Paper to be presented at the DRUID 2012

on

June 19 to June 21

at

CBS, Copenhagen, Denmark,

How Large Scale Research Facilities Connect to Global Research

Giancarlo Lauto
CBS
INO - Research Centre on Biotech Business
gl.ino@cbs.dk

Finn Valentin
CBS
INO - Research Centre on Biotech Business
fv.ino@cbs.dk

Abstract

We conceptualize Large Scale Research Facilities (LSRFs) established to pursue big-science projects as ?collaboration hubs? that increase the external connectivity of regional innovation systems. We take as our empirical case the Neutron Science Directorate at Oak-Ridge National Laboratory in Tennessee (USA), hosting one of the foremost neutron scattering facilities in the world. Bibliometric analysis of the 589 publications from the facility authored by at least one US-scientist in 2006-2009 shows that LSRFs are indeed powerful hubs in the creation of research networks. Scientists employed at the facility drive a substantial part of the collaborations in this network, but a more important role is played by external scientists affiliated with universities and research laboratories. The latter also show stronger global connectivity, as brought out by regression models of propensities of individual researchers to collaborate internationally. International connectivity is strongest in basic research, and appears to form a trade-off against other drivers of team-internal coordination costs such as social and institutional distances.

Jelcodes:O31,O38

1. Introduction

The increasing dependency of economic growth on knowledge stresses the centrality of science and technology policy for the competitiveness of regions and nations (Lundvall, Borrás, 2004). Research organizations play a key role in systems of innovation as contributor of the cognitive resources that support technological innovation. This contribution comes in a variety of forms (Salter, Martin, 2001): the traditional activities of research and education help building the knowledge base and the human capital of a system of innovation; furthermore, demand for advanced scientific instrumentation stimulates innovation in the suppliers' sector (Rosenberg, 1992); scientists' expertise supports firms in technological problem-solving; scientific discoveries fuel high-technology entrepreneurship (Audretsch et al., 2005). The studies on the geography of innovation have emphasized that spillovers of scientific knowledge tend to remain spatially constrained and – provided that the industrial system is characterized by an adequate level of absorptive capacity and sectorial specialization – sustain the generation of innovation (Feldman, Kogler, 2010).

Besides connecting applied research to technological development, research organizations matter for regions because they provide access to the global sites of production of scientific knowledge. Scientific knowledge is characterized by the possibility of being transferred across different places of production and application maintaining its meaning unchanged by virtue of its more abstract and universal nature (Asheim et al., 2011). Indeed, the increasing interconnectedness of scientific research has been demonstrated by numerous studies, focusing primarily on the macro-level, taking countries or disciplines as units of analysis (e.g. Abbasi et al., 2011). While engineering-based innovations benefit from exchanges of tacit knowledge that are favored by personal interaction and physical proximity (Arundel, Geuna, 2004), scientific knowledge provides the basis for more path-breaking and science-based innovations (Fleming, Sorenson, 2004). The connectivity of a research organization to the global scientific community helps establishing knowledge flows that increase the variety of knowledge base of a system of innovation preventing cognitive lock-in and increases the variety of human capital (Bathelt et al., 2004). Accordingly, policy tools have been developed with the purpose improving the scientific capacity of system of innovations through collaborative networks (Melkers, Wu, 2009).

This literature has provided us with a clear understanding on the impact of research organizations on regional systems of innovation. However, universities are the prevailing institutional type of research organization analyzed by these studies. Within public research organizations, knowledge production in universities is organized according to different principles than in government laboratories regarding e.g. institutional goals, control and reward systems (Whitley, 2000). The present paper examines Large Scale Research Facilities (LSRFs) established to pursue 'big science' projects. Despite their particular organizational features and their very large resource requirements LSRFs are strikingly under researched.

Compared to university settings, scientific collaboration in LSRFs is institutionalized, giving less room to spontaneous interactions among scientists. Due to the sizeable financial resources required to establish and run the facilities, LSRFs depend on the sponsorship of governments, who often mandate such facilities within broad policy goals, such as foreign policy or national defense, or to specific public missions, e.g. energy or health (Wagner, 2006). As we will discuss below, the particular features of LSRFs reduce the coordination costs of collaboration, expectedly increasing their connective capacity as compared to other kinds of research organizations. It has been pointed out that the institutional setting characterizing LSRFs in particle physics has driven the diffusion of a participative model of organization of scientific collaborations that appears specific of that field (Chompalov et al., 2002).

LSRFs have been the object only of few studies. Historical accounts have brought out the contribution of civil and military 'big science' projects to the formation of the 'science region' of Silicon Valley (Kargon et al., 1992), and LSRFs have been studied as tools of foreign policy (Flink, Schreiterer, 2010). A small number of case studies examined LSRFs as bridge between academic and industrial research (Langford, Langford, 2000; Peerbaye, Mangematin, 2005), and as procurement stimulator of innovations by suppliers of advanced instrumentation (Autio et al., 2004; Merz, Biniok, 2010). Studies of team organization in LSRFs adhered to a qualitative approach to examine the role of trust to reduce conflict within the team and with the management (Shrum et al., 2001), and describe problem framing and technical practices in the organization of scientific work (Hackett et al., 2004). To the best of our knowledge, no quantitative study has examined the patterns of international scientific collaboration in LSRFs, although precisely that ranks highly in the funding rationale of governments and backing agencies. This paper contributes to filling this gap.

The purpose of this study is to investigate how the role of LSRFs as 'knowledge attractors' for international research collaboration. Drawing on Boschma's (2005) theory on the relationship between proximity and innovation, we study how cognitive, social and institutional conditions affect the formation of international collaborations associated with LSRFs. That allows us to examine how international collaboration is affected by the institutional affiliation of scientists, by the disciplinary profile of research projects, and whether basic-oriented projects attract more international collaborators than do applied studies. Should the latter turn out to be the case, an important trade-off emerges whereby increase in international connectivity of a facility is pursued at the cost of applied investigations that may be of more direct technological relevance to its host region.

To answer these questions, we take as our case of the Neutron Sciences Directorate at the Oak Ridge National Laboratory (ORNL/NSD) in Tennessee (USA), hosting the world's most important facilities for neutron scattering. By means of a bibliometric analysis of the peer-reviewed publications produced in the period 2006-2009, we map the global connectivity appearing from the author information for these publications. While descriptive data on the collaboration patterns from ORNL/NSD is part of this paper, our main analytical effort goes into modeling propensities for global research connectivity associated with general attributes of projects (such as their orientation towards basic vs. applied issues) or with general attributes of scientists' collaboration patterns (e.g. their social or institutional distance).

In our study of this specific LSRF we blend insights from theories in economic geography and management science to examine, with quantitative methods, the micro-level drivers of scientific collaboration, an issue that has generally been investigated with qualitative approaches. Our study is relevant for policymakers involved in the financing and design of LSRFs. In the coming years, new facilities are being implemented while existing facilities are being substantially upgraded (ILL, 2011). Motivated by high expectations in terms of socioeconomic returns, nations and regions compete for hosting these research infrastructures[1]. Design decisions ranging from instrumentation to conditions for access will affect these facilities regarding their connectivity to global research and other key outcomes. Yet, little empirical evidence guides these decisions.

[1] A current example is offered by the policy processes in Scandinavia and at European level to secure the location of a next generation European Spallation Source outside Lund in the Øresund region (ESFRI, 2003).

The remainder of the paper is structured as follows. After outlining the theoretical framework and the hypotheses in the next section, we present the design of the empirical study. We then turn to the analysis of the findings, while the final section is devoted to discussion and concluding remarks.

2. Theory

2.1 Incentives and costs of collaborative research

Our conceptualization of LSRFs as a vehicle for connectivity of regional systems of innovation to non-local sources of knowledge stems from the observation that LSRFs are a peculiar model of organization of scientific research that is explicitly designed to enhance collaborative research above the level of the 'standard' model of academic research (Ponomariov, Boardman, 2010; Wagner, 2006). Research collaboration has two sides, in that it offers not only advantages for specific projects but also various types of costs associated with its coordination. International collaborations represent a special case, where both advantages and costs are exaggerated. As we will see later, the institutional features of LSRFs help reducing coordination costs while maintaining the benefits unchanged.

In their summary of the benefits offered by collaborative research, Katz and Martin (1997) note first that it facilitates division of intellectual work and the pooling of cognitive inputs and expertise (Melin, 2000). Furthermore, it permits the accomplishment of projects that hardly could be realized by an individual investigator, as in multidisciplinary studies that bring together specialists in different areas, and in technology development projects involving academic and industrial researchers (Heinze, Kuhlmann, 2008). Not surprisingly, collaborative research has established itself as the typical model of knowledge production in the large majority of scientific fields (Adams et al., 2005). Zooming in on the specificities of international collaborations, Dahlin et al. (2005) point out that collective problem solving benefits from the mingling of the cultural backgrounds, perceptions and worldviews that are associated to national cultures; however, they recognize that this effect is not as strong as that associated with the combination of different cognitive inputs. Indeed, international connectivity impacts directly on the cognitive dimension, alleviating the dependency of a scientist, or a group, from the pool of scientific knowledge available at local level. It is possible, particularly in cutting-edge studies, that the expertise necessary to effectively carry out the research is owned by scientists affiliated to one of the centers of excellence around the world. The positive impact on internationalization on scientific quality is testified by the higher citation rates obtained by internationally coauthored research (Frenken et al., 2010; Melkers, Kiopa, 2010).

The accomplishment of collaborative projects depends on effective coordination of the research team with regard to a series of intellectual and organizational issues, such as the alignment of the priorities of team members and the execution of investigations, and the definition of roles, organizational routines, and protection of intellectual property (patents and publications) generated by a project (Adams et al., 2005; Cummings, Kiesler 2007).

As we will see in the next section, the coordination costs of collaborative research, international research in particular, can be minimized by building teams in which the members benefit from different types of proximity.

2.2 Proximity as a mechanism of coordination of research collaborations

Boschma (2005) suggests that the outcomes of collaborative innovation are influenced by the proximity characterizing the actors involved, in terms of *geographic, institutional, social, cognitive and organizational* dimensions. An optimal distance along each of these dimensions favors learning and absorption of inputs from external sources, while keeping low the uncertainty associated with their coordination. Boschma sees the cognitive dimension as being more important than the others: a certain level of cognitive proximity is regarded as a precondition in the knowledge production process, while the other dimensions to some extent form mutual substitutes, so that more distance along a given dimension can be overcome by higher proximity along another. In this framework, the *geographic* dimension refers to spatial distance among actors. Spatial proximity permits face-to-face interaction, frequent feedback, non-verbal forms of communication necessary to the diffusion of tacit knowledge, and supports the construction of trust-based relationships. Trust is a key factor in uncertain activities, as it helps thus reducing coordination costs and the risk of opportunistic behavior. The *institutional* dimension refers to formal rules and cultural norms, values and routines that permit coordination of actions of individual and groups through mechanisms of social cohesion. Drawing on Hoekman et al. (2009) and Ponds et al. (2007), we emphasize that the institutional dimension operates at two distinct levels: first, *national systems* as a whole differ from one another depending on elements such as culture, language and legal framework. We refer to this aspect of the institutional dimension as the '*system level*'. Second, organizations belonging to the same '*institution-type*' are characterized by common goals, values and incentive structure that - in strong institutions - are only partially affected by the system level in which they operate. In science, the principal institution-types are universities, research centers, and firms. Each of these research organizations is characterized by specific institutional features that to some extent tend to remain the same in different national systems, hence making it important to decompose institutional effects into the two levels of 'institution-type' and 'system level'. The *social* dimension refers to the social embeddedness of relationships, e.g. those based on friendship, long-term commitment, and experience of repeated collaboration, all of which benefit coordination by restraining opportunistic behavior. The *cognitive* dimension refers to characteristics of the knowledge bases that underpin innovation activities. On the one hand proximity between the different parts of a knowledge base – as in the case of scientists who share the same background and research practices – eases absorption and processing of information, learning and coordination by mutual adjustment. On the other hand, excessive cognitive distance may impede these processes and may lead a team to undertake less risky and imaginative projects, weakening the novelty of outcomes (Hudson, 1996). A balanced cognitive distance permits the exploration of alternative sources of knowledge and leads to original recombination of knowledge (Nooteboom et al., 2007). As we discuss later, features of scientific fields and degree of codification of knowledge affect costs of coordination in collective production of new knowledge. Finally, the *organizational* dimension refers to the governance of innovation activities in terms of reliance on hierarchy and tight relationships vs. markets and loose networks mechanisms. We acknowledge the importance of this dimension, but lack of empirical data on precisely this dimension prevents us from exploring it further in this paper.

We suggest that international collaborations carry higher search and coordination costs compared to their domestic counterpart. In terms of the proximity/distance dimensions highlighted above, these costs refer to the *geographic* and *system level* dimensions. International collaborations typically imply larger physical distance. This means a higher need for resources (in terms of time and travel costs) to achieve a suitable level of direct interaction, as in the cases of scientists meeting regularly in person, or conducting a substantial part of their work at a LSRF. On the other hand, solutions economizing on travel costs – such as the articulation of the projects into 'packages' developed autonomously by researchers who work from remote locations and coordinate exploiting ICT – presents the drawback of not allowing exchanges of tacit knowledge. Furthermore, national specificities at *system level* potentially generate disparities among partners, requiring additional coordination effort, whether scientists work at the same location or not. With regard to the research environment, differences along this dimension concern the structure of academic incentives and criteria of assessment of research at university-level, funding institutions, legal framework, management practices, and language (Adams et al., 2005; Cummings, Kiesler, 2007). The importance of this kind of factors has been proven by evidence on the European context suggesting that national differences impede the formation of research collaboration even after controlling for other factors such as physical distance and language (Hoekman et al., 2010).

We argue that research collaboration is restrained regarding the amount of overall coordination costs it can accommodate without impeding its results. Hence a trade-off exists between the different dimensions of proximity/distance. Increasing distance along one dimension restrains the distance that can be accommodated along the other dimensions. Specifically regarding international collaboration, from this theoretical argument we infer that its distance on the *system level* and the *geographic* dimensions may be offset by reducing the distance along other dimensions. Therefore we expect internationalization to increase with decreasing distance on the cognitive, institutional, or social dimensions.

In this study, we analyze how cognitive, social and institutional distances within research teams affect the level of internationalization of their LSRF-related research.

2.3 LSRFs as mechanisms to reduce coordination costs

LSRFs present a number of institutional features particularly favorable to the establishment of collaborations and to the reduction of their coordination costs. These features can be found only partially in other types of research organizations. First, LSRFs are indivisible resources that combine costly and technologically complex facilities. Since they cannot be reproduced for individual use, scientists are induced to team up in collaborative projects (Katz, Martin 1997); moreover, the use of shared technologies and instrumentation triggers standardization of research practices reducing coordination costs along the cognitive dimension. Second, LSRFs include a permanent scientific staff specialized in research based on the instrumentation of the facility (Ponomariov, Boardman, 2010). The agglomeration of specialized scientific and technical capabilities increases the visibility of the resident researchers in the scientific community. So, whenever a non-resident researcher seeks for competencies in the scientific community, he/she will likely address the search efforts towards more prominent institutions. This aspect is particularly important to foster international collaborations, as scientists cannot rely on their informal knowledge of the local scientific community to identify potential partners: it has been pointed out that visibility of scientists tend to decline with physical distance, so these institutions lower the search costs for physically distant partners (Hoekman et al., 2010). Finally, access to LSRFs is generally granted on the basis of a competitive assessment of the scientific quality of the projects and their relevance for the research strategy pursued by the facility. As we mentioned in the introduction, LSRFs are mission-oriented institutions that contribute to the fulfillment of science policy objectives. Ex-ante this selection reduces the cognitive heterogeneity of projects and scientists, allowing collaborative research to accommodate higher levels of geographic and system level distance in the composition of teams.

On the basis of these characteristics of LSRFs, all of them indicating lower coordination costs, we should expect their research collaboration to be less affected by the various proximity-restraints identified above. The theories on these restraints were developed with reference to collaborative research in other institutional settings (universities and firms, primarily). To our knowledge the present paper is a first attempt to asses if they also hold for LSRFs, a research institution explicitly designed to foster and to build on collaborative research. We test whether internationalization of research collaboration at a specific LSRF is subject to the same proximity restraints as has been identified for other research institutions.

2.4 Hypotheses

With regard to the cognitive dimension, in scientific fields characterized by tight theoretical and methodological coordination, e.g. Physics, scientists share the same priorities and methodologies independently from the organization or the national research system they belong to (Whitley, 2000). The high degree of intellectual coordination reduces the necessity of negotiating goals of experiments and meaning of results. This reduces the coordination costs of collaborative research and makes it easier for scientists affiliated to any research institution around the world within the discipline to participate in a project. It is not surprising that work carried out at big-science labs in Physics is characterized by a higher intensity of collaboration than the average of field (Newman, 2004). Hence Hypothesis-1: *Scientists operating in tightly ordered disciplines – such as in mono-disciplinary investigations in Physics – have a higher propensity for international collaborations*.

Orthogonal to differences across disciplines, other cognitive differences between projects emerge from their orientation towards theoretical investigation vs. technology development. More basic-oriented projects rely on the combination of codified knowledge to a larger extent than do projects addressing technological issues where the tacit component plays a larger role (Asheim et al., 2011). In basic-oriented studies, reliance on fundamental and abstract theories reduces the necessity of negotiating the meaning and relevance of results as compared to technology development projects that needs an ad-hoc application of specific bodies of knowledge. Again, we find a reduction of coordination needs due to the cognitive features of a project. Moreover, as already mentioned, codified knowledge is characterized by better transferability across distant sites than tacit knowledge. This enhances the involvement of non-local scientists in a project. Consistent with these arguments, a positive relationship between internationalization and orientation towards basic issues has been found in many studies (e.g. Abramo et al., 2009). Hypothesis-2: *Scientists who participate in projects investigating more basic issues have a higher propensity to establish international collaborations*.

Turning to the institutional dimension, each type of research organization – universities, research laboratories, firms – represents a different setting as they do research motivated by distinct purposes – respectively, advancing scientific knowledge, providing solutions to issues of social relevance, developing technological innovation – and are characterized by different cultural norms and reward structures (Dasgupta, David, 1994; Whitley, 2000). Multi-institutional projects exploit complementarities among the values and perspectives characterizing each institutional type and are particularly important in fields that investigate issues crossing the traditional boundaries between disciplines and between fundamental and applied research (Heinze, Kuhlmann 2008). However, these differences may give rise to conflicts regarding research strategies and disclosure of results. Personal interaction favors trust-building and hence reduces conflicts arising from diverging institutional values. Similarly, homogeneity of cultural values and acquaintance with the different aspects of a national system lower coordination costs in multi-institutional projects. So, we may expect that geographic and system level proximity matter less in mono-institutional projects and become relevant when different types of organizations are involved. The relationship between geographic, system level and institutional distance has been explored by Ponds (2009) in a study on publications of Dutch research organizations in eight science-based technologies for the period 1988-2004. The study finds that collaborations within academia have a pronounced international scope, while those between academia and non-academic organizations take place at a national scale. Evidence of the contribution of personal interaction to overcome institutional differences is given by Ponds et al. (2007) who find that geographical proximity is more relevant for the establishment of multi-institutional collaborations than among organization of the same type. Hypothesis-3: *Scientists who enter teams that are homogeneous in terms of institutional affiliation have a higher propensity to establish international collaborations*.

From the same argument we may infer that scientists from institutional types with prevalent occurrence also outside the US more easily may find homogenous international partners. That is the case particularly for universities. The plenitude of universities outside the US, combined with their variation in terms of research specialization, provides university scientists with a larger and more differentiated pool of potential international partners. That makes it easier for university scientists to identify useful international partners who, at the same time, offer institutional proximity. To this we may add the effect of the cognitive argument presented above that tacit knowledge favors local knowledge flows (Arundel, Geuna, 2004). The knowledge flows associated with the advanced engineering conducted by the LSRF-internal scientists has a comparatively larger share of such tacit components, hence strengthening its local and domestic orientation. Hypothesis 4: *Scientists employed by a LSRF have lower propensity for international collaboration than scientists employed by universities.*

Furthermore, a particular institutional position is represented by scientists who are affiliated to organizations with different institutional nature. Multiple affiliations are likely to increase scientists' familiarity with different cultural and cognitive settings and to sustain the development of relational skills. This eases the establishment of collaborative relationships with different partners, as well as expands scientists' social capital, increasing the opportunities to play the role of boundary spanners. In particular, Ponomariov and Boardman (2010) find that affiliation to a university large-scale research center increases the extent of scientists' cross-institutional collaborations. Hypothesis 5: *Scientists with multiple affiliations have a higher propensity to establish international collaborations*.

Theory emphasizes the role of trust as a mechanism to lower the risk of opportunistic behavior and to enable more open flows of knowledge. We saw that geographic proximity permits direct interaction that facilitates trustworthy relationships. A different form of social proximity is represented by prolonged and repeated professional interactions: personal relationships and success in previous collaborations are an important driver of trust building (Horwitz, Horwitz, 2007). Leveraging on the advantages offered by social proximity, a project team can accommodate higher levels of distance in other dimensions. Hypothesis-6: *The more repeated collaborations a scientist has with the other team members in a collaborative project, the higher the propensity to establish international collaborations*.

3. Research Design

3.1 Empirical setting

The empirical study investigates the cognitive, social and institutional factors that drive the establishment of international research collaborations at ORLN/NSD. Established in 1943, the Oak-Ridge National Laboratories is a multidisciplinary center financed by the U.S. Department of Energy. The laboratory conducts basic and applied research in the areas of neutron science, biological systems, energy, advanced materials, supercomputing and national security. The laboratory has a staff of about 4600 and a budget of USD 1.65 million in 2011 (http://ornl.gov/ornlhome/about.shtml). Since 2006, the research program in neutron science is managed by the Neutron Sciences Directorate that employs 600 scientists, technicians and administrative staff, and operates two of the world's most advanced neutron scattering facilities: a Spallation Neutron Source, that became operative in 2006, and a High Flux Isotope Reactor (HFIR), completed in 1965 and renovated in 2007.

Since 2006, all peer-reviewed publications involving staff or resources of ORNL/NSD are publicly listed on the directorate's website. We retrieved full bibliometric records from ISI-Web of Science of the publications produced in the period from 2006 to 2009 - the most recent year for which the complete list of production is available on its website.

3.2 Unit of analysis

For each publication we identified the host institution of each author. Our unit of analysis is scientists who, in the entire period, have been affiliated only to US-based organizations: in other words, we consider as focal scientists not only ORNL/NSD-affiliated, but any US-based scientist who worked at ORNL/NSD facilities or together with ORNL/NSD-affiliated scientists. For each focal scientist we consider the network of collaborations defined by the co-authorship of publications resulting from projects carried out at the facility or involving ORNL/NSD personnel. We consider the authors who published at least one Article or Proceeding Paper (excluding those who published only other document types), and at least one publication with valid CHI-Level classification. Within these collaboration networks, we identify the 'international' authors, i.e. those who, in a given publication, were affiliated only to non-US organizations. It should be noted that a given author could be classified as 'international' in a given publication, and US-based in another if he/she changed affiliation during the observation period; however, that author is excluded from the set of focal scientists.

3.3 Data and measures

The total NUMBER OF INTERNATIONAL CO-AUTHORS present in each focal author's collaboration network is the dependent variable of our regression models. Differences across authors in the size of their network, however, may affect the volume of international partnerships. To take this effect into account we introduce the NUMBER OF UNIQUE PARTNERS as 'exposure' parameter in the regression models (Long, Freese, 2006). The exposure parameter has the important implication for the interpretation of our findings that estimates in the models now reflect the extent to which single US scientists engage international partners as an underlying propensity regardless of their overall number of collaborators.

We characterize each focal scientist along a series of cognitive, social and institutional dimensions.

At first, we assign each author to an INSTITUTION-TYPE. Four of these characterize focal scientists who, for the entire period of analysis, have been affiliated exclusively to one of the following institutions: ORNL/NSD or any other department at Oak-Ridge National Laboratories ('Resident' scientists), Universities, Research Laboratories, and Companies. Among Resident scientists, the Spallation Neutron Source is the unit most frequently indicated by the scientists who explicitly reported an affiliation to a specific facility or department, indicating that this is the principal locus of research for Oak-Ridge-affiliated scientists included in our dataset. In detailed analyses, we distinguish between scientists affiliated to the University of Tennessee and to any other American University, to depurate the effect of the institution-type 'University' from the influence of context-specific effects associated to the close relationship characterizing Oak-Ridge and University of Tennessee. Research Laboratories are government funded research organizations conducting a broad range of research programs. The most frequent examples of Research Laboratories in our sample are US Federal Laboratories that carry out basic and applied research with the goal of pursuing national security mission. Although ORNL/NSD is part of the network of these Federal Laboratories, we consider it as a distinct type being the focal organization in our study: this allows us to detect differences in the pattern of internationalization between ORNL/NSD and the other similar organizations. The institution-type 'Secondment' includes those who have been affiliated to ORNL/NSD or any other department at Oak-Ridge, and to another institution; 'Multiple' characterizes the authors who have been affiliated to a variety of institutions, but not to ORNL/NSD. Both the two latter types do not distinguish between multiple affiliations in a paper and changes of affiliation during the period. In the regression models, we take 'Resident' as the benchmark institution-type.

The indicators of the cognitive profile of focal scientists are the disciplinary areas characterizing the ORLN/NSD-related projects they are involved in, and the positioning along the continuum between basic and applied research.

ISI-Subject Categories are employed to differentiate focal scientists' disciplinary specialization (FIELD). Scientists whose entire ORLN/NSD-related production is characterized by any of the Subject Categories corresponding to subfields of Physics are defined as 'Physics specialized', while those spanning other disciplines in addition to Physics are defined as 'Physics multidisciplinary'. The residual category 'Other disciplines' includes scientists with no publications in Physics.

We use the CHI classification to collocate each focal author's production along the continuum between basic and applied research. The classification has been developed by CHI Research, a private company, and assigns ISI recorded journals to a 'research level' on the basis of their contents and scientific field (Narin et al., 1976). For non-biomedical fields, the levels are: 1–applied technology, 2– engineering science-technological science; 3–applied research-targeted basic research; 4– basic scientific research. It is possible to notice that the major breaking point in the classification occurs between levels 3 and 4, with the latter indicating an explicit basic orientation. For each author, we calculate the average CHI-Level associated to ORLN/NSD-related production: we construct the dummy BASIC ORIENTATION taking value 1 if the average CHI-Level of a given author's research is higher than 3.

We then consider the social and institutional proximity of each focal author with his/her collaborators. INSTITUTIONAL PROXIMITY expresses the number of collaborators who are affiliated to an institution of the same type as the focal author. To build this variable, we recognize that the institution-types 'Resident' and 'Research Laboratories', and 'Secondment' and 'Multiple' are homogeneous: as already mentioned, ORNL/NSD being an US Federal Laboratory, scientists affiliated to these institutions are not expected to face institutional barriers when establishing a collaboration with colleagues in other Research Laboratories. Scientists categorized in 'Secondment' and 'Multiple' groups have in common the affiliation to organizations with different institutional nature, and thus can be considered homogeneous. The following Table 1 summarizes how the variable is constructed.

Table 1 Construction of the variable 'Institutional proximity'.

Institution-type of focal author	Institutionally homogeneous institution-types
Resident	Resident + Research Laboratory
Secondment	Secondment + Multiple
University	University
Research Laboratory	Resident + Research Laboratory
Business	Business
Multiple	Secondment + Multiple

SOCIAL PROXIMITY expresses the total number of repeated collaborations established by each focal author in projects addressing ORNL/NSD-related research. E.g. focal author X co-authors two papers with scientist A and four with B: this means that X has established one repeated collaboration with A and three with B, leading to a social proximity score of four.

For each focal scientist, we include in the regression models four controls: the NUMBER OF PUBLICATIONS, the average annual citations received by his/her ORLN/NSD-related production (PUBLICATION IMPACT), the quality of an author as TOP-SCIENTIST, and the AVERAGE PUBLICATION YEAR. The first control accounts for the influence of volume effects. The two next variables account for the fact that more promising projects and more visible scientists tend to attract more collaborations. To identify 'top-scientists', for each Subject Category characterizing the papers in our dataset, we detected the 50 authors who, in the period 2003-2009, have the highest number of publications in the top-10 journals by impact factor. We used a dummy taking value 1 if a focal author is included in that list. We introduce the fourth control to remove the effect of time-dependent processes that are specific to ORNL/NSD, such as the completion of SNS in April 2006 and the renovation of HFIR between 2006 and 2007 (http://neutrons.ornl.gov/facilities/SNS/history/).

3.4 Analytical strategy

We first present a descriptive examination of our data, followed by an analysis based on inferential statistics. Since our dependent variable is a count and is characterized by a high presence of zeros, we use a Zero Inflated Negative Binomial (ZINB) model. ZINB offers distinct estimates for the effect of changes in each predictor on the chance of having zero collaborators – in the zero-inflated part – and on the likelihood of establishing an additional collaboration – in the negative binomial part. For this reason, a positive estimate in the zero-inflated part indicates a negative effect to internationalization. We used Vuong tests to assess the superiority of ZINB regression over Negative Binomial. We exclude that the estimates are affected by multi-collinearity since the maximum Variance Inflation Factor is lower than the threshold value of 10 in each model.

4. Findings

4.1 Descriptive statistics

In the period 2006-2009, 1163 scientists affiliated only to American organizations worked on ORNL/NSD-related research publishing a total of 590 papers. We exclude from the analysis 81 scientists who are present *only* in one paper that has 96 coauthors, of which 5 are international. This paper represents an exceptional case in our sample, involving a considerable large amount of researchers who participated exclusively in that project. We thus identify 1082 are 'focal' scientists.

The 589 valid papers mobilize a collaboration network of 1801 scientists and 339 organizations. Almost 60% of organizations (197) are non-domestic and about 40% of scientists (719) have at least one international affiliation in the period of analysis.

Looking first at the organizations, we find that Universities are the most represented institution-type, followed by Research Laboratories. About 30 Companies, mainly American, have been involved in projects related to the facility. We then consider the distribution of scientists' affiliations (Table 2): choosing this unit of analysis, we consider each affiliation of multiple affiliated authors as a distinct observation. For this reason, the total number of affiliations is 2169, higher than that of unique authors (1801). Looking at affiliation, rather than at individual scientists, we can capture the 'intensity' of participation of each institution-type. Indeed, American Universities and Research Laboratories seem to follow different patterns of involvement. While a broad set of universities (91) takes part to ORNL/NSD-related research with an average of 6.75 scientists, a smaller number of research laboratories (22) participates with a number of scientists that, on average, is almost triple (19). This fact seems to indicate a strong connective capability of ORLN/NSD at domestic level. However, more disaggregated data (not presented here) indicates the prevalence of specific organizations: the most frequent partner organization is the neighboring University of Tennessee, accounting for 5.2% of affiliations, followed in importance by various research laboratories that are part of the system of the US Department of Energy federal laboratories. The importance of organizations belonging to the network of the US Department of Energy probably comes not only from institutional proximity, but also from the close collaboration in the construction and testing of SNS and HFIR facilities. Looking at the international institutions involved, we find that ORNL/NSD-related research has paved the way to collaborations with a similar number of University and Research Laboratories, but the latter, again, provide larger numbers of scientists (on average, two times higher than the former). The international research laboratories are organizations homologous to ORLN/NSD in Europe, China and Japan. We notice that firms participate with a number of scientists that is smaller compared to the other institution-types.

Table 2 Institution-type of organizations and scientists involved in ORNL/NSD-related projects.

Institution-type	Organizations	Total affiliations	Avg. affiliations of unique collaborators
Oak-Ridge	1	416	-
US-University	91	615	6.75
US-Research Laboratory	22	413	18.77
US-Business	28	66	2.36
INT-University	96	258	2.69
INT-Research Laboratory	95	395	5.80
INT-Business	6	6	1
Total	339	2169	6.40

Although preliminary, this descriptive evidence provides hints on the importance of institutional and geographic proximity for the establishment of research collaborations.

We now turn our attention on the focal scientists, i.e. those affiliated only to American organizations in the entire period of analysis, to appreciate their connective capability. Table 3 reports the descriptive statistics relative to the key analytical variables for the valid sample of 1082 focal authors.

The descriptive statistics highlight some important features of ORLN/NSD-related research. First, the distribution of publications is skewed: even if the average number of papers per author is 2.47, the large majority - about 62% - has produced only one publication.

Second, the cognitive profile shows an interesting form of specialization. More than two thirds of the focal scientists publish in Physics, but most of them (41%) do so in a multidisciplinary form, combining Physics with other disciplines. We also see a pronounced orientation towards more basic studies (the average and median CHI-Level is 3 in a scale from 1 to 4).

Third, looking at the patterns of collaboration, we observe that the distribution of unique and international collaborators is uneven. On average, a focal author has 15 co-authors of which 2.7 are international. However, the median number of coauthors is lower (9) and more than 50% of focal scientists have no international partners. This finding indicates a segment of highly connected scientists.

Finally, we see again the institutional diversity of US scientists undertaking research at ORLN/NSD: more than 70% of them are affiliated to other organizations than the focal facility. 22% come from Research Laboratories, while 37% come from Universities, of which the local university of Tennessee accounts for only 5%; 13.5% has a double affiliation.

Table 3 Descriptive statistics of the key analytical variables

Variable	Mean	Std. Dev.	Median	Min	Max
INTERNATIONAL PARTNERS	2.711	6.135	0	0	54
UNIQUE PARTNERS	15.323	17.557	9	1	145
INSTITUTIONAL PROXIMITY	7.713	9.746	5	0	114
SOCIAL PROXIMITY	5.189	13.202	0	0	127
PUBLICATION IMPACT	7.735	16.753	3	0	248.67
N. PUBLICATIONS	2.812	4.006	1	1	36
AVG. PUBLICATION YEAR	2007.606	.947	2007.667	2006	2009
INSTITUTION TYPE	n.	%			
Resident	276	25.51			
Secondment	73	6.75			
University	399	36.88			
of which					
University of Tennessee	*55*	*5.08*			
Other Universities	*344*	*31.79*			
Research Laboratory	236	21.81			
Business	38	3.51			
Multiple	60	5.55			
FIELD					
Physics specialized	297	27.45			
Physics multidisciplinary	445	41.13			
Other disciplines	340	31.42			
BASIC ORIENTATION	540	49.91			
TOP SCIENTIST	17	1.57			

Table 4 compares the volume of collaborations of the different institution-types, disciplinary field, orientation, focusing on international partnerships.

Table 4 Mean and median size of collaboration network by institution-type.

	N. of unique collaborators		N. of international collaborators	
	Mean	Median	Mean	Median
Resident	17.61	11	3.17	0
Secondment	32.26	22	6.19	4
University	11.87	9	2.03	0
Research Laboratory	13.52	9	2.19	1
Business	7.39	8	.37	0
Multiple	19.32	13	4.40	2
Total	15.32	9	2.71	0

The Table suggests a positive relationship between connectivity and multiplicity of affiliation, represented by institution-types 'Secondment' and 'Multiple'. Residents are part of large networks, whose international component is smaller than that of scientists with double affiliations. Universities and Research Laboratories have a similar distribution of unique collaborations and a similar share of international partners. Finally, industrial scientists are more nationally focused, despite a collaboration network comparable to that of other institution-types.

4.2 Results of regressions

Finally, we investigate the drivers of internationalization using inferential modeling. The distribution of our dependent variable – NUMBER OF INTERNATIONAL COLLABORATIONS – is characterized by a considerable share of observation with a value zero. The use of Zero-Inflated Negative Binomial (ZINB) regression models allows us to distinguish the factors enabling the collaboration with at least one international partner, from those affecting the size of the international network. The logit part of the models predicts the likelihood of an author to have zero international partners – so, negative coefficients indicate the likelihood of establishing at least one collaboration. The count part predicts the likelihood of increasing by one unit the number of collaborations.

In Table 5, Model 1 includes controls only; Model 2 includes the variables on institution-type and the two cognitive variables of BASIC ORIENTATION (benchmarked to applied orientation) and FIELD (the effects of 'Physics multidisciplinary' and 'Other disciplines' are benchmarked against 'Physics specialized'). Model 3 brings in variables on INSTITUTIONAL and SOCIAL PROXIMITY.

Table 5 Zero inflated negative binomial regression of number of international collaborators of focal authors. Coefficients and standard deviation (in parenthesis).

	Model 1		Model 2		Model 3	
	Logit	Count	Logit	Count	Logit	Count
INSTITUTIONAL PROXIMITY					- .061*** (.021)	.001 (.005)
SOCIAL PROXIMITY					-.047 (.043)	.017*** (.004)
BASIC ORIENTATION			-2.971*** (.691)	-.022 (.101)	-2.719*** (.619)	-.147 (.097)
FIELD (base: Physics specialized)						
Physics multidisciplinary			-2.890*** (.811)	-.040 (.134)	-2.363*** (.766)	-.199 (.115)
Other disciplines			-1.816** (.798)	.030 (.148)	-1.759** (.743)	-.036 (.138)
INSTITUTION-TYPE (base: Resident)						
Secondment			-.378 (.578)	-.055 (.164)	-1.142* (.655)	.103 (.181)
University			-1.184** (.513)	-.114 (.144)	-.930** (.398)	.041 (.133)
Research Laboratory			-2.214*** (.646)	-.118 (.146)	-1.914*** (.560)	-.016 (.139)
Business			.560 (.892)	-.146 (.580)	.441 (.860)	-.002 (.611)
Multiple			-19.833*** (1.273)	-.133 (.179)	-30.386*** (1.510)	.015 (.163)
PUBLICATION IMPACT	-.080*** (.030)	.010*** (.003)	-.051 (.034)	.010*** (.003)	-.048** (.024)	.008*** (.003)
TOP SCIENTIST	-17.372*** (2.550)	.339 (.227)	-17.813*** (4.301)	.327 (.231)	-11.848* (7.102)	.201 (.197)
N. OF PUBLICATIONS	-.312*** (.072)	.021*** (.007)	-.206*** (.074)	.020** (.008)	.008 (.132)	-.024** (.011)
AVG. PUBLICATION YEAR	-.246* (.125)	.135*** (.042)	-.110 (.181)	.156*** (.046)	-.078 (.161)	.148*** (.044)
CONSTANT	493.647* (252.367)	-273.691*** (83.724)	224.321 (363.206)	-314.277*** (91.741)	158.972 (323.185)	-299.109*** (89.077)
UNIQUE COLLABORATIONS		exposure		exposure		exposure
Log likelihood	-1751.118		-1708.464		-1683.554	
N. of observations	552	530	552	530	552	530

***Sig. 1%; ** Sig. 5%; * Sig. 10%

Table 6 Difference between institution-types, results of Wald test (and significance in brackets) on coefficients of Model 3.

	Logit	Count
Secondment–University	.07 (.786)	.12 (.734)
Secondment-Research Lab	.80 (.370)	.42 (.518)
Secondment–Business	2.11 (.146)	.03 (.866)
Secondment–Multiple	342.27*** (.000)	.23 (.633)
University-Research Lab	4.01** (.045)	.27 (.602)
University–Business	2.39 (.121)	.00 (.944)
University–Multiple	399.45*** (.000)	.03 (.861)
Research Lab–Business	5.93** (.015)	.00 (.982)
Research Lab–Multiple	388.77*** (.000)	.04 (.846)
Business–Multiple	308.02*** (.000)	.00 (.988)

***Sig. 1%; ** Sig. 5%; * Sig. 10%

The controls-only Model 1 indicates that publication impact and individual prominence in the academic community positively affect propensity to internationalization: all the subsequent models confirm that the latter factor has a strong impact in enabling the establishment of the first international collaboration, while the former tends to contribute also to the volume of collaborations. Publication impact turns to be one of the few drivers of network size.

The subsequent models permit us to test the hypotheses.

Hypothesis-1 conjectured a higher propensity for international collaboration in Physics as compared to other disciplines. Model 2 (along with following models) refutes this hypothesis, showing stronger international orientation in other disciplines and when Physics is combined with other disciplines. The effect is limited to the establishment of non-domestic collaborations, rather than to the size of the network.

Turning to basicness of research, the other cognitive variable, we see no effects on the size of international networks. However, the logit part of Model 2, and all subsequent models, offers strong evidence that specialization in more basic oriented projects increases the propensity for a scientist to have at least one international collaboration partner, hence confirming *Hypothesis-2*. This result suggests that policy makers face a trade-off relating to the policy objectives for LSRFs. As noted above, the rationale for LSRFs in regional growth strategies often refer to expected effects of spillovers on local technological innovation. If LSRFs, in response to these aspirations, increase their focus on applied areas of research it appears to detract from their ability to fulfill the other policy objective of serving as a knowledge attractor for the global scientific community.

The count part of Model 2 also shows that Institution-types do not differ from one another in their propensity to give access to *large* international collaboration networks. The logit part instead indicates that scientists affiliated to Universities and Research Laboratories, as compared to Residents, have a higher propensity to establish an international presence in their collaborations. In a model not presented here, we replace the university-dummy with two variables expressing affiliation to Tennessee and to any other university. We find that the positive effect of University is actually due to scientists affiliated to *other* universities (coefficient in the logit part -.900, significant at 5% level), while those working at Tennessee University, that has a long tradition of collaboration with Oak-Ridge, do not contribute to internationalization. These effects remain robust even when proximity variables are introduced in Model 3, providing support for the conjecture of *Hypothesis-4* that the propensity to internationalization of ORNL/NSD scientists is lower than that of university scientists. Wald tests in Table 6 (based on estimates from Model 3) indicate that scientists affiliated to Research Laboratories (other than ORLN/NSD) have an even higher propensity than University scientists for international partnering. Note that these findings run counter to simple descriptive observations in Table 4 of the number of international partners for different institution-types. It makes a critical difference, when instead we consider the general tendency for international partnering of single scientists, and also control for a range of their additional attributes.

Among the different types of institutional association, scientists with Multiple affiliations have the highest propensity to establish some international presence in their collaborations. Their propensity is higher than any other institution-type, as shown Wald tests on the results of Model 3, confirming *Hypothesis-5.*

Model 3 introduces effects of institutional and social proximity. Consistent with *Hypothesis-3* and *6* both forms of proximity enable internationalization, although in slightly different patterns. Institutional proximity is conducive for the establishment of international presence in collaborations, while social proximity has a stronger effect in increasing the *number* of partners. These findings are highly informative for the arguments presented in the theory section to the effect that LSRFs would not be subject to the proximity restraints in partner selection as have been found for other institutional types (e.g. firms and universities). From the findings in Model 3 we learn that is not the case. Increasing distance on the social and institutional dimensions of partner selections significantly lowers their tolerance for accommodating also geographic and system level distances associated with international partnering.

Since social proximity counts the number of repeated collaborations in ORNL/NSD-related research, Model 3 may have led to misrepresentations by including also focal scientists involved in one collaboration only. Therefore we tested in a Model not reported here the robustness of our social proximity measure by including only focal scientists with more than one collaboration. Results are consistent with the previous model, although estimates for Universities turn insignificant while maintaining their sign.

5. Summary and policy implications

The paper has examined LSRFs as knowledge attractors, focusing on factors affecting their ability to act as magnet for global research talent. The key vehicle for that attraction is research collaborations involving scientists affiliated with the facility itself or with the regional or national research institutions forming the local context of the facility.

Taking ORLN/NSD as our LSRF-case and focusing on its patterns of research collaboration 2006-2009 we find that it has activated a large network of collaboration at domestic level. Nevertheless, about 50% of US-scientists taking part in projects at the facility have not established international partnerships, and international orientation among those who have is not homogeneous.

Our analysis of ORLN/NSD, however, has been arranged not for deeper penetration into the specificities of this particular facility. Rather, our study was designed to enhance generalizations from this single case. For this purpose the theory section anchored the phenomenon of international research connectivity in a more general theory on research collaboration, in particular their coordination costs of as seen from the perspective of the individual scientist. Seen through this lens, cross-border collaboration represents one of multiple types of distances that must be accommodated in the coordination of collaborative research. Using this theoretical perspective, broadly accepted in the economics and sociology of science, is one way of enhancing generalizations from our case-based findings. It allows us to conjecture that the coordination costs associated with cross-border distance is likely to be traded off against other types of distances within the same collaboration. Indeed by having this – and other hypotheses derived from theory – confirmed by our findings, we learn that scientific work at LSRFs seems to be restrained by the same proximity effects as have been identified for academic teamwork in general. This result is not only novel to the literature; it is also surprising in light of the arguments (presented in Section 2.3) that several fundamental characteristics of LSRFs could be expected to neutralize these restraints.

In further pursuit of generalizability we applied econometric tools allowing us to consider propensities of individual US scientists for international research connectivity, as observable from their research associated with this facility. Applying a number of statistical controls we focused on variations in this propensity across different institutional types, different cognitive profiles, and different types of proximity/distances within research teams.

Regarding variations across institutional types we find that, compared to ORNL/NSD residents, higher international connectivity is provided by scientists from other institutional types, Universities and Research Laboratories in particular. Policy makers investing in local LSRFs to enhance the global connectivity of their region may find these results interesting. They suggest that national/regional universities and laboratories operating as the institutional context of the LSRF, play an important, complementary role in getting the most out the ‘connectivity potential’ of the facility. This seems to call for programs aimed at ensuring the widespread involvement in research at the facility of scientists coming from universities and government laboratories in its host region. More specifically these programs should take into account the particular potential of scientists with experience in multiple institutional settings (Research Laboratories, Universities, and Business). Our findings show they are strong drivers of global research connectivity, arguably based on their familiarity with the rules of multiple environments.

With regard to variations in internationalization across different cognitive profiles, we find that the involvement of top scientists and the execution of high quality research merits particular attention since they are powerful drivers of internationalization. Similarly, orientation towards more abstract and theoretical issues enhances international connectivity, arguably because basic research is less reliant on exchanges of tacit knowledge than studies aimed at technology development. In the analysis above we already highlighted how this pattern implies an important trade-off in the policy objectives guiding LSRFs: if they are directed too heavy-handedly towards applied and technology-related agenda most likely that will detract to some extent from their deliverables regarding connectivity to the global research community.

We also find that narrow disciplinary specialization does not support global connectivity. LSRFs that explore multidisciplinary investigations around a core disciplinary area do not compromise – rather enhance – internationalization, as long as they privilege more theory-driven projects.

Turning finally to findings on social and institutional-type proximity they both contribute significantly to international connectivity. Restraining distances on these two dimensions allow scientists to accommodate larger distances in terms of geography and differences between different national science systems. The key policy implication from this role of social proximity comes from recognizing the potential offered by pre-existing strong networks of scientists residing at the facility or in its context universities and Research Laboratories. Our findings show that the existing network of a scientist notably affects his/her reach into new global research connectivity.

From the positive effects on internationalization observed for institution-type proximity we learn that scientists can take on more cross-border collaboration when they find their partners in the same type of research institution as their own. From a policy perspective this finding underscores how important it is to involve in the research of a LSRF scientists coming from those universities and Research Laboratories which form its national/regional context. They represent stronger institutional proximity to the Universities and

Laboratories in other countries, where the potential for global research connectivity predominantly is found.

The role of LSRFs in creating connectivity to the global scientific talent pool is a critical mechanism in their policy rationale. The overall message this study offers to policies designed to implement that rationale is that while connectivity among researchers may have some stochastic dimensions, it also has quite profound self-organized regularities. This paper has highlighted regularities associated with the ability of research collaborations to come to terms with different dimensions of distance between team members. Restraints in this respect grow out of the increases in coordination costs associated with increases in these distances. Ultimately the need for scientists to take these costs into account – whether or not they articulate them as such – is rooted in the fundamental principles by which the self-organization of the scientific community delivers steady advancement of human knowledge (Dasgupta, David, 1994; Merton, 1957; Polanyi, 1962). We hope this paper exemplifies that the development of science policies – in this case those referring to the hosting of LSRFs – may benefit from a deeper interest in the self-organized regularities of the scientific community.

Acknowledgments

The Authors are grateful for comments and information provided by Ian Anderson, Associate Laboratory Director for Neutron Sciences at ORLN, and for the help with data collection provided by Nina Jensen Kierbye. Research for this paper was carried out in the context of Øresund Materials Innovation Community project, and was funded by Interreg IV-A.

Appendix: Table of correlations

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. N. international collaborators	1.000														
2. Institutional proximity	0.526	1.000													
3. Social proximity	0.626	0.504	1.000												
4. Basic orientation	0.134	-0.052	0.092	1.000											
5. Physics multidisciplinary	0.237	0.346	0.304	-0.226	1.000										
6. Other field	-0.175	-0.219	-0.210	-0.230	-0.566	1.000									
7. Secondment	0.153	-0.013	0.266	0.041	0.142	-0.111	1.000								
8. University	-0.085	-0.136	-0.185	0.149	-0.176	0.077	-0.206	1.000							
9. Federal Lab	-0.044	-0.014	-0.115	0.028	-0.023	-0.068	-0.142	-0.404	1.000						
10. Business	-0.073	-0.100	-0.066	-0.130	-0.047	0.130	-0.051	-0.146	-0.101	1.000					
11. Multiple	0.067	0.003	0.037	0.178	-0.055	-0.042	-0.065	-0.185	-0.128	-0.046	1.000				
12. Publication impact	0.142	0.033	0.130	0.200	-0.042	-0.071	0.058	0.040	-0.054	-0.025	0.118	1.000			
13. Top scientist	0.160	0.110	0.208	0.023	0.045	-0.038	-0.034	0.011	0.005	-0.024	-0.031	-0.001	1.000		
14. N. of publications	0.468	0.453	0.868	0.087	0.277	-0.199	0.363	-0.211	-0.150	-0.078	0.127	0.110	0.216	1.000	
15. Avg. publication year	0.073	-0.008	-0.007	-0.010	-0.004	0.129	0.018	0.125	-0.092	-0.033	0.073	0.0800	-0.039	-0.019	1.00

References

Abbasi, A., Hossain, L., Uddin, S., Rasmussen K.J.R. (2011). Evolutionary dynamics of scientific collaboration networks: multi-levels and cross-time analysis. Scientometrics, 89(2), 687-710.

Abramo, G., D'Angelo, C.A., Di Costa, F. (2009). Research collaboration and productivity: is there correlation? *Higher Education*, 57(2), 155-171.

Adams, J.D., Black, G.C., Clemmons, J.R., Stephan, P.E. (2005). Scientific teams and institutional collaborations: Evidence from U.S. universities, 1981-1999. *Research Policy*, 34(3), 259-285.

Arundel, A., Geuna, A. 2004. Proximity And The Use Of Public Science By Innovative European Firms. *Economics of Innovation and New Technology*, 13(6), 559-580.

Asheim, B.T., Boschma, R., Cooke, P. (2011). Constructing Regional Advantage: Platform Policies Based on Related Variety and Differentiated Knowledge Bases. *Regional Studies*, 45(7), 893-904.

Audretsch D.B., Lehmann E., Warning S. (2005). University spillovers and new firm location. *Research Policy*, 34 (7), 1113-1122.

Autio, E., Hameri, A.P., Vuola, O. (2004). A framework of industrial knowledge spillovers in big-science centers. *Research Policy*, 33(1) 107-126.

Bathelt, H., Malmberg, A., Maskell, P. (2004). Clusters and knowledge: local buzz, global pipelines and the process of knowledge creation. *Progress in Human Geography*, 28(1), 31-56.

Boschma, R. (2005). Proximity and Innovation: A Critical Assessment. *Regional Studies*, 39(1), 61-74.

Bozeman, B., Boardman, C. (2003). *Managing the New Multipurpose, Multidiscipline University Research Centers: Institutional Innovation in the Academic Community*. IBM Cnter for The Business of Government.

Chompalov, I., Genuth, J., Shrum, W. (2002). The organization of scientific collaborations. *Research Policy*, 31(5), 749-767.

Cummings, J.N., Kiesler, S. (2007). Coordination costs and project outcomes in multi-university collaborations. *Research Policy*, 36(10), 1620-1634.

Dahlin, K.B., Weingart, L.R., Hinds, P.J. (2005). Team diversity and information use. *Academy of Management Journal*, 48(6), 1107-1123.

Dasgupta, P., David, P.A. (1994). Toward a new economics of science. *Research Policy*, 23(5), 487-521.

ESFRI - European Strategy Forum on Research Infrastructures - Working Group on Neutron Facilities (2003). *Medium to long-term future scenarios for neutron-based science in Europe*, retrieved at http://ess-europe.org/uploads/esfri_report.pdf, on April 30, 2012.

Feldman, M.P., Kogler, D.F. (2010). Stylized facts in the geography of innovation. In B.H. Hall, N. Rosenberg (Eds.), *Handbook of the Economics of Innovation, Vol. 1* (pp.381-410). Amsterdam: Elsevier.

Fleming, L., Sorenson, O. (2004). Science as a map in technological search. *Strategic Management Journal*, 25(8-9), 909-928.

Flink, T., Schreiterer, U. (2010). Science diplomacy at the intersection of S&T policies and foreign affairs: toward a typology of national approaches. *Science and Public Policy*, 37(9), 665-677.

Frenken, K., Ponds, R., Van Oort, F. (2010). The citation impact of research collaboration in science-based industries: A spatial-institutional analysis. *Papers in Regional Science*, 89(2), 351–371.

Hackett, E.J., Conz, D., Parker, J., Bashford, J., DeLay, S. (2004). Tokamaks and turbulence: research ensembles, policy and technoscientific work. *Research Policy*, 33(5), 747-767.

Heinze, T., Kuhlmann S. (2008). Across institutional boundaries? *Research Policy*, 37(5), 888-899.

Hoekman, J., Frenken, K., Tijssen, R.J.W. (2010). Research collaboration at a distance: Changing spatial patterns of scientific collaboration within Europe. *Research Policy*, 39(5), 662-673.

Hoekman, J., Frenken, K., Van Oort, F. (2009). The geography of collaborative knowledge production in Europe. *The Annals of Regional Science*, 43(3), 721-738.

Horwitz, S.K., Horwitz, I.B. (2007). The Effects of Team Diversity on Team Outcomes: A Meta-Analytic Review of Team Demography. *Journal of Management*, 33(6), 987-1015.

Hudson, J. (1996). Trends in Multi-authored Papers in Economics. *Journal of Economic Perspectives*, 10(3), 153-158.

ILL - Institut Laue-Langevin (2011). Report from the ILL Associates' Working Group on Neutrons in Europe for 2025. Available at http://www.ill.eu/fileadmin/users_files/documents/news_and_events/news/Report_from_ILL_Neutron_Working_Group.pdf

Kargon, R., Leslie, S. W., Schoenberger, E. (1992). Far beyond big science: Science regions and the organization of research and development. In P. Galison, B. Hevly (Eds.), *Big Science. The growth of large-scale research* (pp.334-353). Stanford: Stanford University Press.

Katz, J.S., Martin, B.R. (1997). What is research collaboration? *Research Policy*, 26(1), 1-18.

Langford, C.H., Langford, M.W. (2000). The evolution of rules for access to megascience research environments viewed from Canadian experience. *Research Policy*, 29(2), 169-179.

Long, J.S., Freese, J. (2006). *Regression models for categorical dependent variables using Stata*. College Station, TX: Stata Press.

Lundvall, B.-Å, Borrás, S. (2004). *Science, technology, and innovation policy*. In J. Fagerberg, D.C. Mowery, R.R. Nelson (Eds.), *The Oxford Handbook of Innovation* (pp.599-631). New York: Oxford University Press.

Melkers, J., Kiopa, A. (2010). The Social Capital of Global Ties in Science: The Added Value of International Collaboration. *Review of Policy Research*, 27(4), 389-414.

Melkers, J., Wu, Y. (2009). Evaluating the Improved Research Capacity of EPSCoR States: R&D Funding and Collaborative Networks in the NSF EPSCoR Program. *Review of Policy Research*, 26(6), 761-782.

Melin, G. (2000). Pragmatism and self-organization: Research collaboration on the individual level. *Research Policy*, 29(1), 31-40.

Melkers, J., Kiopa, A. (2010). The Social Capital of Global Ties in Science: The Added Value of International Collaboration. *Review of Policy Research*, 27(4), 389-414.

Merton, R.K. (1957). Priorities in scientific discovery: a chapter in the sociology of science. *American Sociological Review*, 22(6), 635-659.

Merz, M., Biniok P. (2010). How Technological Platforms Reconfigure Science-Industry Relations: The Case of Micro- and Nanotechnology. *Minerva*, 48(2), 105-124.

Narin, F., Pinski, G., Gee, H.H. (1976). Structure of the Biomedical Literature. *Journal of the American Society for Information Science*, 27(1), 25-45.

Newman, M.E.J. (2004). Who Is the Best Connected Scientist? A Study of Scientific Coauthorship Networks. *Lecture Notes in Physics*, 650, 337-370.

Nooteboom, B., Van Haverbeke, W., Duysters, G., Gilsing, V., Van den Oord, A. (2007). Optimal cognitive distance and absorptive capacity. *Research Policy*, 36(7), 1016-1034.

Peerbaye A., Mangematin (2005). Sharing Research Facilities: Towards A New Mode of Technology Transfer? *Innovation: Management, Policy, Practice*, 7(1), 23-38.

Polanyi, M. (1962). The republic of science: Its political and economic history. *Minerva*, 1(1), 54-73.

Ponds, R., Van Oort, F., Frenken, K. (2007). The geographical and institutional proximity of research collaboration. *Papers in Regional Science*, 86(3), 423-443.

Ponds, R. (2009). The limits to internationalization of scientific research collaboration. *The Journal of Technology Transfer,* 34(1), 76-94.

Ponomariov B.L., Boardman, P.C. (2010). Influencing scientists' collaboration and productivity patterns through new institutions: University research centers and scientific and technical human capital. *Research Policy*, 39(5), 613-624.

Rosenberg, N. (1992). Scientific Instrumentation and University Research. *Research Policy*, 21(4), 381-390.

Salter, A.J., Martin, B.R. (2001). The economic benefits of publicly funded basic research: a critical review. *Research Policy*, 30(3), 509-532.

Shrum, W., Chompalov, I., Genuth, J. (2001). Trust, Conflict and Performance in Scientific Collaborations. *Social Studies of Science*, 31(5), 681-730.

Wagner, C.S. (2006). International collaboration in science and technology: promises and pitfalls. In L. Box, R. Engelhard (Eds.), *Science and Technology Policy for Development, Dialogues at the Interface* (pp.165-176). London, UK: Anthem Press.

Whitley, R. (1984). *The Intellectual and Social Organisation of the Sciences*. Clarendon: Oxford University Press.