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Shadows of the past in international cooperation: Collaboration profiles of the top five producers of science

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This article aims at a characterization of the cooperation behavior among five large scientific countries (France, Germany, Japan, United Kingdom and United States of America) from 1986 to 1996. It looks at the cooperation profiles of these countries using classical measures such as the Probabilistic Affinity. The results show the major influence which historical, cultural and linguistic proximities may have on patterns of cooperation, with few changes over the period of time studied. A lack of specific affinities among the three largest European countries is revealed, and this contrasts with the strong linkage demonstrated between United States and Japan. The ensuing discussion raises some questions as to the process of Europeanization in science. The intensity of bilateral cooperation linkages is then studied with regard to field specialization by country, and this analysis yields no general patterns at the scale studied. Specific bilateral behaviors are also analyzed.

Introduction

Collaboration has received much attention by scholars as a central feature of the scientific community, especially since a bibliometrical approach and basic hypotheses on international cooperation were put forth by *de Beaver & Rosen*,[1] and *Frame & Carpenter*.[2] Historians of science and sociologists of various schools have stressed different forms of and roles for cooperation in the advancement of science.

Co-signed publication provides readily available data for monitoring "cooperation" among scientists. The interest and limits of co-authorships for science policy studies have recurrently been described in the literature.[3-7] These authors reviewed various forms of collaboration and co-authorships, two distinct notions. Most studies deal with "institutional collaboration", using international databases that record multiple addresses of authors, primarily the *Science Citation Index*. Scientometricians have introduced a variety of technical measurements of co-authorship.

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The role of co-authorship in the network of science has been investigated from many points of view. "Does it pay to cooperate?", the reward of cooperation in terms of citations, has been investigated by *Herbertz*,[8] *Narin & Whitlow*[9] and *Van Raan*.[10] The form that cooperation takes has also received attention. The relationship between co-authorship and social stratification of science has been studied from different points of view by *Pao*[11] and *Kretschmer*.[12] The consensus which has emerged from various schools of thought on the importance of cooperation in science raises in turn the importance of co-authorship indicators to where they are becoming an integral part of science monitoring systems at a number of levels.

At the international level, a great variety of applications can be found in the literature: studies of the state-of-the-art of specific countries,[13-16] the shape of continental networks,[17-19] the international openness of specific zones,[20] and North-South relations in scientific collaboration. Larger scope studies have been produced by *Schubert & Braun*[21] and *Leclerc & Gagné*.[22] Referring to the work of *Callon* on "continentalization" and "archipelagos" of science,[23] *Leclerc* and *Gagné* stressed the stratification of (sub-)continental networks. *Okubo* et. al.[24,25] analyzed the level of resemblance and the main characteristics of the collaboration patterns among 98 countries in different fields of science.

As in cases of institutional collaboration studies, collaboration and co-authorships do not completely overlap in international collaboration studies. International co-authorship is an easy yardstick to use, but it addresses only one of the many aspects of international collaboration. Studies of the mobility of students and scientists,[26-28] of multi-national mega-science programs (CERN, observatories, etc.) and of supranational programs such as those mounted by the EU[29] clearly show that collaboration is only partially reflected by co-authorship indicators.*

As emphasized in the scientometric literature, co-authorship is a complex phenomenon. Many factors interact, including science policy decisions (bilateral or multilateral cooperation programs) and decisions by individual scientists at the micro-level. It is widely recognized that the level of international co-authorship is, in the first instance, determined by the size of the country. Secondarily, it is influenced by "proximity" between countries, either physical (geographical) proximity or immaterial proximity stemming from cultural affinity in a broad sense (historical, linguistic), or by socio-economic factors. These proximities influence, consciously or unconsciously,

* As a result of measuring the collaborations by use of the address field in ISI databases, an article from CERN, for instance, bearing only the Swiss address of this organization, is not considered as an international co-published article, though co-signed by several authors of various national origins.

the micro-decisions of scientists, as reflected in regular patterns that appear at the macro-level. Few attempts have been made to combine some of these factors in quantitative modeling. Recently *Nagpaul*[30] built an econometric model including three types of distance: geographic, socio-economic (development level), and thematic proximity. Each of these three variables was revealed to be significant. A large body of literature has been built in the recent years on the concept of proximity in regional economics and economic geography.

This article aims at a characterization of international collaborative behaviors of five large producers of science – three European nations (France, Germany, the United Kingdom), the United States and Japan, starting with a general hypothesis that relations in science reflect a complex mixture of cultural and geographical proximities in which common historical experience plays a central role.

We first describe the international cooperation profiles of the five countries using absolute volume of co-authorships and Probabilistic Affinity Index (PAI). The changing pattern of collaboration profiles over 10 years is depicted. The influence of various combinations of physical and immaterial "proximities" is investigated. Second, we examine the force of probabilistic affinity between two countries in relation to their visibility in different fields of science. Is the bilateral partnership likely to be influenced by the perception of relative strength or weaknesses in terms of specialization? In other words, are there prevailing collaboration patterns, such as preferential collaboration in strong fields common to the two countries ("co-option" pattern), in weak fields common to them both ("solidarity" pattern), or in fields of contrasting level of strength (asymmetrical "master-pupil" pattern)?

Sources and methods

Sources, disciplinary breakdown, specialization measures

Science Citation Index and *Compumath* databases, produced by the Institute for Scientific Information (ISI), namely a customized extract of the "Integrated Citation File", are used as basic sources in this study. Aggregations and classifications of scientific disciplines are generated by the Observatoire des Sciences et des Techniques (OST, Paris). To cope with short-term fluctuations of data, we used a 3-years-average. The study is based on two periods, *1996 (1995-1997)* and *1986 (1985-1987)*, and on the ISI dynamic set of journals.

The 31 scientific disciplines used in this article have been defined according to a principal classification based on cross-citations among journals, with further assignments of ISI-defined specialties.[31]

The field specializations are described in terms of an "Activity Index" for production and its equivalent "Attractivity Index" (*Schubert* et al.[32]) for citations. These are the common observed/expected ratios for tables actors-fields. The underlying count is fractional counting for publications and citations (for a discussion see *Lindsey*[33]). The fractional rule is also applied to all overlapping sets, for example the assignment of journals. The most citable types of document are used: articles, notes, letters, reviews. For citations, the window used is "5 years" including the publication year; the window is shorter for the very last years.

Various types of normalization of observed/expected indexes can be used. The Activity Index, one of the basic statistical indexes for contingency table studies, is also widely used in technology and economic studies under the name of Revealed Advantage Index. Renormalization of the interval is sometimes useful. A simple renormalization between –1 and +1, with neutral value 0, is [$a<1 \mid b=a-1$; $a>=1 \mid b=1-(1/a)$]. *Grupp* (1994) recommended the logarithmic form of a, with boundaries, $c/100=\tanh(\ln a)=(a^2-1)/(a^2+1)$. Statistical significance was addressed by *Engelsmann & Van Raan*[49] and *Grupp*.[56] For the PAI index defined below, the interval of variation has been normalized. For the Activity Index, since the scale of variation in the present study is small, we kept the original form in the figures.

Co-authorship measures

Basic counting. A variety of counting methods exist for co-authorship (for a review see *Maltras*[34]). In this study we deal with "institutional co-authorship" (address level). We use two classical methods of counting, the fractional and the whole/distinct count. In the fractional count used here, the rationale is both an "article" and "institutional" view. The weight of every publication is 1, distributed among the bilateral linkages of institutions. In the whole/distinct count, the rationale is both a "link" and a "country" view. If an article has two US institutional addresses, one French, and one Japanese, "1" is attributed to each pair USA-FRA, FRA-JPN, USA-JPN. By convention, we also set USA-USA to 1. For given pairs of countries the two measures may differ by a few percentage points. The whole count gives stronger implicit weight to articles in multilateral cooperation. Graphical representations are based on the fractional count.

In order to examine a stable relationship between countries, small collaborations that yield less than 5 annual (fractional) co-authorships are not shown, but they still

participate marginally in the computation of the indexes. However, most of the tiny linkages provide a very consistent view with the main ones. For France for instance, we find such partners as Comoro Islands, Congo etc. For the United Kingdom, Saint Lucia, Malta, Sierra Leone etc.

Coauthorship indexes. In addition to measures of global cooperation behavior (percentage of articles in collaboration, in international cooperation, etc.), many methods for characterizing co-authorship linkages have been proposed. Each type of measure is constructed to meet specific needs.

Gross volume of coauthorship, without any normalization, is relevant in some science policy contexts. A look at these exchanges which fully reflect size and power effects is a first step toward understanding the structure of international exchanges. From this point of view, the major international linkages connect United States to large European countries, Japan and Canada. It is also worth noting that in the decade under examination the gross volume of international co-authorship doubled. Let n(i,j) the volume of co-authorship between countries i and j.

Collaboration profile, with one-way normalization is the next tool to use in analyzing collaboration. *Miquel* et al. used a pair of inclusion indexes (share of country j in the total coauthorships of i or Affinity Index AFI(i,j), and its counterpart AFI(j,i)) to characterize asymmetrical relationships between two countries.

$AFI(i,j) = n(i,j) / n(i)$, where $n(i) = \Sigma_j n(i,j)$, total coauthorship linkage of i

AFI is a measure of the amount of collaboration between a given country (A) and another (B), compared to the total collaboration of the given country (A) with the entire world, in a given field of science, during a given period of time. See *Okubo* et al.[24].

AFI highlights the attractiveness of a partner in collaboration in a particular field. AFI(i,j) is naturally influenced by the global size of the partner j, and conversely for AFI(j,i). The asymmetry of partners is stressed in the comparison. For inclusion indexes as well as other co-authorship indexes, variants exist according to the reference: external coauthorships, all coauthorships, all publications. The application of Affinity Index (AFI) to science policy has been implemented by *Leclerc*[35] for measuring the internationalization of Canadian science. *Arunachalam* et al.[36] used AFI to analyze science trends in Asia.

The mutual inclusion approach (Salton-Ochiai or its square "equivalence index"; or in additive form Jaccard) aggregates the two relations into a symmetrical index. m(i) notes the total frequency of i rather than the sum of co-authorships of i.

$OCH(i,j) = m(i,j) / [m(i)m(j)]^{1/2}$

a usual inclusion index, bilateral, is $m(i,j) / \min(m(i),m(j))$.

The Salton index is influenced by the size of partners, as are inclusion indexes. Frequently used, especially for mapping purposes,[21, 37] it offers an interesting synthesis between gross volume and Probabilistic Affinity, as discussed below. However, using this index in a comparative context can be difficult, precisely because of this trade-off.

For a given country (i) the rank of partners, by gross volume or by Affinity Indexes AFI(i,j), reflects first of all the scientific importance of its partners in terms of total co-authorship. Table 1 shows the list of the first rank cooperating countries in the world, which would be expected to appear at the top of most countries' list of partners. As usual, the United States is predominant, with 20.9% of total international co-authorship (about 64,000 fractional links) and 32.5% of the world annual output (about 514,000 publications SCI-CMCI). For the other countries studied, shares in co-authorship vary: 8.8% (UK), 8.6% (Germany), 6.6% (France) and 4.2% (Japan). The shares in total output range from 32.5% (USA), 8.5% (Japan), 8.4% (UK), 6.6% (Germany) and 5.2% (France). Japan, with a low propensity to international cooperation, loses several ranks in gross co-authorship, compared with its total scientific output.

Table 1
Countries ranks measured by international co-authorships and scientific output, 1995-1997

Rank	Rank of countries measured by international co-authorships (fractional count)	Rank of countries measured by international co-authorships (whole distinct count)	Rank of countries measured by total publication (fractional count)
1	USA	USA	USA
2	GBR	GBR	JPN
3	DEU	DEU	GBR
4	FRA	FRA	DEU
5	CAN	CAN	FRA
6	JPN	JPN	CAN
7	ITA	ITA	ITA
8	RUS	NLD	RUS
9	NLD	RUS	AUS
10	AUS	CHE	ESP
11	CHE	AUS	NLD
12	ESP	ESP	IND
13	SWE	SWE	SWE
14	CHN	BEL	CHN
15	BEL	CHN	CHE

The Probabilistic Affinity Index (PAI) is a classic ratio of observed to expected values in contingency tables, similar to an activity index or an attractivity index in another context. The index is fully normalized by the size of both countries (total co-authorship in margin).

PAI= $n(..)n(i,j) / n(i)\,n(j)$ where $n(i)=\Sigma j\ n(i,j)$.

A unit value of the index indicates neutrality; when the index is above 1, the two countries collaborate more than expected, with respect to their scientific size. The PAI removes the effect of size, at the expense of larger significance intervals for the index when values of marginals are small. A small country concentrating its collaboration with a few partners will record very high ratios. The PAI is a convenient means for highlighting small specific relationships. In this article the interval of variation of PAI is renormalized to range from –1 to 1. The neutral value becomes 0. We use the terms positive or negative affinities in this respect. Let a = PAI and normalized PAI $d = (a^2-1))/ (a^2+1))$. The error on d can be deduced from the error measurement on a proposed by *Schubert* et al.[32], $\Delta a \leq a / [n(i,j)]^{1/2}$.

The application of probabilistic indexes to coauthorship has been studied by *Schubert & Braun*,[21] and *Luukkonen* et al.[38] The index has been applied to international studies (*Leclerc & Gagné*;[22] named, however, "proximity index" by these authors. We reserve this name – proximity or similarity – for Salton-Ochiai or Jaccard indexes, which comply with similarity index requirements). OST has used it since 1993, to stress the extent to which scientific relationships are marked by cultural, linguistic and historical factors.[39,40] As we shall see later, fractional and whole counts give by and large similar results. The index may be defined with or without auto-coauthorships (the diagonal of the matrix). Keeping the diagonal makes the index dependent on the propensity of countries to internal co-authoring, which varies greatly among countries, and may bias comparisons. In this study, auto-coauthorship is neutralized by a classic iterative process of recalculation of margins, so that the final value in the diagonal becomes neutral (order-zero reconstitution). Missing values treatment in contingency tables has been extensively discussed in the statistical literature (see *Goodman*[50]), and in data analysis literature, especially in French works about correspondence analysis (references can be found in *Nora-Chouteau*[51] and *De Leeuw & Van der Heijden*[52]). Following previous *Price*'s work,[53] applications to diagonal treatment in scientometric matrices are also found in *Noma*[54] and *Tijssen* et al.[55]

The PAI allows the study of small countries' collaboration behavior, observable either in an influence zone pattern (for instance French-speaking African countries), or in relationships between small actors. Also, privileged relationships, such as

Australia-New Zealand, or intra-Scandinavia linkages, tend to depress affinity towards all other partners of these countries. When the diagonal is neutralized, the values of PAI are especially sensitive to the structure of the table. If, for example, Scandinavia were considered as a single entity instead of separate countries, its affinity towards other countries would be more favorably rated. The interpretation of indexes is strictly dependent upon the type and the level of breakdown.

Other types of co-authorship measures, for instance multilateral collaboration indicators, have been introduced by *Nederhof & Moed*[41] and developed by *De Lange & Glänzel*.[42]

None of these indicators can pretend to give the "best" view on collaboration. Each one sheds light on particular aspects of international exchanges. Rather than the synthetic view given by the Salton-Ochiai measures, we will base our study on the complementary views provided by gross volume on one hand, and the PAI on the other.

Patterns of cooperation measured by PAI

To get an early idea of the patterns to be observed, the first 15 partners of the five countries under study, when measured by gross volume, are listed in Table 2 (column "Vol."). If size were the only determinant of international co-authorship, these first 15 partners should be the countries of Table 1 (rank by fractional count) in the same order. This is only approximately true. The ranking by gross volumes reflects both the general hierarchy of Table 1 and specific preferences expressed by PAI (fractional count).

France

Among the first partners of France, Italy and Spain are both important and preferred in terms of gross co-authorships and PAI. The other partners, the United States, Germany, the United Kingdom and Canada, are top ranked countries in terms of gross co-authorship, but are the low ranking partners of France when measured by PAI. Japan which shows the six largest international activity in the world, ranks only 12th, with a negative PAI, as a partner for France. It ranks behind smaller collaborative countries such as Italy, the Netherlands, Belgium or Poland. In this regard, Japan is neither an important nor a preferred partner for France in science.

Table 2
First 15 partners of the 5 countries in decreasing order measured by gross volume, and PAI for the 15 selected partners, in fractional counting, 1996

France		Germany		United Kingdom		Japan		United States	
Vol.	PAI	Vol.	PAI	Vol.	PAI	Vol.	PAI	Vol.	PAI
USA	MAR	USA	AUT	USA	AUS	USA	KOR	CAN	KOR
DEU	BEL	GBR	CHE	DEU	ESP	GBR	CHN	GBR	ISR
GBR	ESP	FRA	RUS	FRA	NLD	DEU	USA	DEU	CAN
ITA	CHE	RUS	POL	AUS	DNK	CHN	IND	JPN	JPN
ESP	ITA	CHE	NLD	ITA	ITA	CAN	AUS	FRA	CHN
CAN	POL	ITA	CHN	CAN	CHN	KOR	CAN	ITA	AUS
CHE	BRA	NLD	FRA	NLD	BEL	FRA	RUS	ISR	ITA
BEL	RUS	JPN	ITA	ESP	FRA	AUS	SWE	AUS	CHE
RUS	NLD	AUT	ESP	JPN	CHE	RUS	GBR	CHE	DEU
NLD	DEU	POL	SWE	CHE	SWE	SWE	DEU	NLD	GBR
POL	GBR	CAN	USA	SWE	USA	ITA	POL	CHN	NLD
JPN	CAN	ESP	GBR	RUS	DEU	IND	CHE	RUS	SWE
MAR	USA	SWE	JPN	CHN	CAN	NLD	NLD	SWE	ESP
BRA	SWE	AUS	AUS	BEL	JPN	CHE	FRA	ESP	FRA
SWE	JPN	CHN	CAN	DNK	RUS	POL	ITA	KOR	RUS

In contrast, practically all countries of the former French Empire in Africa and the Maghreb show high probabilistic affinities for France, even though the absolute number of co-authorship is low. In case of the linkages between France and its ancient colonies, the effects of cultural proximity and economic relationships dominate the effect of geographical distance, just as is the case between former British Empire or Commonwealth countries and the UK as we shall see later.

The combination of geographical and (partial) linguistic proximity can explain the high probabilistic affinities between France and Belgium, and also between France and Switzerland. Geographical proximity coupled with a shared Mediterranean culture can also account for the preferential linkages established between France and Spain, France and Portugal, and to a lesser degree, France and Italy. In the same manner, cultural proximity links France-Romania and France-Greece. Medium-high affinities for France are limited to two zones: Latin America and Eastern Europe/Russia (Fig. 1a).

The three circles constituted by French-speaking countries, Latin-culture countries, and the traditional linkages with Russia and Eastern countries depict almost the entire spectrum of preferred partners of France. This pattern has been reinforced between 1986 and 1996.

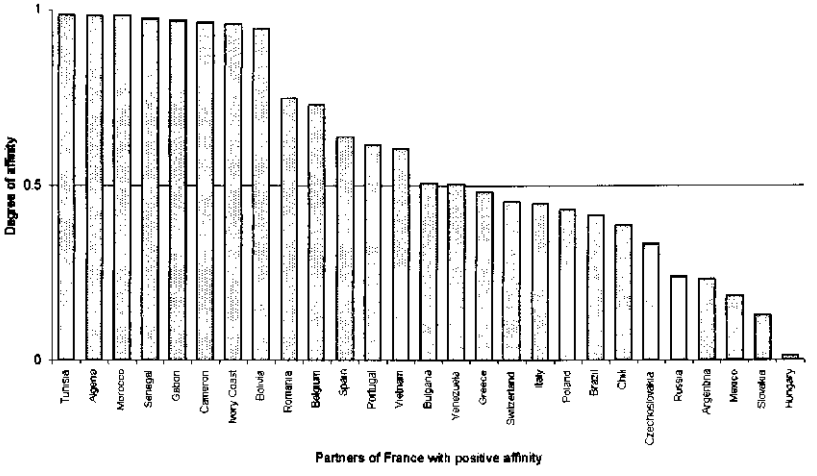

Fig. 1a. Positive probabilistic affinities between France and its partners in science, 1996

In contrast, France shows mediocre affinities for Germany, the Netherlands, the United Kingdom and Canada (slightly below 0). France conducts a strikingly low cooperation with Asian countries, whether the partner be Japan, China, or the four dragons. Likewise, the distance with the former Commonwealth countries is great. Apparently, cultural distance is the major factor influencing probabilistic affinities between France and its partners.

It clearly appears that for France, when size effect is removed, partnership with big countries becomes either "neutral" (Germany or the United Kingdom) or negatively rated (United States and Japan).

Germany

In the case of Germany the cultural and economic area of influence strongly overlaps with geographic proximity. The scientific relationship is built with the same rationale. Strong probabilistic affinities are observed with adjacent and culturally akin countries. The linguistic and geographical proximity are determinants for strong PAI between Germany and Austria, and Germany and Switzerland. PAI for the overall Eastern

European countries is also high, partly as a result of the former East German network inside the COMECON. Relationship between Germany and Russia, and Germany and Switzerland is high in gross volume as well as in PAI.

The United States, the United Kingdom and France are the top-ranked partners in terms of gross co-authorship, but the probabilistic affinity between Germany and the four other countries studied in this article is neutral or negative. It should be noted however that the landscape would have been different if Western and Eastern Germany were treated as two different entities in 1986. The probabilistic affinity between West Germany and the United States would have been higher (see *Leclerc & Gagné*[22]). The linkage between Germany and the United States increased slightly over the decade.

PAI between Germany and the European Union countries such as France, Italy and Belgium are not far from the neutral value. The probabilistic affinity between Germany and the United Kingdom is even lower, but improved over the decade by 0.1. The link between Germany and France remains stable. A positive PAI is recorded with Denmark and the Netherlands (Fig. 1b).

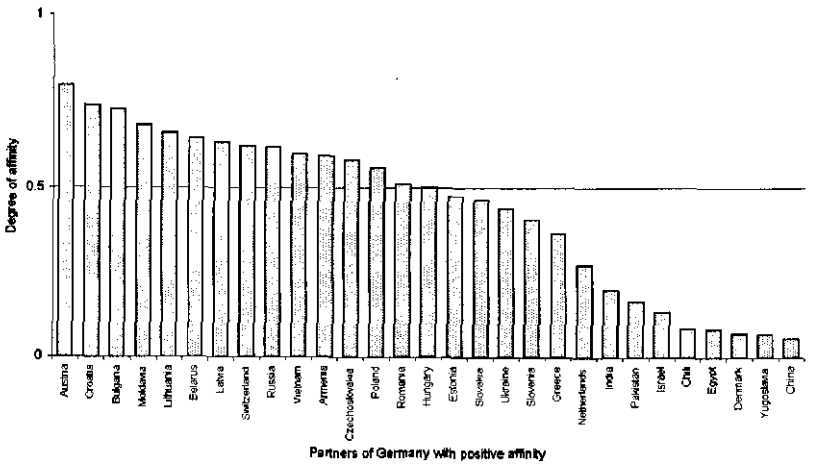

Fig. 1b. Positive probabilistic affinities between Germany and its partners in science, 1996

Germany has negative PAI with the former Commonwealth nations, Australia and especially Canada. Japan is not a preferred partner for Germany either, as it is found to be the 8th partner when measured by gross volume of co-authorship. Probabilistic affinities are also negative with small Asian countries, African countries and Latin American countries. However, PAI towards India, Pakistan, and China is positive in 1996.

The United Kingdom

Apart from Ireland, the important partners of the United Kingdom in terms of probabilistic affinity are the African and Caribbean English-speaking countries (Gambia, Jamaica, Uganda, Nigeria, Kenya, Ghana...), the Middle-East and Gulf countries (Iran, Turkey, Saudi Arabia) and other Asian countries (Sri Lanka, India, Pakistan, Malaysia, Hong-Kong, Singapore...) (Fig. 1c). Not surprisingly, the relationships with Australia, New Zealand and South Africa indicate a positive PAI, demonstrating the strength of cultural linkages rooted in history. Among these countries, Australia represents a high volume of co-authorship in absolute terms.

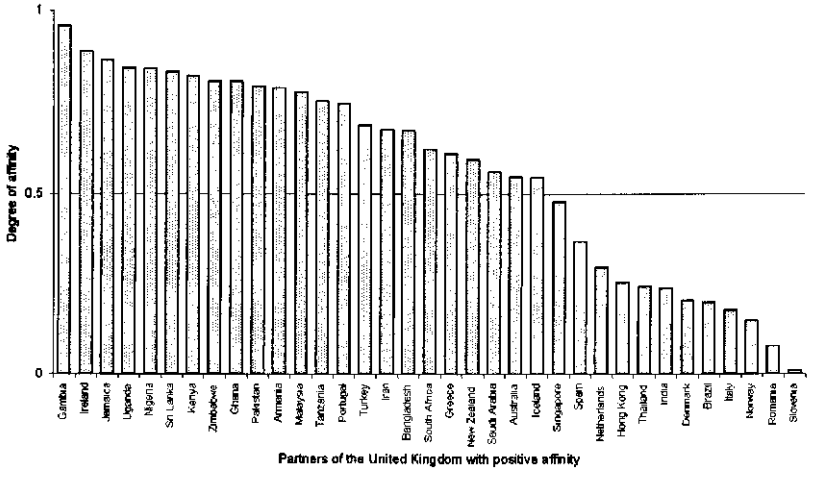

Fig. 1c. Positive probabilistic affinities between the United Kingdom and its partners in science, 1996

In contrast, the relationship between the United Kingdom and Canada, not negligible in absolute terms, is unexpectedly mediocre in relative terms. The low PAI may be partially due to the exceptionally strong linkage of United States-Canada that lowers any interaction of Canada with other countries. Similarly, PAI between the UK and the USA remains slightly negative and stable over the decade, in spite of the great gross volume.

The United Kingdom has strong PAI with some European Union countries. Top-ranked are Greece followed by Spain, the Netherlands, Denmark and Italy. Italy is highly ranked in absolute terms as well. In contrast, the level of affinity for France is neutral, and negative for Germany, though these countries are among the first three partners of the United Kingdom when measured by gross volume. Thus geographical proximity does not appear to be the dominant factor of the United Kingdom's international pattern of collaboration. A decade earlier, the United Kingdom's affinity towards France and Germany was lower by 0.1.

The lowest PAI is observed between the United Kingdom and East-European countries, Russia, the FSU nations, Asian countries (including Japan) and, to a lesser extent, Latin American countries. The linkage with Japan improved however, starting from a very low level (-0.46) in 1986 and becoming -0.25 by 1996, and the gross volume between them is not negligible either. But for Russia/FSU, linkages are low both in gross volume and in PAI.

As a whole, the United Kingdom's international scientific ties are more the result of historical connections than geographical proximity. The clear contrast between the collaboration profiles of Germany and the United Kingdom suggests that several decades of EC relationship do not erase historical linkages. Profiles seem to be rooted in more longstanding interactions as implied by the stereotype that contrasts British "marine power" with German "continental power".

Japan

Japan has a much smaller number of partners than the other four countries. In 1986, an extraordinarily strong probabilistic affinity with the United States (0.5) was one of the conspicuous features of Japan's collaboration profile. Six Asian countries (Philippines, Korea, Taiwan, Thailand, China, India) showed a higher affinity, but with low absolute co-authorship values. Canada came in slightly below neutrality, followed by a few European countries (Germany and Belgium).

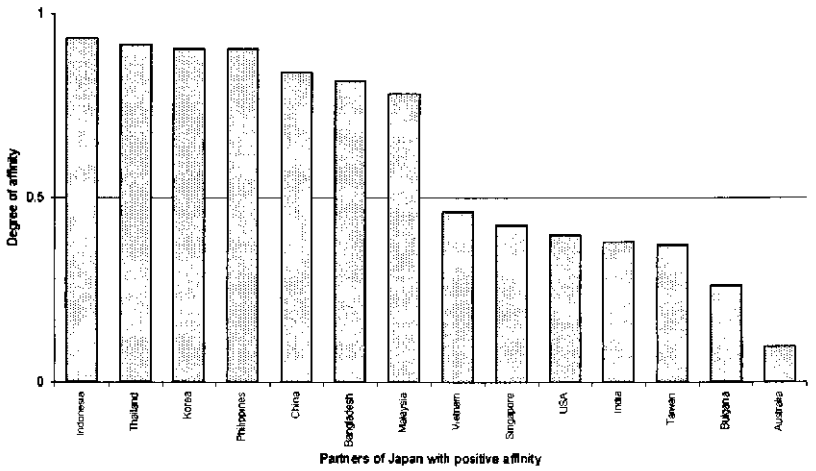

Fig. 1d. Positive probabilistic affinities between Japan and its partners in science, 1996

Ten years later, international partners have diversified. A collection of Asian and Pacific Rim countries (Australia, and close to neutrality, Canada) have positive affinities with Japan (Fig. 1d). Co-authorship with China is important in PAI as well as in absolute terms. Nevertheless, a strong affinity (0.4) persists with the United States, which is also the first partner of Japan by gross volume. When size of a country is eliminated by PAI, the big partner that ranked high in gross volume tends to be superseded by smaller partners of a specific linkage. This is not the case with the USA-Japan relationship, indicating extraordinarily strong scientific ties between them.

Around neutrality we find Bulgaria, Russia and Hungary. In contrast, Japan's and the European countries' affinities are relatively low. Even its preferred European partner, Sweden, followed by the United Kingdom and Germany, have negative PAI, though the last two nations are one of the top ranking partners of Japan in terms of gross co-authorship (Table 2). Gross co-authorships between Japan and France is only half of the expected level. Moreover, PAI with France and Germany have strongly decreased over the decade, from -0.47 to -0.61 between Japan and France, and from -0.10 to -0.26 between Japan and Germany.

As was seen with Germany, Japan's geographical proximity and historical relationships tend to overlap and explain the strong linkages between Japan and its Asian neighbors (Korea, China and Taiwan). The post-war historical relationship with the United States has substantially strengthened the scientific ties between the United States and Japan. The situation will perhaps change in the not too distant future as Japan is trying to enhance the level and diversity of its scientific international partnership, very low for a country of such size. It may also change as European countries are increasingly attracted to Far-East countries as partners in economic and technologic activities.

United States of America

The collaboration pattern of the United States is obviously a very particular one. Being a dominant country in the international scientific arena, the United States interact actively with a substantial number of countries. Large deviations of affinities are not to be expected among its partners, since this country contributes heavily to shaping the world average. Not surprisingly, the internationally active countries in terms of the size of international co-authorships are the most important partners of the United States by gross volume – Canada, the UK, Germany, France and Japan. Canada and Japan are both important and preferred (PAI). Geographical and historical proximity strengthen the scientific ties among them, not to mention scientific size.

Probabilistic affinity values superior to 0.5 are also found between the United States and Taiwan, Korea, Panama, Lebanon and Israel. Most of the countries closely related to the United States can be classified into three circles, the Pacific Rim, the American Continent, and the Middle East. The most important partners in the first circle are Taiwan, Korea and Japan, and in the second, Panama, Peru, Costa Rica, Ecuador, Venezuela, Mexico and Brazil. US's PAI with China, Australia and New Zealand are slightly positive. In the third circle Israel is a prominent partner. With much lower absolute co-authorships, a very high affinity is recorded for Lebanon and, to a lesser degree, for Egypt, Turkey, and Iran. There are also high probabilistic affinities between the United States and the Central Asian countries, especially India and Pakistan.

PAI with Western European countries are mostly negative, even lower with Southern European countries (Italy as an exception). The weakest links are recorded with Eastern European countries/Russia and African countries.

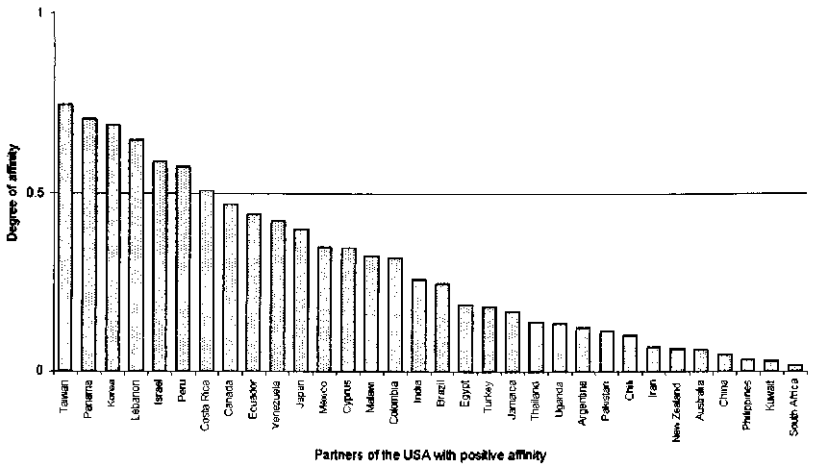

Fig. 1e. Positive probabilistic affinities between the United States and its partners in science, 1996

The network of the scientifically largest partners of the US is clearly shaped by the circles of general political influence.

Overall views of international relationships among the five countries

Collaboration patterns cannot be attributed to a sole factor, but rather to a complex mixture including cultural, linguistic, economic and geographical determinants. These factors are not easy to distinguish. We limit our discussion here to some qualitative observations about the relations between them. Nevertheless, PAI does highlight a certain number of the many aspects of international relationships.

First, it reveals the limit of the scientific sizes, alone, as a predictor of relationships. The list of partners chosen by a particular country and that of partners chosen by the entire worldwide scientific community are not identical. We have mentioned above the case of Japan among France's partners.

Our second remark is that the three European countries do not show mutual preference. Though they exchange intensively in gross volume, their level of exchange is much lower than what would be expected from their geographical proximity and from

their partnership in the European Union. The three profiles of France, Germany and the United Kingdom are in sharp contrast with one another, stemming from different cultural backgrounds. The French-speaking community especially in Africa, the English-speaking and former Commonwealth countries, and medium sized countries located near Germany still firmly maintain their scientific ties respectively with the three distinct "poles" of the European Union. The presence of international research institutes, such as the IRD – formerly ORSTOM – in France and the mobility of students reinforce these relationships. A large part of the tight connections established by France, Germany and the United Kingdom respectively are, therefore, constructed outside Western Europe. Germany is a nodal point connecting the Eastern European countries to the European network. The United Kingdom shows positive affinities with seven European Union countries, though it exchanges less volume with the EU countries than do France or Germany.

Spain and Italy connect to both France and the United Kingdom. The Netherlands are linked to Germany and the United Kingdom. These countries create an intra-EU PAI network more strongly than do the top three European countries. Switzerland, which is outside of the European Union, also links to France and to Germany, notably through CERN and other international collaborative projects (co-authorship, as mentioned earlier, can underestimate collaboration in this particular case).

In terms of changes over the period, there is a substantial increase of gross volume of international co-authorship between 1986 and 1996 (Table 3A&B). The volume of co-authorship has doubled over the period (for an earlier situation see *Narin & Whitlow*[9]). However if one projects the volume of collaborative linkages created between two countries in each of the two countries' entire international scientific activity by use of the Affinity Index (AFI), one can observe that the weight of one country in another has hardly changed over the decade for France, Germany and the United Kingdom (Table 4A&B). The percentage of the EU countries in the total international collaboration of these three countries (fractional count) has only grown slightly over the period: 34 to 35% for Germany, 41 to 42% for France, 36 to 37% for the United Kingdom. In spite of the gross volume that increased substantially, this increase did not affect the importance of each other in their cooperative activities.

In addition to above observation, it should be noted that PAI also remained strikingly stable during the same period (Table 5A&B). One observes only a slight improvement of the probabilistic affinity for United Kingdom-France (+0.10) and United Kingdom-Germany (+0.09). Is "continentalization of science" really prevailing at the European level? As far as the top trio is concerned, the answer is rather negative if we look at probabilistic affinity.

Table 3A
World share of international co-authorships between five countries, 1996, in fractional counting

Countries	France	Germany	Japan	United Kingdom	United States
France	–	0.6%	0.1%	0.6%	1.3%
Germany		–	0.3%	0.7%	2.1%
Japan			–	0.3%	1.7%
United Kingdom				–	2.1%
United States					–

Table 3B
Evolution of gross volumes of international co-authorships, between 1996 and 1986 (1986=100)

Countries	France	Germany	Japan	United Kingdom	United States
France	–	234	235	251	193
Germany		–	230	236	210
Japan			–	341	228
United Kingdom				–	188
United States					–

Table 4A
Affinities among 5 countries, 1996, in fractional counting

Countries	France	Germany	Japan	United Kingdom	United States
France	–	6.8	3.2	6.6	6.3
Germany	8.9	–	6.8	8.0	10.1
Japan	2.1	3.3	–	3.4	8.1
United Kingdom	8.9	8.2	7.1	–	10.1
United States	20.2	24.5	40.2	24.0	–

% of each line-country in the total international cooperation of a column-country.

Table 4B
Evolution of affinities among 5 countries between 1996 and 1986

Countries	France	Germany	Japan	United Kingdom	United States
France	–	+0.2	**–0.7**	**+0.7**	**–0.8**
Germany	–0.2	–	**–1.5**	+0.3	–0.2
Japan	0	0	–	**+1.2**	**+0.5**
United Kingdom	**+0.5**	+0.3	**+1.3**	–	**–1.4**
United States	**–4.9**	**–1.9**	**–9.2**	**–4.9**	–

Significant variations in bold face.

Table 5A
PAI (diagonal corrected, normalized interval) among 5 countries, 1996

Countries	France	Germany	Japan	United Kingdom	United States
France	–	–0.02	–0.61	–0.05	–0.28
Germany	0.00	–	–0.26	–0.15	–0.12
Japan	–0.51	–0.23	–	–0.25	+0.40
United Kingdom	–0.02	–0.07	–0.22	–	–0.14
United States	–0.23	–0.09	+0.44	–0.09	–

Above diagonal: fractional count, below diagonal: whole distinct count.

Table 5B
Variations of PAI: PAI(1996) – PAI (1986)

Countries	France	Germany	Japan	United Kingdom	United States
France	–	+0.02	**–0.14**	**+0.10**	**–0.06**
Germany		–	**–0.16**	**+0.09**	**+0.08**
Japan			–	**+0.21**	**–0.05**
United Kingdom				–	–0.03
United States					–

Significant variations in bold face.

If we take a more global look at intra-EU relationships, the most spectacular phenomenon concerns the patterns of Ireland, Greece and Portugal. These countries clearly tend to "continentalize", probably as a result of European programs. They achieve it chiefly through relationships with small and medium-size countries. The process of "European convergence", noted by other bibliometric measures,[43] does not appear as a major phenomenon in co-authorship (a similar observation for earlier periods was made by *Moed* et al.[44] and *Leydesdorff*[45]). So far continentalization seems to develop among small and medium-size countries.

Our third remark is that the trans-Pacific linkage established between the United States and Asian countries seems stronger than the trans-Atlantic one between the United States and the European countries. This is probably due to the Pacific Rim solidarity intensified by the recent emergence of Asian countries in the mainstream scientific community. Among the top-five bilateral relationships, the United States and Japan record the strongest tie. While none of the European countries showed a strong probabilistic affinity with another big producer of science, for the United States "strong partners" in terms of size (Japan and Canada) are also "elective partners" in terms of probabilistic affinity.

By and large, the comparison of profiles over ten years reveals a remarkably stable landscape. Though the total number of partners has increased for each country, the core partners remain mostly unchanged. Despite the high sensitivity of the PAI, the stability of country-profiles over the period suggests a permanence of factors determining international collaborative behaviors. This is so much the more remarkable given that, in the interval, the amount of international collaboration, in gross figures, has roughly doubled for these countries. The picture would appear less stable when examining countries of smaller size, such as the peripheral EU countries.

Cooperation and field specialization

It is expected that two countries have more collaboration in terms of volume in the fields where they are both specialized, owing to a simple size effect (insofar as co-authorships are connected to total publications). Global models have to take this into account, as does for instance *Nagpaul*.[30] The PAI calculated at the field level neutralizes this size effect. If this probabilistic affinity still shows a field dependence, since all background factors (geography, culture) are field-neutral, other factors are at work. We will not consider scale effects (thematic proximity at the sub-field level that can influence co-authorships), but will only address possible effects of specific behaviors, such as co-option or master-pupil relationship. We limit ourselves here to a brief description of the relation between PAI and cross-specialization.

Cross-specialization between countries

The cross-specialization of pairs of country can be graphically presented. Each field of science is plotted in a diagram with Activity Index of country i (in this field) in abscissa and Activity Index of country j in ordinate. Figure 2a presents such cross-specialization in the case of France and Japan. Japan specializes in chemical engineering and medical chemistry, while France specializes in mathematics, earth sciences and microbiology. They are both relatively weak in biomedical engineering, ecology, public health, but strong in materials science as well as applied physics. The plots are mainly scattered on the first diagonal quadrants. This observation suggests that relative strength and weakness of France and Japan reside in similar areas of science, therefore their production profiles resemble each other (an analogy pattern). This pattern is in contrast with "a complementary pattern" where plots are mainly located on the second diagonal quadrants, indicating that the two countries in comparison produce complementary

global scientific knowledge (the United Kingdom and Germany would provide such a picture). A global distance between patterns of pairs of countries could be calculated using classical distance/dissimilarity index.

The specialization measurement applied to the relative citation shares, instead of publication shares, constitutes the Attractivity Index of *Schubert* et al.[32]. The landscape illustrated by the Attractivity Index can be significantly different from that highlighted by the Activity Index, depending on the citation performance of a country in a specific area of science. The cross-specialization of France and Japan measured by citation shares (Fig. 2b) by and large resembles the previous publication picture. Nevertheless there are some differences. For France, oncology and analytical chemistry, for example, become weaker in the citation profile, while general physics and mechanical engineering improve their position. As for Japan, its strength in terms of attractivity increases in optics, but weakens in neurosciences.

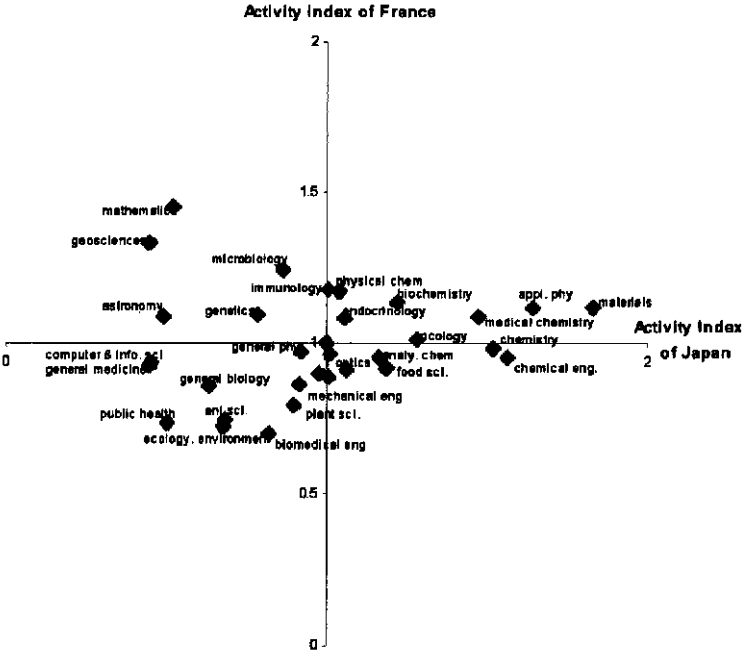

Fig. 2a. Cross-specialization of Japan and France measured by scientific publication, 1996

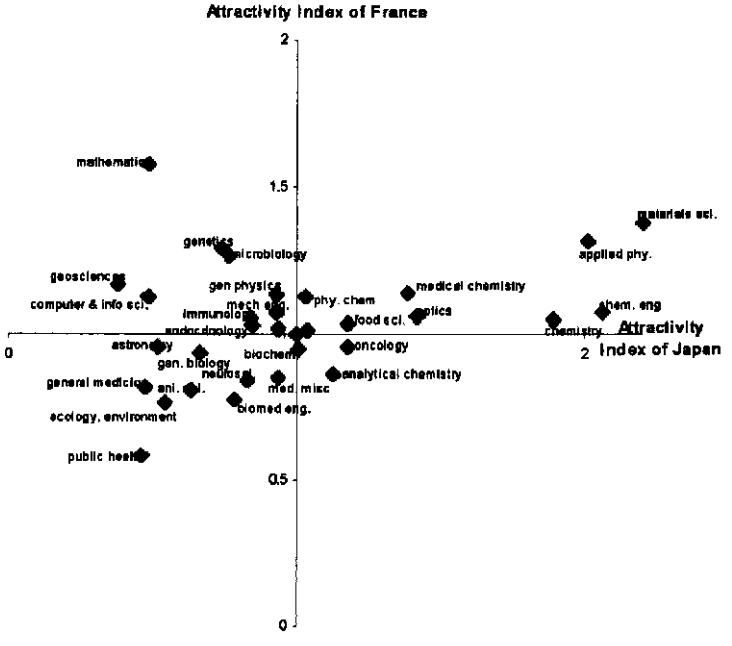

Fig. 2b. Cross-specialization of Japan and France measured by citations, 1996

Although both views of specialization are appealing, we limit ourselves here to cross-specialization measured by the Attractivity Index, more suitable to our topic, and will investigate the relations between collaboration and relative "strengths" or "weaknesses" of countries.*

Cross-specialization between countries measured by Attractivity Index

Figure 3 describes the specialization of Germany and the United Kingdom in terms of attractivity. Field plots line up from right to left, depicting a typical "complementary pattern" of specialization. Germany shows its strength in physics and chemistry, while the United Kingdom specializes in biology and medical research. Plant science is the only field in which the two countries' specialization coincides. Germany-United States,

* "Strength" or "weakness" only refers to the type of measure used, i.e., for a given country, the ratio of world share of citations in the field to world share of citation in all fields.

Japan-United States, Japan-United Kingdom, France-United States, France-United Kingdom combinations show, to varying degrees, a complementary pattern of specialization.

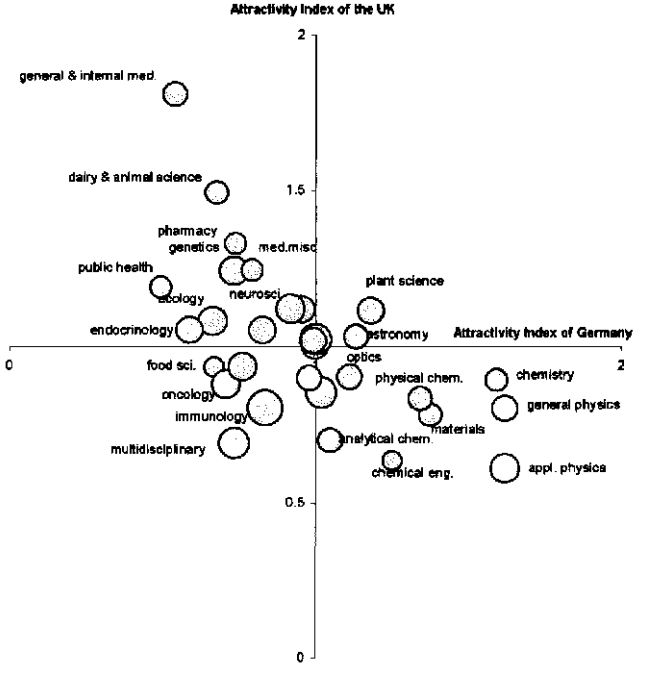

Fig. 3. Cooperation between Germany and the United Kingdom, Degree of Affinity by field, 1997

In contrast, the Germany-Japan pattern, with field plots lining up from left to right, depicts a typical example of an "analogy pattern". Both countries show high relative citation shares in chemistry, applied physics, chemical engineering and materials science, but weak shares in general & internal medicine and public health. The combinations Japan-France, Germany-France, and United States-United Kingdom more or less follow this pattern.

As a whole, we can observe the well-known situation of a "biology-specialized pole" (US, United Kingdom) versus a "materials-technology-specialized pole" (Germany, Japan), with France occupying an intermediate position.

Collaboration patterns in relation to attractivity

Is affinity between countries, after country normalization, affected by the attractivity of collaborating partners? In the game of co-authorship, all combinations follow some kind of rule. An actor (researcher, institution, country) who has a great capability in a particular field may search for a partner equally specialized or visible. He may also accept knowledge transfer or complementary work with a relatively less specialized/visible collaborator. Stratified collaborations (see *Kretschmer*[12]) may be a dominant pattern of collaboration, but unequal "master-pupil" relationships also have their own rationale. Micro-level (author level) analysis may be suitable for a detailed description of such patterns of collaboration behavior. We can nevertheless try to examine at the macro-level the relations between the level of specialization in scientific fields and collaborative behaviors among countries.

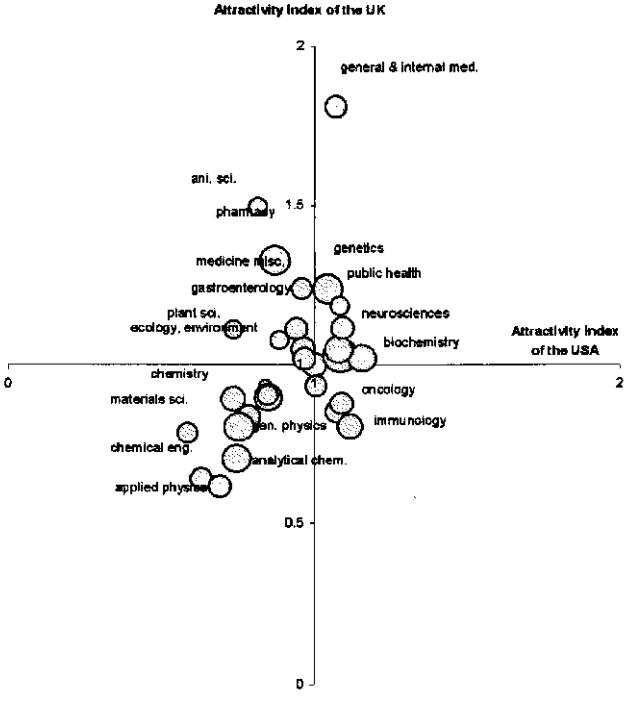

Fig. 4. Cooperation between the United States and the United Kingdom, Degree of Affinity by field, 1996

The degree of affinity (Probabilistic Affinity) between the two countries in each field is visualized in the third dimension (bubble graphic) upon the cross-specialization diagrams x-y (Fig. 3–6). There are three basic behaviors:

• *Co-option behavior*, with maximum PAI occurring in fields of strong attractivity of the two countries. This is the prevailing pattern of collaboration, whatever the specialization profile of two countries. In 7 out of 10 combinations, affinity between two countries tends to be stronger in shared fields of excellence. United States-United Kingdom (Fig. 4), France-United States, Germany-United States, Japan-United States, United Kingdom-Japan, Japan-Germany and France-Germany collaborate in this manner. Every collaboration involving the United States follows this pattern. The co-option pattern may also partly be explained by an inverse causality, as international collaboration can create a greater visibility.

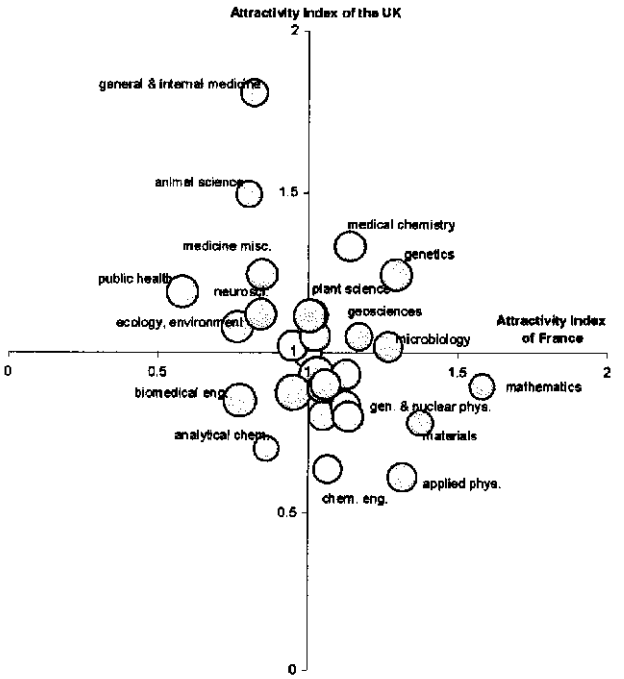

Fig. 5. Cooperation between France and the United Kingdom, Degree of Affinity by field, 1996

• *Solidarity behavior*, with maximum affinities observed in shared areas of weak attractivity. This can be observed for the collaboration of France-United Kingdom (Fig. 5) and Germany-United Kingdom, within complementary cross-specialization profiles. As co-option, this can be seen as a "cooperation between equals".

• *Master-pupil behavior*, an asymmetrical pattern of collaboration occurring in a field of excellence of one country and in the field of weakness of the other. It can reflect an efficient learning strategy for the country acting as a "pupil".* Relationship between France and Japan shows this type of collaborative pattern (Fig. 6).

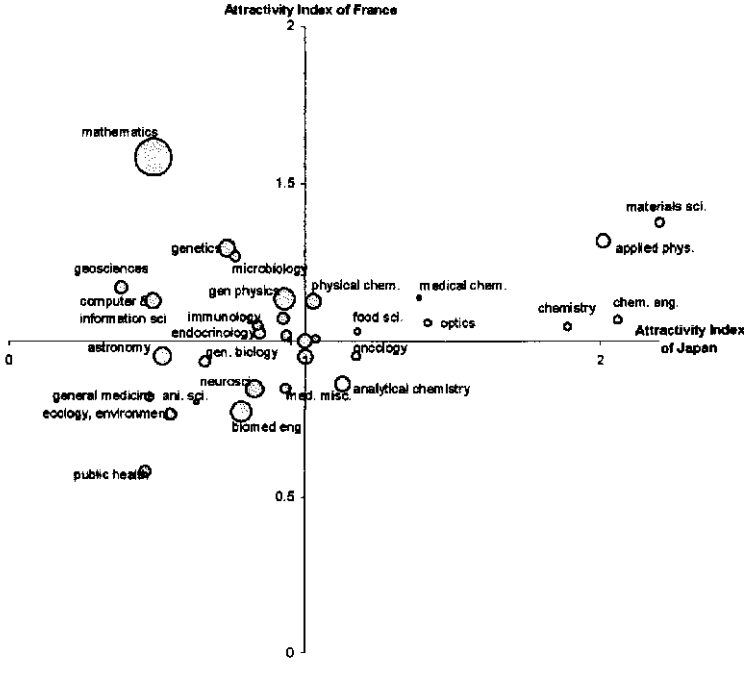

Fig. 6. Cooperation between France and Japan, Degree of Affinity by field, 1996

* The cross-specialization pattern trivially constrains the existence of particular behaviors; e.g., "master-pupil relationships" cannot be observed in strictly analogous profiles.

Most pairs of countries do not exhibit a "pure" master-pupil behavior with homogeneous levels of affinities within quadrants, and strong variations between quadrants. However the dominant forms appear as: Collaborative linkages as a direct function of attraction. In other words, the strongest affinities are observed in shared strong fields, followed by affinities in strong areas of one or the other, ending in lowest affinities in the fields where both countries are weak. This can be seen as a logical pattern of learning and teaching, and a rational way of competence building. The pairs France-United States, France-Germany, United States-Germany and United Kingdom-Japan, follow this pattern.

An alternative pattern when the pair of countries exhibits the lowest affinity in the field of strength of one of the partners. The typical example of this pattern is seen in the Germany-Japan relation where exceptionally low affinities are observed in Japan's fields of strength. Other examples are United States-United Kingdom, and Japan-United States. In such combinations, either Japan or the United Kingdom is reluctant to cooperate in their fields of strength, or their partners do not wish to act as "pupils".

A clear master-pupil pattern is observed in the France-Japan relationship. Their PAI is the highest in the fields of strength of France, and the lowest in those of Japan. Japan seems to profit from the scientific excellence of France in selected areas, while France seems to be reluctant to act as a pupil, or Japan as a professor. The hypothesis of "master-pupil" behavior at the macro-level requires the use of additional indicators such as researcher mobility and qualitative data before any conclusions are drawn, but as far as Japan and France are concerned, some research tends to confirm this type of collective behavior.[46,47] Generally, Japan collaborates either in the strong field of its partner or in the fields of force of the two, as if it intends to profit from the partners' competencies to reinforce its own position. The United Kingdom shows, to a lesser extent, a similar behavior of learning attitude in collaboration. A contrasting behavior is that of France which frequently creates the strongest scientific ties in its fields of specialization. Germany also shows this pattern.

Conclusions

Probabilistic Affinity Index enables a second-order detailed description of coauthorship relations to be determined at first-order by size effects. It is appropriate to detect underlying phenomena sometimes obscured by gross exchanges figures. The complementary analyses in terms of volume and PAI give interesting insights on international collaboration networks. Our conclusion is threefold:

1. *Area of political and cultural influence* is probably still the most accurate predictor of scientific network for the five countries examined. Scientific relationship can stem from a former imperial relationship, a linguistic community, or contemporary geopolitical or economic interests. The five countries studied have in common an experience of colonial or dominating political influences. Geographical and historical determinants interact in complex ways. Geographical proximity can be determinant in a situation where the linguistic/cultural factor is considered as invariant.[48] But in cases where a cultural difference exists, the geographical factor is frequently masked by the cultural factor. For the three European countries networks are quasi-polar. Preferential linkages within the zone of influence, which bears the imprint of history and culture, reinforce weak mutual interactions among the three countries despite geographical proximity and the partnership within the European Union. Geographical proximity is also a matter of interpretation, since the Pacific Rim may, in a sense, be considered as a natural neighborhood of the United States.

2. *The limits of "continentalization" in Europe.* A remarkable aspect of the European PAI pattern is its stability over the period under study, especially considering the sensitivity of this measure. A basic explanation would find its roots in either the historical implications or geographic constraints. The historical inertia also seems to curb the continentalization process put forth by *Leclerc & Gagné*[22] on 1990 data. The strongly voluntarist process at work in the European Union still seems far from ineluctably bringing about a homogeneous collaboration space, although some indications of convergence exist for other criteria. The mutual affinities of the trio show only a slight improvement between 1986 and 1996. In contrast, a changing pattern is clearly noted for small countries within the European Union. This aspect deserves further study.

3. *The effect of specialization.* We also conducted a field-level analysis to sketch the relation between cross-specialization and probabilistic affinities. Is collaborative intensity affected by the perception of the relative strengths and weaknesses in particular fields? The conclusion is not clear-cut. The "co-option behavior" appears as the prevailing pattern of collaboration, whatever the specialization profile of two countries. To a certain extent, this pattern may be reinforced by the size and visibility effects. A typical "solidarity" pattern is less frequently observed. An interesting behavior pattern, the "master-pupil" relationship is also analyzed. Some countries are willing to take the role of "professor", or are reluctant to act as pupils (France, Germany), while others prefer the "pupil" role (Japan, sometimes the United Kingdom). The field-effect does not seem to alter the order of influence of various factors on international cooperation, i.e., first, co-authorship size of partners; second, cultural factors; third, geographic

proximity. But in some relationships, France-Japan being the best example, adopting or rejecting a dependency attitude can bring a significant modulation to these fundamental factors.

Further analysis of scientific collaboration could rely on econometric models, such as gravitational models used in international trade, or the kindred regression model quoted above. However, interaction patterns between geographical and cultural or economic factors are country-dependent. The difficulties of such formalizations root in this complexity.

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