Research centers of the world: Strength, networks and nodality. An analysisbased on bibliometric indicators

Christian Wichmann Matthiessen, Annette Winkel Schwarz & Søren Find

Abstract

This paper is the first presentation of the major research metropoles of the world in terms of research strength, interrelations and nodality within the global research networks. The data are papers in Science Citation Index 1996-98 produced by authors from "greater" urban regions of the world analyzed in general terms using indicators as coauthorship and citings. The recent shifts in the industrial geography combined with the advancement of regional and urban competition set focus on different themes. The importance of the knowledge base in regional and urban competition is generally recognized although relations between urban and regional economic growth and knowledge level are far from clear. The nine top-level international research nodes of the world are Amsterdam-Hague-Rotterdam-Utrecht, Basel-Mulhouse-Freiburg, Copenhagen-Lund, Genéve-Lausanne, London, Mannheim Heidelberg, Montreal, Paris and theSan Francisco Bay Area. When also counting national links five other centers find their way into the top-level as research nodes, Baltimore, Boston, Los Angeles, New York and Philadelphia. Most United States centers of prominence are more national oriented than most of the European cities as are most of the centers of Great Britain and Germany.

Keywords

Research, urban systems, metropolitan competition, networks, bibliometric method.

Christian Wichmann Matthiessen, Institute of Geography , University of Copenhagen, Oster Voldgade 10 DK 1350 Copenhagen K.
e-mail: cwm@geogr.ku.dk
Annette Winkel Schwarz & SørenFind , Technical Knowledge Center of Denmark, Postbox 777 DK 2800 Lyngby.

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Universities, research institutions, firms and leaders of (large) urban agglomerations interact at a growing rate in creating a solid knowledge base for their city. They do so because they share the view that the local knowledge base is of increasing importance for urban economic growth and change. They also do so because a high and growing level of investments in research and development is worthwhile for activating the region. And they do so in spite of a their belief that distance plays a less and less important role and that access to information is almost universal in the "information society". There has indeed been a remarkable decrease in communication and transportation costs in the latest decades, giving way to networking over long distances. And if one asks scientists about their individual pattern of contacts they will often point out that it is international or even global. But when summarized for scientists of a given region it turns out that the "gravity model" gives the best explanation of contacts with other regions. This implies that short physical distance between scientists is still an important criterion for cooperation. Synergies between ideas and direct face to face communication between scientists still are major factors of productivity (Andersson & Persson, 1993). So is economy of scale in the successful development of ideas (Zhang, 1994).

"Cities and regions are being profoundly modified in their structure, and conditioned in their growth dynamics, by the interplay of three major interrelated, historic processes: a technological revolution based on information technologies, the formation of a global economy that works as a unit in a worldwide space for capital, management, labor, technology and markets, and the emergence of a new form of economic production and management characterized by the fact that productivity and competitiveness are increasingly based on the generation and distribution of new knowledge" write Castells & Hall (1994) in their book on technopoles of the world. In their Swedish study on urban growth Andersson, Anderstig & Hårsman (1990) link innovation capacity and high economic growth rate on the municipality level and find a clear positive relation. We assume that a solid knowledge base is reflected in the economic life of a given city, and the assumption is founded on examples like the location pattern of the pharmaceutical industry, the Cambridge Phenomenon (Wickstead, 1985; Keeble, 1989) and the Silicon Valley experience (Hall, 1997).

Castells & Hall (1994) remark that no region can prosper without some level of linkage to sources of innovation and production, and that a new industrial geography with different levels of specialization and diversity of markets is advancing rapidly. In a world economy whose productive infrastructure more and more is made up by information flows, cities and regions are increasingly becoming critical agents of economic development. Cities and regions thus throw themselves into the roles of entrepreneurs. Their leaders want to engage their local area in competition by attracting new activity in the form of investments and visitors (Berg, Braun & Meer, 1998). They also want to establish the best framework for local firms, which are the real competitors. The strengths and structural characteristics of individual regions are often grouped in broad themes under different headings. One of these groups is inevitably marked as creativity or categorized under related headings as knowledge, innovation or research and development.

Scientific wealth can be analyzed in terms of the fast growing number of research papers and documents. Nations are often taken as units of analysis since statistics are presented on a national scale and can be used as input data. Another reason is that many quantitative studies of research production use the large bibliometric data banks directly. When doing so, the obvious registration unit is again the nation, because it is easy to identify the nation in the address of the author of a given publication. May (1997) presented an overview of scientific wealth of nations and pointed out that level of productivity was different as was profile of specialization. But in a world of rising importance of regions and cities as sites of competition and as producers of strategic plans it is also of interest, especially for investors, local planners and people "selling" cities to identify comparative positions in scientific strength. The university as a knowledge source for local or regional spin-off has rarely been investigated empirically, write Geenhuizen, Nijkamp and Rickenberg (1997), but evidence based on analysis of coauthorship (Andersson & Persson, 1993) suggests that local and regional spin-off is an important factor for economic development.

The recent shifts in industrial geography combined with the advancement of regional and urban competition set focus on different themes. In this paper research strength of the major research metropoles of the world is analyzed in general terms because the importance of this theme in regional and urban competition is generally recognized although relations between urban and regional economic growth and knowledge level, as mentioned above are far from clear. The present paper analyses the scientific strength and the interrelations between the centers using indicators such as coauthorship and citations. The aim is to identify the research s of the world defined as nodal cities, which gives access to large research networks, and who plays important roles in the research community of the world. A spacious geographical urban delimitation is combined with a systematic use of Science Citation Index (SCI)[1] to elaborate a reasonably significant list of important research centers measured by research output registered

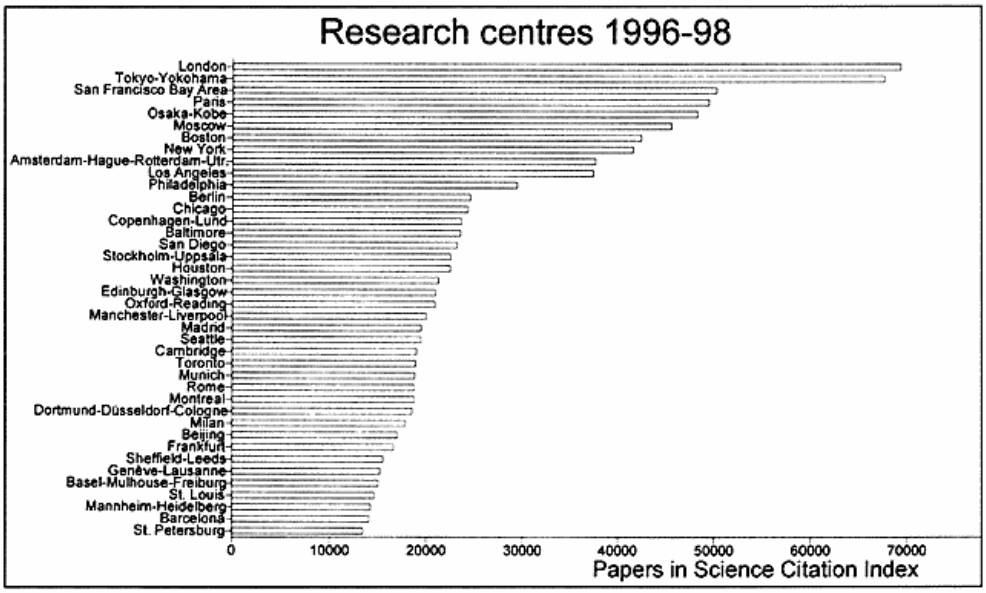

Figure 1: Top-40 research centres of the world. Ranking based on number of papers produced by authors located in city.

under the address of author's institution. Data compilation on research is discussed in reports from Eurostat and OECD and the method used here is related to this work[2]. The analysis covers the urban units presented in figure 1. They represent the largest scientific centers of the World, measured by output of SCI-registered papers 1996-98 in science, medicine and engineering with all the biases and problems inherent in this type of data. International bibliographic databases are useful tools for study of many aspects of the international research system, but the data are not unproblematic, due to various biases of coverage, to different publication patterns in different disciplines and to technical intricacies, like multiple authorships[3] (Schwarz et al., 1998). Some analysts find it impossible to evaluate scientific productivity on the basis of publication and citation data. We obviously do not share such an opinion. Our conclusion is that analyses based on bibliographic data can give indications (but indications only) of a quantitative nature, but that interpretations must be seen in the light of the shortcomings and biases inherent in the data.

Delimitation of urban units

There exists no easy way to obtain comparable data on large cities. National statistical offices delimit urban units by different philosophies, postal services do not provide lists of place names or postal numbers clustered to comparable functional urban units. Series of attempts at constructing a European counterpart to the metropolitan region concept of the United States are still short of results which can be used for the purpose of comparing the scientific base of large cities. NUREC (1994) works on this, and so do other organizations, like the Reclus-Datar group (Reclus-Datar, 1989; Cattan et al, 1994). This French group has done the original work on categorizing and analyzing the urban system of the European Union. In general the closest one comes to a generally accepted definition of the urban unit is the United Nations' *urban* area concept, but it is purely physical and based on distance between buildings. This widely used UN-definition is actually an anachronistic delimitation of greater urban units, especially when it comes to comparative studies, because distance between buildings does not determine function, although distances influence function. Extension and density in urban regions differ due to tradition, legal factors, physical layout, and development stage.

In default of a general formal or functional definition, we have used a spacious physical concept as the basis for identifying a borderline for each large agglomeration conceptualized as a "greater"-urban region. We have used the NUREC-concept and thus added neighboring local units to the urban area defined by the UN-method, and further added additional local units if densities of urbanized areas on detailed topographical maps indicated suburbanisation. We have checked this with population figures to find an acceptable extension of the single agglomeration. Outside the NUREC-atlas area delimitations are estimates. Homogeneity of estimates has been given priority but no precise method has been used. We have further combined neighboring agglomerations to units when transport time between city centers is below 45 minutes. This way of delimiting units in a rather spacious manner and using a strict rule to aggregate the units thus established combines similar cities which interplay at large (for example the units of the Rhine-Ruhr area), but also puts together dissimilar cities of little interplay (for example Oxford and Reading). We have been careful not to let our different level of knowledge on the cities influence the exercise.

Research Output: Mega-cities of the World

The top-40 research centers are listed and ranked in figure 1. Concentrations of research output form a distinct pattern, with North America, the northwestern part of Europe, and Japan in dominating positions. 10 urban regions constitute the top level when it comes to research output. London and Tokyo-Yokohama are outstanding as number one and two. They are followed by the San Francisco Bay Area, Paris, Osaka-Kobe, Moscow and Boston. Also New York, Amsterdam-Hague-Rotterdam-Utrecht and Los Angeles join this super-league (to use terminology from sports). The next group of 8 metropoles is lead by Philadelphia and Berlin followed by Chicago, Copenhagen-Lund, Baltimore and San Diego. Also Stockholm-Uppsala and Houston belong to this primary league. The rest of the cities on the list form a secondary league (to stay with sport language) with 22 participants. This group is dominated by European cities. Also 3 United States centers and 2 Canadian cities are found here together with Beijing and St. Petersburg.

National patterns of concentration are obvious, relating to differences in policy over centuries. Nations with a tradition of urban concentration, like France and Russia, demonstrate a very centralized pattern of research output, and nations with a tradition of deconcentration like Germany, Great Britain and the United States demonstrate a decen-

tralized pattern also for the production of research results. There are also clearly differences effected by university location policy, ranging from the university-town or campus philosophy, with Cambridge as an example, to the capital-city university structure with Washington, Rome and Madrid as examples. Size of research output of a city measured by number of papers produced by scientists located in the greater urban area itself, clearly demonstrates a pattern that deviates fundamentally from the way the large cities of the world generally are conceptualized. Even relatively small cities by population like Cambridge or Stockholm-Uppsala present themselves as very large centers when it comes to research output. Clearly a pattern of economic development stage is also reflected in the ranking of the centers. What must be remarked too is the very high number of large research centers located in Great Britain and the United States.

To obtain this list of the top-40 cities of the world measured by research output we have tested many other cities in order to do justice to all. For the European centers we have registered output 1996-98 for the 39 centers which ranked highest 1994-96 (Matthiessen & Schwarz, 1999) measured by methods similar to the one presented here. The European cities are ranked almost identically in 1994-96 and 1996-98, and the list in figure 1 excludes cities like Zurich, Brussels-Antwerp, Vienna, Helsinki, Lyon and a series of East European metropoles. They are simply not large enough in research output to find their way into the global top-40 list.

For the rest of the world 31 centers have been measured, but only 18 found their way into the top-40 list. Centers like Auckland, Dallas, Denver, Detroit, New Delhi, Singapore, Sydney and Tel Aviv are not large enough to enter this list. For the years 1996-98 Science Citation Index registers 2.768.615 papers on a world base. Out of these large number of papers the 40 largest centers presents 1.071.716[4]. The dataset for analysis in the present paper comprehends these 40 cities. It registers output measured as papers, coauthorship between authors from each pair of cities and citations from authors in all cities to authors in the other cities.

Research Cooperation: Coauthorship Patterns

The way researchers work together takes many paths and reflects cooperation on different levels and of different types. With the focus on intercity links we use coauthorship between authors from different cities as an indicator and presents two analytical steps. Intercity coauthorship in general terms reflects the total of national and international patterns, while intercity coauthorship between researchers in different cities from different nations indicate the international pattern. The interaction pattern of researchers mirrors the flows of ideas and reflects attraction patterns and traditions of cooperation. It is influenced by similarities and differences of many types and also reflects different kinds of barriers for contacts. Research cooperation contributes to the status of a given city and demonstrates the nodal position of the centers in question. The geography of coauthorship is indicated on two similar map-type diagrams[5]. Observed coauthorship is linked to expected level of coauthorship between scientists of two cities estimated from statistical averages across intercity links considered[6].

Total intercity coauthorship numbers 186.445 cases and the major links are demonstrated in figure 2, where links of 200 percent or more of the expected coauthorship between two cities are indicated. The diagram is dominated by national intercity-links within the United States with major nodes being Boston, Los Angeles, the San Francisco Bay Area, New York, Philadelphia and Baltimore. National patterns of Great Britain and Germany are also evident and some additional strong urban interrelations within-nations are presented by Canada, Japan, Russia, Spain, Italy and Switzerland. A number of international links within Europe demonstrate a more international perspective than the American one except for Great Britain, whose scientists are as nationally focused as the researchers from the United States. Important European nodes are cities like London, Genève-Lausanne, Mannheim-Heidelberg, Basel-Mulhouse-Freiburg, Munich and Berlin. Only two intercontinental links are strong enough to be indicated on the diagram. The 12 centers mentioned above represent the top-level of intercity relations of coauthorship and are thereby characterized as major nodes in terms of the total (national plus international) research network.

International intercity coauthorship numbers 115.473 cases and the major links are demonstrated in figure 3, where links of 140 percent or more of the expected international coauthorship between two cities are indicated. The diagram differs fundamentally from the diagram in figure 2. European cooperation dominates the picture of strong international interrelationships, and only few (8) strong links are intercontinental. The highest level international nodes comprise Genéve-Lausanne, London, Paris and Amsterdam-Hague-Rotterdam-Utrecht followed by Basel-Mulhouse-Freiburg, Mannheim-Heidelberg, Copenhagen-

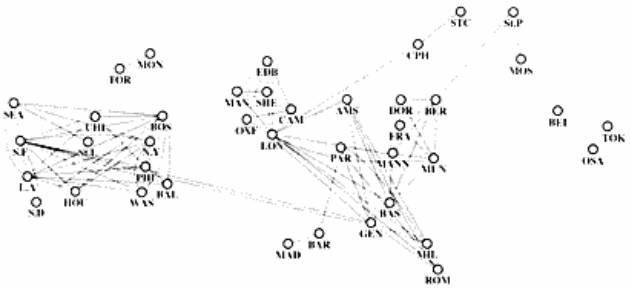

Figure2: *Intercity coauthorship. Total of national and international links larger than 200 percent of the expected volume indicated (expected volume is defined in not 6)*

Lund, Montreal, the San Francisco Bay Area and Rome. These 10 centers are the strongest nodes in the international intercity relationship pattern of coauthorship.

Leaders and Followers: Citation Patterns

Researchers cite other researchers when they use results, discuss papers, reflect on or criticize methods and findings. Many motivations lie behind the way people cite other people. We assume that the overall pattern of citing reflects or indicates mutual respect for the cited paper although there are other motives for citing. The pattern of citing reflects many underlying structures like distance, language, nationality, religion, culture, economic blocks and even friendship (there are notorious examples of "clubs" of mutual citing). Citing traditions differ from discipline to discipline, from university to university and between the university world and other producers of research output, like private enterprise, public institutions and organizations. An idea or result might be so advanced or untraditional that it is not immediately or generally understood as a break-through, and thus nobody cites the paper. The profile of citing patterns is very complicated but in our opinion analysis of citing patterns anyway gives a meaningful presentation of leaders and followers. The mere number of citations in the dataset is so large that it can comprehend a lot of such noise in the data. We count a total of 1.425.779 citations in the dataset of which 1.000.985 are international[7]. The total number of papers in the same dataset is 1.071.716 and in average each paper is cited 1,36 times by authors from other cities and 0,98 times by authors from other cities located in other nations. The period of publishing and of citation is 1996-98 which implies that citing is expected to be lower for the newest of the papers than for the older ones. The analysis of citing links aims at identifying leading cities to give an additional characterization of research pattern.

In figure 4 average citations by authors from all other cities to papers from the cities indicated are ranked by citation-receiving cities. The variation of citing is large. Papers from the most cited unit San Diego are on the average cited 2,3 times and papers from the least cited city Beijing are cited 0,3 times. The leading citation receiving cities mostly are located in the United States and also in the north-western part of Europe. The very top level belongs to the US-cities San Diego, St. Louis and Seattle. They are closely followed by the European centers Mannheim-Heidelberg, Cambridge and Basel-Mulhouse-Freiburg. The top level also includes Baltimore, the San Francisco Bay Area and Boston. The mid level presents cities located all over the world, and the bottom level of low ranking cities comprises units from Spain, Japan, Russia and China. Close to the bottom end of the list we also find three old European manufacturing centers.

To eliminate the national factor of citing we present a ranking of the cities based only on citations from authors based outside the nation of the city in question[8].Average number of citation per paper span from 1,7 (Basel-Mulhouse-Freiburg) to 0,3 (St. Petersburg). The ranking is presented in figure 5. As expected, this ranking clearly differs from the ranking in figure 4. Cities within smaller nations get more prominent ranks and European cities are generally better positioned than cities from the United States. The highest ranking US-city San Diego is thus located on the 14th place of the list. San Diego was number one on the list in figure 4. The top level contains Basel-Mulhouse-Freiburg, Genève-Lausanne, Cambridge and Mannheim-Heidelberg closely followed by Toronto, Oxford-Reading and Montreal. The top level also counts Stockhol- Uppsala, Amsterdam-Hague-Rotterdam-Utrecht, Copenhagen-

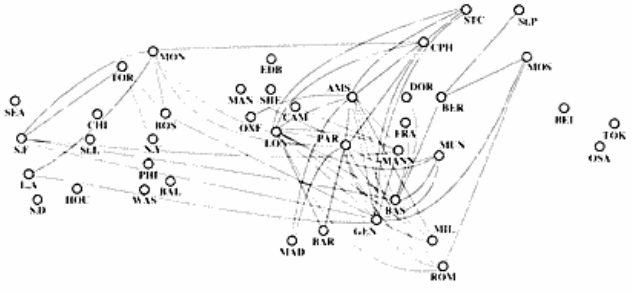

Figure3: *Intercity coauthorship. International links lager than 140 percent of the expected volume indicated (expected volume is defined in note 6)*

Lund and Edinburgh-Glasgow. The middle part of the list gives place to North American and European centers. The bottom end is dominated by Japanese, Chinese and Russian cities.

The next analytical step was to incorporate the volume of citations and combine it with the average number of citations per paper. The way research centers draw attention from other researchers is, as mentioned, influenced by many factors, one being the quality profile of research. A given city can present a uniform quality level for all disciplines of science or it might have disciplines of high and low quality represented in its profile. The latter combination is probably normal although some centers presents high quality research over the whole spectrum of disciplines and other centers only have few disciplines of high quality. Because of these differences the total volume of citations is assumed also to provide meaningful information about the pattern of mutual respect and links of innovation and thus to indicate level of research leadership. This is demonstrated in two diagrams one with national plus international intercity citations the other with intercity citations only from researchers in other countries.

City to city pattern is demonstrated in figure 6 showing the nodal cities (in terms of total citations) which are identified with their international status only part of the picture. Three clusters of leaders can be identified. Group 1 is composed of 7 cities of very high impact (measured as average citation rate of their publications) and medium level of total number of citations. This group comprises San Diego, Seattle, Baltimore, St. Louis, Cambridge, Mannheim-Heidelberg and Basel-Mulhouse-Freiburg. Group 2 presents high impact and very high total volume of citation to the 3 cities of the group, the San Francisco Bay Area, Boston and New York. Group 3 combines moderate impact of citations with high total volume. The five members of group 3 are London, Los Angeles, Philadelphia, Paris and Amsterdam-Hague-Rotterdam-Utrecht. The United States' dominance in these 3 leading categories of cities reflects the pattern of a very large volume of citations within USA. This pattern is also present within Germany and Great Britain, but not at the intense American level.

The international dimension of citation patterns is presented in the diagram in figure 7, where within-nation citations are deducted from the total. The picture of leading cities on the international scene differs from the pattern derived from total citations. Four high-level categories of international centers are identified. Group 1 presents very high impact of papers and a medium volume of total citations. This leader category has 4 member cities, all European, Basel-Mulhouse-Freiburg, Cambridge, Genève-Lausanne and Mannheim-Heidelberg. Group 2 is composed of centers of high impact and medium number of citations. Members of the group are 6 cities, Toronto, Oxford-Reading, Montreal, Copenhagen-Lund, Stockholm-Uppsala and Edinburgh-Glasgow. The third category is of high impact and large volume of citations and has one member only, Amsterdam-Hague-Rotterdam-Utrecht. Group 4 represents moderate impact and high number of citations. This category has 4 members, London, Paris, the San Francisco Bay Area and Baltimore. The four types of leader-cities are largely European dominated, and only 4 cities from North America achieve a position as international nodes with this approach.

Summary and Discussion

In this paper we have identified the 40 largest research centers of the world measured in general terms of research output. The pattern of cooperation and the pattern of citing between these large units have been analyzed and we have looked at two dimensions of cooperation and innovation links. One dimension is represented by the total of intercity-relations, the other by the international parts of these links. Synthesizing the analysis to a simple picture of the major global system and identifying nodes of research is as complicated as all summaries of categories are.

The primary categories of research centers are presented as two top-level groups, one comprising the nodes in the network measured as total links, the other identifying the international nodes. When the *total* of national and international intercitylinks are summed up we can identify eight major nodes in the dataset. They play prominent roles, although some of them are more engaged in national than in international networks. The eight cities (mentioned in alphabetical order) are Baltimore, Basel-Mulhouse-Freiburg, Boston, Los Angeles, Mannheim-Heidelberg, New York, Philadelphia and the San Francisco Bay Area. When we turn to the *international* dataset and point out the international centers of the research networks, we find nine nodal cities on the highest level, Amsterdam-Hague-Rotterdam-Utrecht, Basel-Mulhouse-Freiburg, Copenhagen-Lund, Genève-Lausanne, London, Mannheim-Heidelberg, Montreal, Paris and the San Francisco Bay Area. Three cities perform high-level nodal functions measured in total as well as international, Basel-Mulhouse-Freiburg,

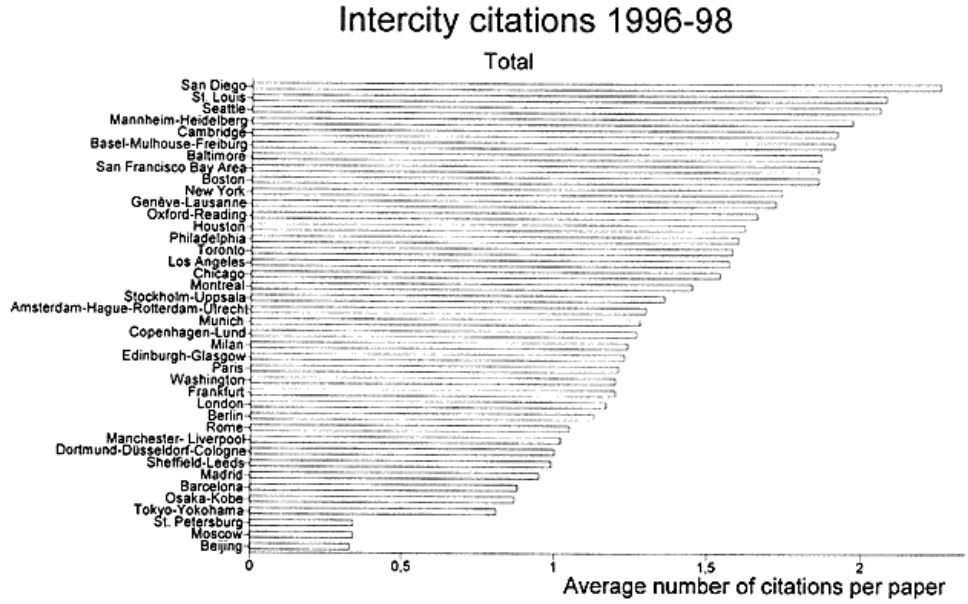

Figure 4: *Ranking of cities by leadership. National plus international links indicated.*

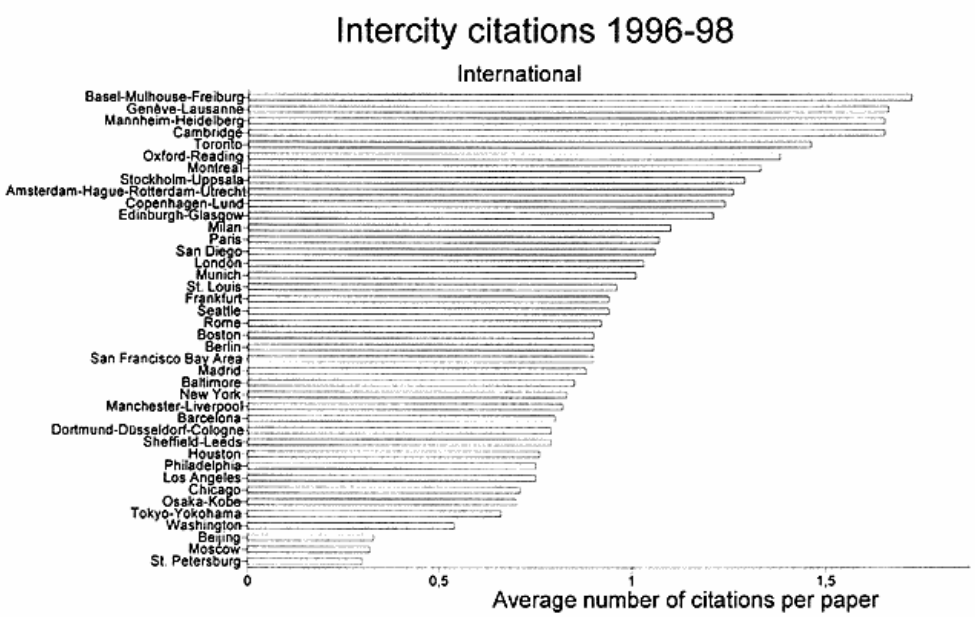

Figure 5: *Ranking of cities by leadership. International links indicated.*

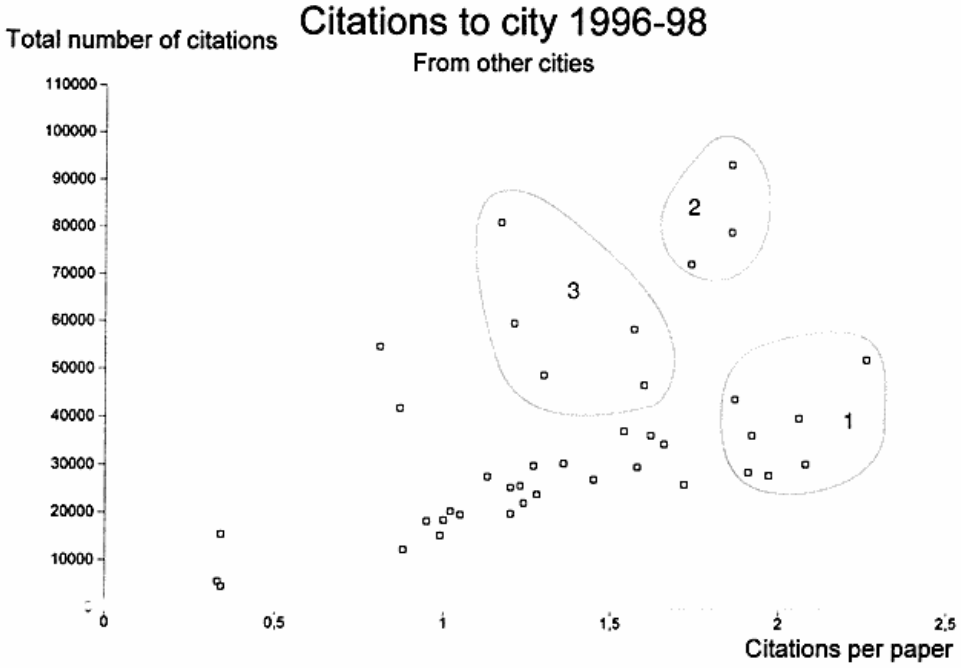

Figure 6: Level and impact of leadership. National pluds international citations.

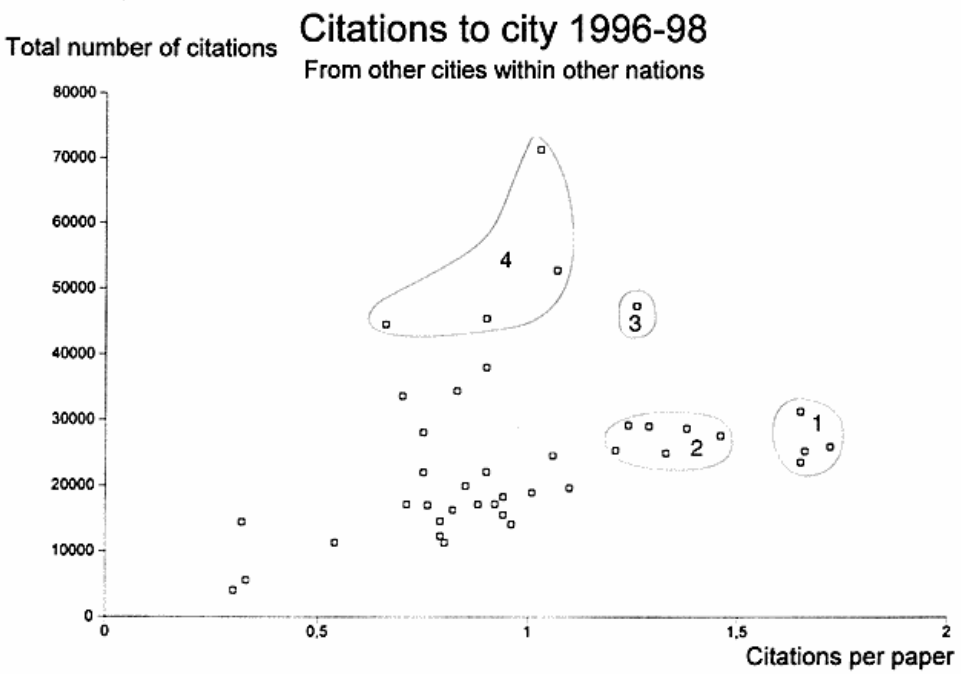

Figure 7: Level and impact of leadership. International citations.

Mannheim-Heidelberg and the San Francisco Bay Area. Altogether 14 cities (the ones mentioned above) are found to be major nodal points in the world measured either in total or in international terms.

A second level of centers are also identified and the secondary nodes of the *total* research network consists of ten cities, Amsterdam-Hague-Rotterdam-Utrecht, Berlin, Cambridge, Genève-Lausanne, London, Munich, Paris, San Diego, Seattle and St. Louis. The seven secondary level nodes of the *international* research network are Baltimore, Cambridge, Edinburgh-Glasgow, Oxford-Reading, Rome, Stockholm-Uppsala and Toronto.

Nodal function of the large research centers have not been directly linked to their economic performance in this paper, but the structure of - and the links within - the network of research represent important aspects of contemporary economic geography and give rise to some additional observations. The picture demonstrated in this paper indicates that economic and political connections, language and distance play roles for the pattern of research networks. By analyzing the dataset we further find that even for this major research centers, national links in general overweigh international links. We also find a much more nationally centered pattern of links within the United States and Great Britain than we expected tentatively. And we observed that centers of small European nations like Switzerland, the Netherlands and Denmark plays important roles as international nodes. We also found that the cross-border metropolitan agglomerations were prime international research centers. Many of the findings need further research to be presented as facts, but the indications are clear.

Notes

1. Science Citation Index (SCI) is a database produced by the Institute for Scientific Information (ISI, Philadelphia, PA) along with a number of related products. It records, for over 5600 journals leading in their field, and for a large number of conference proceedings and other research publications, all contributions with full bibliographic description, all authors with affiliations subject codes for journals all references (citations) to the research literature. The online version is available as "SciSearch" in major hosts, e.g. DIALOG and STN. Details are given on http://www.isinet.com/products/citation/citsci.html. Recently, a version with extended search facilities has been launched as "Web of Science". Details are given on http://www.isinet.com/prodserv/citation/wosprev.html. There is a large literature on applications of these databases. A number of indicators useful for comparative analysis of R&D productivity, and of problems related to data analysis are discussed in Schwarz et al (1998).

2. Several publications contain definitions and recommendations concerning data compilation with a view to establish indicators for uniform and internationally comparable measures of input, processes and output of regional R&D and innovation. Starting from OECD handbooks on national indicators, in particular the "Frascati Manual" (OECD 1974), and the "Oslo Manual" (OECD 1992) the reports extend the scope to cover regional aspects (EUROSTAT, 1996 and 1997).

3. Multiple authorship is registered so that each author carries one bibliographic unit. This implies that papers with several authors counts as equally many items in the statistics. While distorting the actual count of papers produced, it accounts for the collaboration links in terms of persons involved.

4. The two figures can not be compared as papers with authors from more than one city are registered on all cities in question.

5. The position of the cities on these maps is not in any way precise. Latitude and altitude, scale and direction differ all over the maps. Distances between cities of different nations are as a rule of thumb indicated larger than distances between cities of the same nation. The maps only give primitive but recognizable gross pictures of the world.

*6. For each of the (40*39)/2 = 780 pairs of cities the number of observed co-publications is COPUBi , where i = 1,...,780. The number of publications in the town with the smallest number of publications of the two in each pair is PUBSMALLi , i = 1,...,780. The number of expected co-publications COPUBEXPi is then calculated as: COPUBEXPi =SCOPUBi * (PUBSMALLi / Σ PUBSMALLi), where i = 1,...,780.*

7. Citations to a paper with coauthorship is counted as one for each participating city. Thus, a citation to a paper with two authors from Berlin and one from Paris, is counted one for Berlin and one for Paris.

8. Urban units with parts located in more than one nation are reduced by within same country citations (Basel-Mulhouse-Freiburg reduced with German citations to Freiburg, French to Mulhouse and Swiss to Basel)

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Notes

1. Science Citation Index (SCI) is a database produced by the Institute for Scientific Information (ISI, Philadelphia, PA) along with a number of related products. It records, for over 5600 journals leading in their field, and for a large number of conference proceedings and other research publications, all contributions with full bibliographic description, all authors with affiliations subject codes for journals all references (citations) to the research literature. The online version is available as "SciSearch" in major hosts, e.g. DIALOG and STN. Details are given on http://www.isinet.com/products/citation/citsci.html. Recently, a version with extended search facilities has been launched as "Web of Science". Details are given on http://www.isinet.com/prodserv/citation/wosprev.html. There is a large literature on applications of these databases. A number of indicators useful for comparative analysis of R&D productivity, and of problems related to data analysis are discussed in Schwarz et al (1998).

2. Several publications contain definitions and recommendations concerning data compilation with a view to establish indicators for uniform and internationally comparable measures of input, processes and output of regional R&D and innovation. Starting from OECD handbooks on national indicators, in particular the "Frascati Manual" (OECD 1974), and the "Oslo Manual" (OECD 1992) the reports extend the scope to cover regional aspects (EUROSTAT, 1996 and 1997).

3. Multiple authorship is registered so that each author carries one bibliographic unit. This implies that papers with several authors counts as equally many items in the statistics. While distorting the actual count of papers produced, it accounts for the collaboration links in terms of persons involved.

4. The two figures can not be compared as papers with authors from more than one city are registered on all cities in question.

5. The position of the cities on these maps is not in any way precise. Latitude and altitude, scale and direction differ all over the maps. Distances between cities of different nations are as a rule of thumb indicated larger than distances between cities of the same nation. The maps only give primitive but recognizable gross pictures of the world.

*6. For each of the (40*39)/2 = 780 pairs of cities the number of observed co-publications is COPUBi , where i = 1,...,780. The number of publications in the town with the smallest number of publications of the two in each pair is PUBSMALLi , i = 1,...,780. The number of expected co-publications COPUBEXPi is then calculated as: COPUBEXPi =SCOPUBi * (PUBSMALLi / Σ PUBSMALLi), where i = 1,...,780.*

7. Citations to a paper with coauthorship is counted as one for each participating city. Thus, a citation to a paper with two authors from Berlin and one from Paris, is counted one for Berlin and one for Paris.

8. Urban units with parts located in more than one nation are reduced by within same country citations (Basel-Mulhouse-Freiburg reduced with German citations to Freiburg, French to Mulhouse and Swiss to Basel)

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