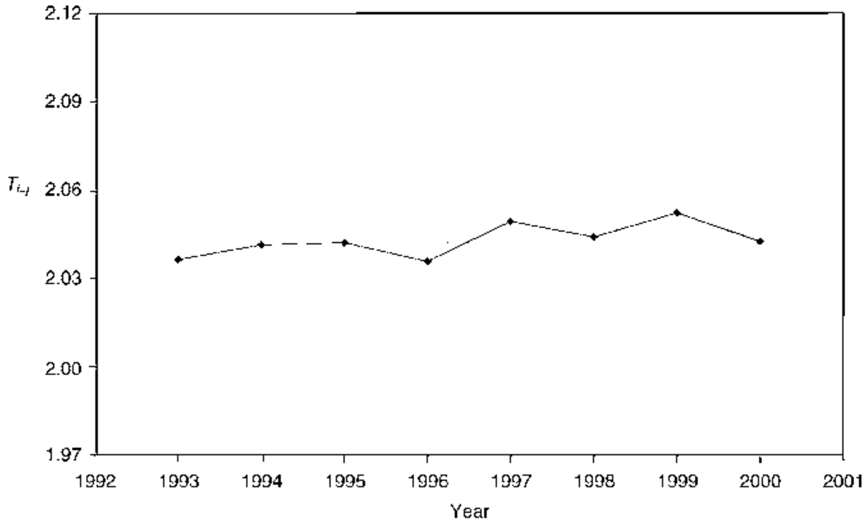

Figure 2. $T_{i=j}$-values indicating the level of integration of all EU countries for intra-national collaborations only.

nationally or an effect of a decreasing bias with regard to the choice of EU partners, or a combination between the two. Figure 2 plots the $T_{i=j}$-values of intra-national collaborations within the EU countries for each year (equation (4)). The results indicate that there is a stable positive bias to collaborate nationally. Over the years, the average value is about + 2.04, which means that the probability of national collaboration is $e^{2.04} = 7.7$ times higher than when partner selection would have been at random. There is no real trend in the national bias over the years. The results at least suggest that the bias to collaborate nationally has not decreased during the period 1993-2000.

Figure 3 plots the $T_{i \neq j}$-values of international collaborations in the EU for each year (equation (5)). From the results, two important observations can be made. First, the bias to collaborate with other EU countries has been negative over the whole period considered. Over the years, the average value is about – 1.62, which means that the probability to collaborate with another member state is, on average, $e^{-1.62} = 0.20$ times lower than when partner selection would have been at random. Second, the negative bias towards European collaboration has become less and less over the years. The integration process as indicated by the trend in Figure 1 can thus be understood as the result of a decreasing bias in the selection of a European partner while the bias towards national collaboration persisted.[11] From this, we can conclude that only the second hypothesis regarding the convergence of international biases is confirmed, while no evidence is found that the bias to collaborate nationally, has declined.

4.3. Country Comparison

The integration values for each of the 15 member states are plotted in Figure 4, following equation (6). Differences between countries are quite pronounced. In particular, the degree of integration is closely related to the size of a country. The

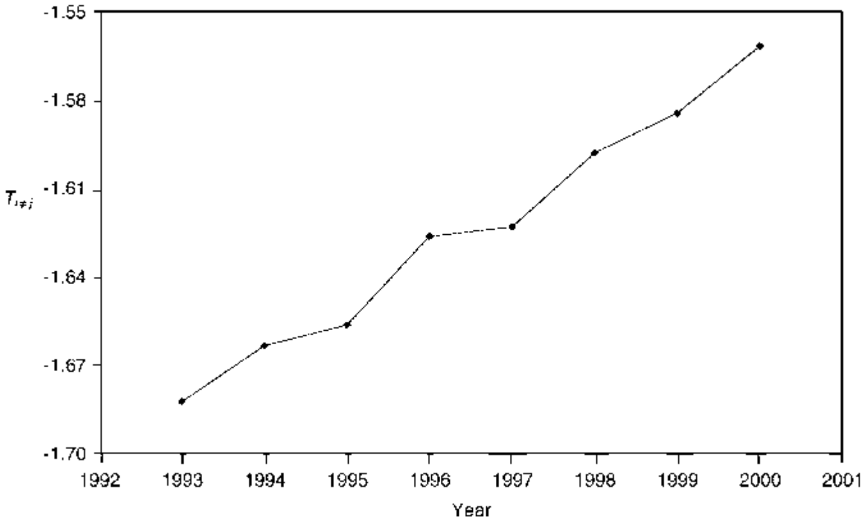

Figure 3. $T_{i\neq j}$-values indicating the level of integration of all EU countries for international collaborations only.

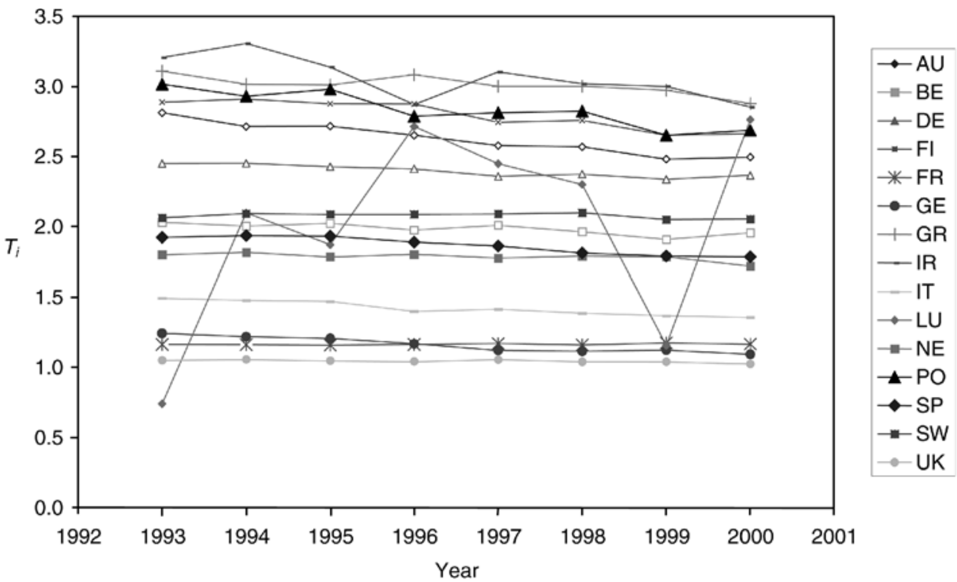

Figure 4. T_i-values for EU countries for intra-national and international collaborations.

three largest countries (UK, Germany, France) have the lowest T_i-values, indicating the highest degrees of integration, while smaller countries (Greece, Finland, Portugal, Ireland) have the highest T_i-values indicating the lowest degrees of integration.[12]

The strong correlation between the size of a country and its level of integration can be further analysed by plotting the yearly q_i-values with the corresponding

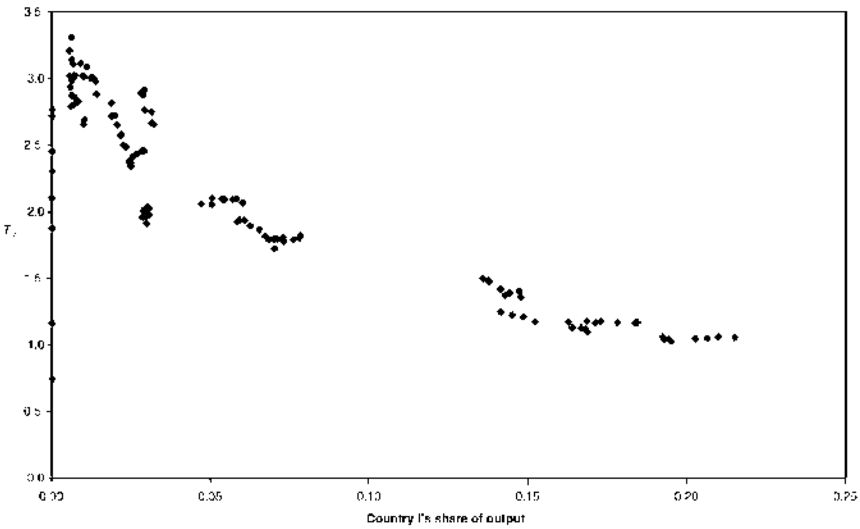

Figure 5. T_i-values for EU countries plotted against their share in output q_i.

yearly T_i-values of each country (Figure 5). Note again here that 'size' does not refer to more conventional measures, such as the number of researchers in a country, but to a country's share in collaborations (q_i) as it is directly derived from the marginal totals of the collaboration matrix. The shape of the function that best explains the scatter plot in Figure 5 is asymptotic rather than linear, suggesting that scale effects are marginally decreasing. The propensity to collaborate internationally thus tends to rise with country size, but decreasingly so. Importantly, the correlation between degree of integration of a country and its share in the research output is not perfect. For example, the share of Sweden is much higher than that of Belgium, while the latter country is better integrated in the European system. Similarly, the share of Greece is much higher than the share of Portugal, but the latter is better integrated. The results can thus be used to benchmark individual countries in terms of their level of integration and what would be expected when their size is taken into account. In this respect, Belgium and Portugal score relatively well compared with countries of similar size.

The positive relationship between country size and degree of integration suggests that larger countries benefit from scale effects that trigger European collaboration. Although comprehensive theories on scale advantages on a national scale are lacking, one can expect that the degree of diversification in scientific research in a country is strongly related to its size. Specialized research institutes require a critical mass regarding investments in training programmes and research infrastructures. If one accepts that more specialized knowledge is available in the larger and supposedly more diversified countries, it will be generally more attractive for researchers from any other country to collaborate with researchers from the larger countries.

A special kind of positive network externality present in larger countries concerns the number of people that are able to communicate in the national language. Clearly, people from smaller countries typically invest in learning languages that are widely spoken throughout the (academic) world. In this sense, language can be considered a network standard, the adoption of which is characterized by network externalities (Arthur, 1989). A related notion is language as a 'hypercollective' good: the more people that are able to communicate in a language, the higher the benefit for each single individual able to communicate in this language (De Swaan, 2001). Following this reasoning, the largest European countries (UK, Germany, France) will enjoy the largest network externalities in that their languages are more widely spoken within the European Union: in particular, English has become the global language in academia.[13]

4.4. Country-Country Comparison

The 225 individual T_{ij}-values for each pair of countries following equation (2) are given in Table 2. Each value in the table is the average over the eight yearly T_{ij}-values in the period 1993-2000. This static representation still gives a fairly good idea of the yearly T_{ij}-values since no single series of the 225 time-series shows a consistent falling or rising trend over time. Put another way, although a clear integration pattern emerges from the collective countries, the country-country dynamics tend to fluctuate over time.

In Table 2, the highest values for T_{ij} are indicated by bold values using an otherwise arbitrary threshold of -1.00. As expected, using this threshold, the strongest collaboration is found for all intra-national collaborations ($i = j$) reflecting the fact that all European countries strongly favour national over European collaboration. The scale effect can now also be observed in greater detail. Larger countries, such as France, Germany, Italy and the UK, have smaller positive bias values to collaborate nationally (ranging from 1.46 to 1.84) while smaller countries, such as Greece, Ireland, Luxembourg and Portugal, have higher positive bias values to collaborate nationally (ranging from 4.22 to 6.16).

There are a number of other country-country values that exceed the threshold of -1.00: Austria-Germany, France-Luxembourg, Belgium-Luxembourg, Finland-Sweden, Belgium-The Netherlands, Germany-Luxembourg, Belgium-France, Ireland-UK, Belgium-Portugal, Portugal-Spain, Denmark-Sweden and Portugal-UK. These results indicate that relative high propensities to collaborate with another country are very much organized along geographical lines: high values are typically found for neighbouring states. Also note that, in many cases, the countries that collaborate relatively often share a common or similar language. However, from the data of the *Science Citation Index* it is not possible to analyse in detail the propensity of researchers to collaborate with researchers that speak the same language. From the information contained in publications records, the working language cannot be derived.

5. Discussion

In this study, it has been proposed to analyse integration as the degree by which interaction patterns among countries are biased. The smaller the difference between the observed frequency matrix of interactions and the matrix of random interactions, the higher the degree of integration. The main novelty of the approach is that it takes into account both the interactions between countries and the interactions within each country. In this way, the measurement of integration among countries is adjusted for differences in the size of the national systems.

The indicator has been applied to data on multiple address publications in the EU to analyse the process of integration of the European science system. Using

Table 2. Country-country T_{ij}-values averaged over the period 1993–2000

	AU	*BE*	*DE*	*FR*	*GE*	*GR*	*IR*	*IT*	*LU*	*NE*	*PO*	*SP*	*SW*	*UK*
AU	**3.63**	−1.92	−2.14	−2.20	**−0.34**	−2.24	−2.08	−2.12		−1.81		−2.19	−2.13	−2.27
BE	−1.92	**3.18**	−1.63	−0.77	−1.40	−1.14	−1.24	−1.99	**2.15**	**−0.33**	−0.90	−1.45	−1.64	−1.58
DE	−2.14	−1.63	**3.40**	−2.28	−1.35	−1.83	−1.56	−2.29		−1.53	−1.52	−2.00	**−0.16**	−1.48
FI	−2.40	−2.54	−1.28	−2.91	−2.04	−3.71	−2.30	−3.28		−2.30	−3.08	−2.55	**−0.47**	−2.34
FR	−2.20	−0.77	−2.28	**1.60**	−1.75	−1.34	−2.00	−1.94	**0.04**	−2.24	−1.02	−1.41	−2.40	−2.06
GE	**−0.34**	−1.40	−1.35	−1.75	**1.68**	−1.19	−1.64	−2.07	**0.06**	−1.47	−1.49	−1.86	−1.74	−1.77
GR	−2.24	−1.14	−1.83	−1.34	−1.19	**4.22**		−2.10		−2.26	−1.70	−2.36	−2.17	−1.19
IR	−2.08	−1.24	−1.56	−2.00	−1.64		**4.69**	−2.19		−1.43	−1.13	−1.81	−1.95	**−0.26**
IT	−2.12	−1.99	−2.29	−1.94	−2.07	−2.10	−2.19	**1.84**	−1.66	−2.25	−1.93	−1.81	−2.45	−2.07
LU		**2.15**		**0.04**	**0.06**			−1.66	**6.16**					
NE	−1.81	**−0.33**	−1.53	−2.24	−1.47	−2.26	−1.43	−2.25		**2.44**	−1.37	−2.19	−2.04	−1.68
PO		−0.90	−1.52	−1.02	−1.49	−1.70	−1.13	−1.93		−1.37	**4.55**	**−0.32**	−1.69	−0.91
SP	−2.19	−1.45	−2.00	−1.41	−1.86	−2.36	−1.81	−1.81		−2.19	**−0.32**	**2.57**	−2.36	−1.66
SW	−2.13	−1.64	**−0.16**	−2.40	−1.74	−2.17	−1.95	−2.45		−2.04	−1.69	−2.36	**2.75**	−1.88
UK	−2.27	−1.58	−1.48	−2.06	−1.77	−1.19	**−0.26**	−2.07		−1.68	−0.91	−1.66	−1.88	**1.46**

Note: Empty cells refer to pairs of countries that did not collaborate in each year. The T_{ij}-values of these pairs can not be averaged since they equal ln 0 for some year(s).

data on institutional addresses in records of the *Science Citation Index* for the period 1993–2000 results show that the process of European integration has indeed occurred. It is also found that the integration process has not been the result of a falling bias of countries to collaborate nationally, but solely the result of a falling bias in the choice of partner in European collaborations. Furthermore, the size of a country correlates with the degree of integration of a country, which indicates that larger countries have contributed most to the process of integration. The latter result has been related to scale advantages arising from diversification and network externalities in large countries. These explanations are largely suggestive and merit further theoretical and empirical elaboration.

From a policy evaluation perspective, the results suggest that European science policy has led to a more even distribution of European partnerships, but has not led to a 'substitution' of national for European partnerships. This is not to say that European science policy has not succeeded. On the contrary, for concerning European collaboration, the bias in partner selection has steadily decreased. European funding, including the equability conditions attached to it, can be expected to have a substantial effect on a more even pattern of collaboration. The fact that the bias to collaborate nationally has not decreased may well reflect the effect of national science policies aiming to increase national collaboration[14] rather than the ineffectiveness of European science policy as such. This is in line with the observation that, from a budgetary point of view, European science policy has not been successful: until now, member states still account for 95% of expenditures on public civil R&D in the European Union (Banchoff, 2002).

The results obtained in this study offer us a macroscopic picture of the integration process since the sample from the *Science Citation Index* includes all disciplines in natural and life sciences. The conclusion that the European union is integrating can by no means be generalized for all the scientific disciplines in which research communities are predominantly organized. It may well be the case that the application of integration measures at the level of scientific disciplines would show disintegration for some disciplines.[15] To look for more detailed explanations of patterns of collaboration, future research could extend the analysis presented here by decomposing the collaboration matrix into the lower level of scientific disciplines. Methodologies based on journal–journal citation reports are readily available and do delineate scientific disciplines using clustering techniques (Leydesdorff & Cozzens, 1993; Van den Besselaar & Leydesdorff, 1996). Alternatively, one can use existing classifications that are available from ISI.[16]

Having delineated scientific disciplines, one can apply the proposed indicators of integration in the same manner as we applied these to the science system as a whole. One can then attempt to explain the level of integration of scientific disciplines as a dependent variable by independent variables that characterize disciplines (tacitness, specificity, appropriability, fixed costs). From earlier patent studies, it has become clear that the spatial concentration of innovative activities in Europe is highly sector-specific (Breschi, 2000). Similarly, one can expect important differences to exist in the degree of European integration of different scientific disciplines.

In addition, one can analyse institutional research collaborations across disciplines using data on publications in interdisciplinary journals to assess whether the European level has become progressively instrumental for interdisciplinary research (Gibbons *et al.*, 1994). Alternatively, one can use journal–journal citations to reveal the interaction patterns between journals belonging to different scientific disciplines. In this context, citations provide one with an indicator of 'flows of knowledge' between scientific disciplines in a similar way to input-output tables that describe the flows of goods and services between industries. A citation approach can make use of existing techniques from input-output analysis including dynamic input-output methodologies (Leontief, 1996).

The research agenda outlined above is also expected to contribute to (European) policy design and policy evaluation. Understanding the determinants of research collaboration from characteristics of scientific disciplines can be helpful in designing policies that promote collaboration and mobility at the level of particular disciplines. For example, the current emphasis of EU science policy on applied knowledge production in Framework Programmes and the lack of EU funding of basic science, has been criticized at various occasions (Pavitt, 2000; Banchoff, 2002). This criticism calls for empirical studies that test whether basic science benefits more from supranational networks, and whether applied science more often emerges from local networks. If so, there may be reasons to readjust the orientation of collaboration and mobility programmes of the European Union towards basic science.

A final note concerns the application of the integration measure to other domains. In principle, the integration measure can be applied to any data that can be summarized in frequency matrices of interaction. Within the context of European integration, valuable information can be generated through labour market analyses using intra-national and European migration data and through the commodity market using intra-national and European trade data. One can also think of studies that analyse the frequencies of intra-national and European collaborations, mergers and acquisitions among firms. Analyses of these kinds would provide us with important empirical and policy-relevant information on the level, structure and dynamics of integration in the European Union. After all, lacking any real precedent, the process of European integration is still both theoretically and empirically poorly understood.

Notes

1. The indicator will be used here to analyse the integration process among countries into a supranational system, but the indicator can equally be applied to lower levels (e.g. integration of cities in a regional system, integration of regions in a national system). In this context, the indicator may be of relevance in urban and regional studies.
2. Katz & Martin (1997, pp. 11-13) discuss at length how multiple address analysis differs from co-authorship analysis.
3. Consequently, a co-occurrence of two addresses in the same country is counted twice. The complete procedure is also illustrated in the example in Table 1.
4. For $x = 0$ we have $x \ln x \equiv 0$. Further note that in information theory one usually uses base two logarithms instead of the natural logarithm to express the value of mutual information in bits. When the natural logarithm is used, as in this study, one speaks of 'nits' (Theil, 1972).
5. Theil (1967) also showed why the mutual information decreases when sectors in an input-output table are aggregated. In this context, he showed that minimization of input heterogeneity of sectors that are aggregated minimizes the loss of information due to aggregation. A similar aggregation procedure, although not followed below, could be applied to the matrices of research collaborations.
6. More recent applications of mutual information in social sciences can be divided into two groups: applications to empirical data and application to simulation data. Empirical applications include the dependence between different donors and different recipients of grants in the United States (Theil, 1972), the dependence between journals as reflected in matrices of journal-journal citation matrices (Leydesdorff, 1991), and the dependence of countries on technologies and markets (Frenken, 2000). The application of mutual information to simulation data concerns the measure-

ment of dependency relations between the states of cells in cellular automata (Langton, 1990) and the characterization of multi-dimensional NK fitness landscapes in terms of the distribution of local optima (Frenken, 2001).

7. Member states are Austria (AU), Belgium (BE), Denmark (DE), Finland (FI), France (FR), Germany (GE), Greece (GR), Ireland (IR), Italy (IT), Luxembourg (LU), The Netherlands (NE), Portugal (PO), Spain (SP), Sweden (SW), and the United Kingdom (UK). Note that the United Kingdom refers to records in the *Science Citation Index* containing addresses from England, Northern Ireland, Scotland or Wales.
8. Being collaborations between an EU country and either Canada, Japan, Russia, Switzerland or the United States.
9. The use of only the first three addresses provides, apart from computational advantages, a way to circumvent the fact that, in some disciplines, collaboration is much more common than in others.
10. The application of the mutual information indicators to regions within a homogeneous territory such as the United States would give an indication of the degree of spatial concentration that is expected to remain. This analysis falls outside the scope of this study.
11. Given the largely unchanged positive $T_{i=j}$-values and the trend of the negative $T_{i\neq j}$-values towards zero, the falling trend in T-values as observed in Figure 1 must be understood as resulting from a rising share of international collaboration as a percentage of all collaborations. The share of international collaborations $\Sigma\Sigma q_{ij}$ $(i \neq j)$ has indeed risen from 0.137 to 0.161, while the share of intra-national collaboration $\Sigma\Sigma q_{ij}$ $(i = j)$ has fallen from 0.863 to 0.839.
12. The result on scale effects is empirically not conflicting with Katz's (2000) result that smaller countries tend to engage more often in international collaboration, because Katz (2000) made use of an indicator that did not relate the amount of international collaborations to the amount of national collaborations.
13. Note that in the *Science Citation Index* from which the empirical data have been extracted, also includes journals in other European languages, although a bias exists towards the inclusion of journals in English.
14. For example, the Dutch government has promoted the creation of national research schools in all disciplines during this period.
15. It is even theoretically possible that all disciplines are disintegrating in islands of collaborating clubs of countries, while the macroscopic system as a whole is integrating. If specific pairs of countries were to specialize in specific scientific disciplines, but different pairs of countries were to specialize in different scientific disciplines, the integration values of disciplines would show disintegration, while the aggregated science system could still show a macro process of integration.
16. http://www.isinet.com
17. An address that is listed before or after another address is treated in the same way. The share of collaborations between two different countries is therefore computed as half the mean to obtain $q_{ij} = q_{ji}$.

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