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REGULAR ARTICLE

Formation and output of collaborations: the role of proximity in German nanotechnology

Claudia Werker[1,2] · Vladimir Korzinov[3] · Scott Cunningham[1]

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Abstract
The development and deployment of technologies depend upon collaborations concurrently relying on proximity between partners. By employing publication data of German nanotechnology, we augment former findings on the relationship between proximity and collaboration in three ways. First, we shed light on how the various forms of proximity affect different stages of collaboration. Particularly, we split geographical proximity into pure physical and systemic proximity. By doing so, we can show that pure physical proximity plays a role early on, as it positively influences the formation of collaborations. In contrast, systemic proximity affects collaborations later on by inducing higher output. Second, innovation systems shape collaboration networks. We learn that specific features of publicly funded German research organizations influence the formation and output of collaborations via organizational proximity or a lack thereof. Third, cognitive proximity has by far the strongest magnitude of effect on both the formation and the output of collaborations. Particularly, existing partnership being cognitively diverse have a lot of potential. Therefore, research policy and university management might consider to stimulating current partnerships, being cognitively different.

Keywords Proximity · Collaboration · Nanotechnology · Germany · Networks

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✉ Claudia Werker
c.werker@tudelft.nl

Vladimir Korzinov
vladimir.korzinov.kit@gmail.com

Scott Cunningham
s.cunningham@tudelft.nl

Extended author information available on the last page of the article

1 Introduction

Collaborations are particularly important for the development and deployment of technologies (European Commission 2009; 2012a). Collaborations facilitate knowledge exchange, create novel insights, promote innovation and lead to economic wealth (Brenner et al. 2011; Lavie and Drori 2012; Pandza et al. 2011). Different forms of proximity can either facilitate or hamper collaborations: geographical, organizational, cognitive, social, systemic or personal proximity all potentially influence collaboration output (e.g. Boschma 2005; Knoben and Oerlemans 2006; Morgan 2004; Petruzelli 2008; Cunningham and Werker 2012; Werker et al. 2016). Empirical results indicate that cognitive, geographical and organizational proximity also affect collaborative output (e.g. Petruzelli 2008; Shapira and Youtie 2008; Broekel and Boschma 2012; Cunningham and Werker 2012; Werker et al. 2016). The effects are not always straightforward, though, e.g., cognitive proximity between partners has the best effect when partners are cognitively close but not too close (e.g. Colombo 2003; Nooteboom et al. 2007; Cunningham and Werker 2012).

In this paper, we will augment the insights on the relationship between proximity and collaboration in three ways: First, we shed light on how the various forms of proximity affect different stages of collaboration. By splitting up geographical proximity, our results indicate that pure physical proximity positively influences the formation of collaborations, while systemic proximity induces higher output. Second, we find that specific features of the German innovation system influence the formation and output of collaborations via organizational proximity or a lack thereof. Third, as cognitive proximity has by far the strongest magnitude of effect on both the formation and the output of collaborations, research policy and university management might find measures influencing cognitive proximity worthwhile.

The paper is organized as follows. Based on theoretical considerations regarding knowledge, proximity and collaboration, we build a conceptual model and hypotheses (Section 2). Then, we delineate the characteristics and potential of nanotechnology in general (Section 3.1) and provide information about the scientific network of German nanotechnology in particular (Section 3.2 and 3.3). Following that, we model the relations between proximity and collaboration including indicators that represent the dependent and independent variables employed (Section 4). Based on that, we provide detailed insights about the relationship between proximity and collaboration for German nanotechnology (Section 5.1) and derive implications for management and policy (Section 5.2). Finally, we round our paper with a short summary of our results and some indications of open research questions (Section 6).

2 Proximity and collaboration: Hypotheses and conceptual model

2.1 Hypotheses

Collaboration is the "working together of researchers to achieve the common goal of producing new scientific knowledge" (Katz and Martin 1997, p. 7). The concept of collaboration is complex and multidimensional for at least two reasons: First, to define who is a collaborator and to measure the exact contribution of every scholar to the final output is very difficult. In fact, research collaboration is ill-defined. Particularly, determining who is an acknowledged partner contributing to the output of collaborations is a matter of social convention and open to negotiation (Katz and Martin 1997). Second, collaborations take place over a long period of time. Time is required in getting to know potential partners, starting the collaboration, actually working together, producing output in terms of publications, patents or innovations, and developing joint research through PhD or master students. Eventually, either the collaboration stops or it is necessary to redesign the collaboration after the original project terminates. As a consequence, what affects collaborations at one stage might not have an influence at another stage.

In the following, we distinguish two stages in the collaboration process, i.e., forming the collaboration and producing output (see also Section 2.2 and Fig. 1). Potential partners must put effort into collaboration by looking for the adequate partner and by starting to build trust that is necessary for the complex and inherently uncertain endeavour ahead. Collaborating partners transfer relevant knowledge, use individual and joint knowledge and create new knowledge as a result. At the same time, collaborations might not lead to tangible output in terms of publications, patents etc., and might even turn out to be unstable. So, an initial joint research project might become the last. Collaborations terminate because of various reasons, such as personal mismatch, e.g. fundamental discontent about the working style or the results achieved, or a lack of cognitive, organizational, physical or systemic proximity (Caniëls et al. 2014; Werker et al. 2016). Moreover, long-standing collaborations might lead to collaboration lock-in because partners stay on one research path no longer able to think out of the box, which might hamper creativity (Boschma 2005).

Geographical proximity dates back to the seminal work of Alfred Marshall on industrial districts that has since been thoroughly investigated ever since (Marshall 1920; Belussi and Caldari 2008). Theoretical and empirical investigations suggest that geographical proximity positively affects the output of research collaborations (Broekel and Boschma 2012; Cunningham and Werker 2012; Knoben and Oerlemans 2006; Katz and Martin 1997). More general, geographical proximity also positively influences the diffusion of knowledge in the network (Rivkin and et.al. 2006). The role of geographical proximity has changed as the need for it "…has in no way died, nor has it become negligible. But it now mostly affects certain stages of the process of production, research or development and does not necessarily lead to the co-location of the actors involved in this interactive process. "(Torre 2008, p. 870).

In line with this reasoning we suggest that geographical proximity contains two aspects masked by using the overall concept of geographical proximity and affecting different stages of the research process, i.e. pure physical and systemic proximity. The

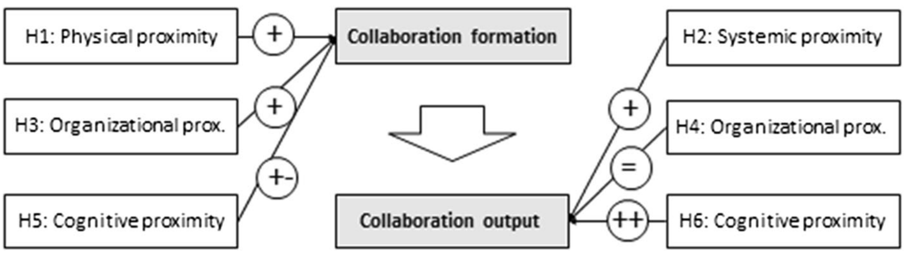

Fig. 1 Proximity influencing formation and output of collaboration: a conceptual model

concept of *pure physical proximity* describes the effects stemming from collaboration partners being close in terms of physical space (e.g. measured in term of km or in terms of the time partners need to travel to each other). Pure physical proximity point to the importance of face-to-face contacts between individuals to carry out successfully research (Lander 2015). Particularly, face-to-face contacts enable individuals to build trust by regular face-to-face communication, even though in our global digitalized world with e-mail messages and Skype communications have become more footloose (Morgan 2004). We suggest that face-to-face contacts are particularly important for forming a collaboration as trust-building is crucial at this stage. Later on in the collaboration pure physical proximity becomes less important, because, for trust-building, temporary physical proximity seems to suffice (Torre 2008). So, we suggest that pure physical proximity only has a positive effect on the formation but not on the output of collaborations:

> *H1: Physical proximity of potential partners positively influences the formation of collaborations.*

Systemic proximity accounts for the effects of geographical proximity that are not due to pure physical closeness but due to the fact that (potential) partners are located in the same innovation system. As innovation systems have been shaped by different political, economic, and cultural influences, being part of the same or neighbouring innovation systems might enable joint research projects because of similar formal and informal institutions (e.g. laws, codes of conducts, routines and habits), language and culture (cf. this and the following Fromhold-Eisebith and Werker 2013; Asheim et al. 2011; Cooke et al. 1997). Moreover, universities, firms and other research organizations being part of the same innovation system are subject to identical policy measures and incentives. As a consequence, collaboration partners within the same or neighbouring innovation systems will talk the same language, have similar goals or at least understand each other's' goals better, know the regional knowledge base and be subject to social control so as to conduct themselves in a collaboration friendly way. We suggest that all these effects of systemic proximity of (potential) partners increase the chances of being more productive in an existing collaboration:

> *H2: Systemic proximity of partners positively influences the output of collaborations.*

Here, we do not account for the possibility that both pure physical and systemic proximity might lead to negative lock-ins, as collaboration partners lack sufficient input from various sources. In line with our reasoning regarding organizational proximity, we argue that the effect is marginal here. As we analyse co-publication in peer-reviewed journals, lacking novelty of papers due to lock-ins would be picked up in the usual global review process.

Organizational proximity means that partners are close with respect to the structure and the related incentives of their organization (Boschma 2005; Petruzelli 2008; Broekel and Boschma 2012; Werker et al. 2016). Former findings suggest that collaborations between the same kind of organization may be easier than between different types of organizations (cf. this and the following Lavie and Drori 2012; Heinze and

Kuhlmann 2008). Universities share costs of their research literature or equipment and facilities by collaborating. Moreover, they have other incentives regarding output, namely, publishing and visibility. In the following, we suggest that the formation of collaboration straightforwardly benefits from organizational proximity because it helps to have a mutual understanding about goals and to find a suitable contractual set-up. In existing collaborations, when producing research output, this is already a given and organizational proximity might become unimportant. Accordingly, we express the hypotheses on the relationships between organizational proximity and collaboration as follows:

> *H3: Organizational proximity of potential partners positively influences the formation of collaborations.*
> *H4: Organizational proximity does not influence the output of collaborations.*

While organizational proximity might help in starting collaborations successfully (Boschma 2005), being too close might lead to lock-ins, i.e. costs of working with organizationally close partners are so low that academics do not search for other partners who might contribute much more to the collaboration. In line with Cunningham and Werker (2012), we ignore the possibility for lock-ins in the following analysis: As we analyse collaborations with the help of publication data, we consider lock-ins to be very unlikely. The reason for this is that authors have to build their argument on the research of others and are controlled by reviewers when publishing in the peer-reviewed journals that we use as our data here.

Cognitive proximity between individuals exists when their knowledge base partly overlap (Boschma 2005; Nooteboom et al. 2007; Gilsing et al. 2008; Cunningham and Werker 2012; Knoben and Oerlemans 2006). Usually, the relationship between cognitive proximity and collaboration is an inverted U-shaped curve (cf. this and the following Colombo 2003). While individuals need a sufficiently similar knowledge base to understand each other, they need to be sufficiently different to learn from each other. In cases where individuals differ substantially, they potentially can learn a lot from each other. Because of their differences learning becomes more difficult, though. Previous empirical investigations show that the relationship between cognitive proximity and collaboration is U-shaped (Cunningham and Werker 2012; Nooteboom et al. 2007). The positive impact of cognitive proximity between collaboration partners increases, peaks and then drops. As knowledge is widely dispersed amongst scholars in scientific networks and diverse due to the interdisciplinary character of nanotechnology, partial overlap of experiences is crucial for successfully collaborating in nanotechnology.

Previous results (see previous paragraph) would suggest to expect an inverted U-shaped relationship between cognitive proximity and collaboration. More specifically, this relationship has been earlier established between cognitive proximity and collaborative output. However, here – to our knowledge, for the first time, we investigate the relationship of cognitive proximity with both the formation and the output of collaborations. We suggest that early on, when starting a collaboration, it is crucial for partners to build on common language and working style. Therefore, in the first stage of the collaboration it is important to be sufficiently close to understand each other but sufficiently different to benefit from the partners' knowledge. In existing collaborations, common language and working style are already given. Thus, we suggest that, in producing output, collaborations benefit from having access to as much different knowledge as possible. Accordingly, we formulate the two following hypotheses:

H5: The likelihood of potential partners to form a collaboration is highest when they are cognitively close but not too close.
H6: The output of collaborations is highest when partners are cognitively distant.

2.2 The conceptual model

The formation and output of nanotechnology collaborations depends on the quality and quantity of the underlying processes of knowledge transfer and creation. As we will show, knowledge transfer and creation may be either enhanced or hampered by proximity of different kinds. In Fig. 1, we summarize the influence of cognitive, organizational, physical and systemic proximity on the formation and the output of collaborations.

Proximity is crucial for knowledge transfer and creation, enabling and stimulating the formation and output of collaborations. The transfer of knowledge takes place during the formation of collaborations and the production of output. While partners collaborate, they also create new knowledge. In Fig. 1 we represent the complex knowledge processes underlying the formation and output of nanotechnology collaborations in a simplified way.

3 The scientific network of German nanotechnology

3.1 Characteristics and potential of nanotechnology

Nanotechnology is considered a crucial source of economic growth and employment opportunities (European Commission 2012a). By 2015 about two million qualified employees are needed globally in nanotechnology (OECD 2009). While the principle idea of nanotechnology dates back more than half a century (Feynman 1960), only since the early 1990s has nanotechnology emerged from and has connected traditional sciences, such as chemistry, physics, materials science, and biology (Islam and Miyazaki 2009). Ever since, there has been a constant flow of new ideas and application areas from nanotechnology (European Commission 2009).

Three characteristics of nanotechnology make collaborations vital for its exploration and exploitation: First, while nanotechnology is still in a rather early stage of its development (Salerno et al. 2008), it has considerable growth potential in the coming decades (Roco et al. 2011). Nanotechnology has huge potential in many research areas and opens possibilities in many fields of application. The reason lies in the very nature of nanotechnology, i.e., material properties are considerably different on the nanoscale as compared to the same material in bulk or macroscopic form (Roco et al. 2011; Miyazaki and Islam 2007). As a consequence

(n)anotechnology holds the promise of leading to the development of smart nano and micro devices and systems and to radical breakthroughs in vital fields such

> *as healthcare, energy, environment and manufacturing* (European Commission 2009, p. 4).

Second, nanotechnology is spread throughout the world (Salerno et al. 2008). Particularly, it drives breakthroughs all over the world in various markets and industries (Roco et al. 2011). Third, nanotechnology has an interdisciplinary character (Salerno et al. 2008). As our surroundings consist of molecules and atoms, there is no difference between titanium particles or proteins when operating at the nano-level. For that reason, nanotechnology unites several fundamental disciplines, being able to solve problems at the resolution of one billionth of a meter.

All three characteristics point to the consequence that single scholars and often even single organizations are not able to handle innovation and technological change in nanotechnology on their own. Therefore, collaborations of partners with various knowledge and skills are key to exploit nanotechnology's potential. The creation, transfer and use of knowledge and innovation are crucial for the development and deployment of technologies such as nanotechnology. Innovation and technological development benefit from complementary skills of individuals, universities, firms, public policy agents and others (Pandza et al. 2011). As knowledge relevant for nanotechnology is too complex to be dealt with by individuals, scholars have to form collaborations supporting the creation, storage and transfer of knowledge and innovation (Salerno et al. 2008). Often collaborations connect individual scholars far beyond their own teams and organizations. Consequently, innovation and technological change in nanotechnology emerge from efforts of scholarly networks rather than from individual efforts (Beaudry and Kananian 2013; Powell et al. 1996). Its potential can be only realized in world-wide international and inter-organizational collaboration networks (Pandza et al. 2011).

For scholars working in the field of nanotechnology their ability to communicate effectively with colleagues and to understand and rely on a broad spectrum of disciplines proves to be crucial for creating new ideas (Heinze and Bauer 2007). In order to be successful, scholars in nanotechnology must have access to and use of knowledge from a broad spectrum of disciplines. As knowledge transfer within collaborations often increases creativity and fosters new ideas in nanotechnology, scholars gain from forming collaborations. In particular, those scholars whose networks are more open for new connections show higher citation scores and higher scientific output (Heinze and Bauer 2007; Islam and Miyazaki 2009). In the following, we consider scholars' external collaborations with scholars from other organizations, regions and countries.

Collaboration partners in nanotechnology do not only have to deal with the potential widespread use and impact of nanotechnology but also with concerns about its potential environmental impacts (Moore 2006) across its full lifecycle (Koehler et al. 2008), e.g., nanoparticles may be toxic, thereby negatively affecting human health (Oberdorster 2010; Gwinn and Vallyathan 2006). Therefore, nanotechnology has increasingly been a topic for social scientific as well as engineering research (Shapira et al. 2010). Such research has lead to improved risk assessment procedures (Grieger et al. 2012), as well as to a more complete investigation of the legal, ethical and regulatory framework for governance (Marchant and Sylvester 2006). The social, economic and policy significance of nanotechnology makes the critical reflection on its use in the context of interdisciplinary collaborations even more important.

3.2 The evolution of the scientific network of German nanotechnology

Germany has been very successful in worldwide nanotechnology, being one of the world leaders in innovative technologies for the past few decades (c.f. this and the following European Commission 2012b; Heinze and Kuhlmann 2008; Jansen et al. 2010). In particular, Germany is the European leader in commercialising nanotechnology.

Dating back to the early 1990s stakeholders have built on Germany's traditionally strong and diverse innovation system. The German innovation system has included both leading universities and research institutes as well as important engineering, IT and manufacturing industries. These industries are supported by strong and innovative small and medium sized companies. The large and diverse system of publicly funded German research organizations contributes considerably to nanotechnology as well (Heinze and Kuhlmann 2008): Specifically, the institutes of the Max-Planck Society, the Fraunhofer Society, the Leibnitz Association, as well as the Helmholtz Research Centres have been carrying out research in nanotechnology. Three of these four kinds of research organizations show particular concentrations (BMBF 2012; Heinze and Kuhlmann 2008): The institutes of the Max-Planck Society focus on fundamental research; those of the Fraunhofer Society concentrate on applied contract research; the Helmholtz Research Centres manage big-science research facilities. In contrast to these clear profiles the institutes of the Leibnitz Association have a diverse and undifferentiated focus. Given the variety of profiles, little collaboration between publicly funded research organizations has taken place (Heinze and Kuhlmann 2008). At the same time, they have collaborated on a regular basis with universities or firms.

3.3 Constructing the scientific network of German nanotechnology from publication data

From publication data we constructed the scientific network of German nanotechnology. In particular, we analysed co-authorship based on publication data. This method allows us to analyse a large sample and provides us with statistically significant results (Katz and Martin 1997). We used the Web of Science database of Thomson Reuters (2012), which contains abstracts, keywords, and the names of authors and their affiliations. We used the query by Arora et al. (2013) specifically designed to capture the latest achievements in nanotechnology. Carrying out this query for the time period from 2010 to 2012 left us with more than 270,000 publications in the Web of Knowledge. We included all publications with at least one author affiliated with a German organization, i.e., about 20,000 publications produced by more than 2000 organizations. Based on these publications we built a network of inter-organizational collaboration using co-authorship; if two authors from different organizations were listed on a publication, we considered this a collaboration. We limit our analysis to inter-organizational collaborations only, i.e. we did not include publications written by co-authors affiliated with only one organization. The resulting scientific networks of German nanotechnology are highly sparse with a long tail of organizations only rarely contributing to nanotechnology. Hence, we focus on the most productive organizations, thereby following a well-established procedure in publication analysis (Lotka 1926).

In the following, we restrict our analysis to the one hundred German organizations most productive in nanotechnology. To identify the one hundred most productive

German nanotechnology organizations, we prepared the data in three steps: First, we disambiguated the names of the organizations in the database, as organizations use variations of their names including English and foreign versions. Second, we allotted research output by equally crediting each author on the paper. Third, we added up all the credits for all existing collaborations between organizations. For a similar scheme of fractionating co-patenting, see Maggioni et al. 2007. Here, we were only interested in the collaborations actually materializing between research organizations. By this scheme we identified the one hundred German organizations most productive in nanotechnology research. The nanotechnology publications of the top one hundred German organizations account for more than 90% of the nanotechnology publications provided by German organizations in the period analysed (and more than 24% of world nanotechnology publications). Therefore, we can give a thorough though not complete picture of the scientific network of German nanotechnology.

The scientific network of German nanotechnology is illustrated in Fig. 2. In order to show the importance of organizations within this network, we calculated the Eigenvector centrality (Hannemann and Riddle 2005). The Eigenvector centrality helps us in identifying the most central organizations within the global structure of the overall scientific network of German nanotechnology. The size of the nodes indicate the level of the Eigenvector centrality, i.e. the higher the Eigenvector centrality, the bigger the node. The thickness of the links between organizations mirrors the amount of joint publications, so the thicker the line, the more output a joint collaborations produces. We fractionate publications to account for the contribution of authors and organizations.

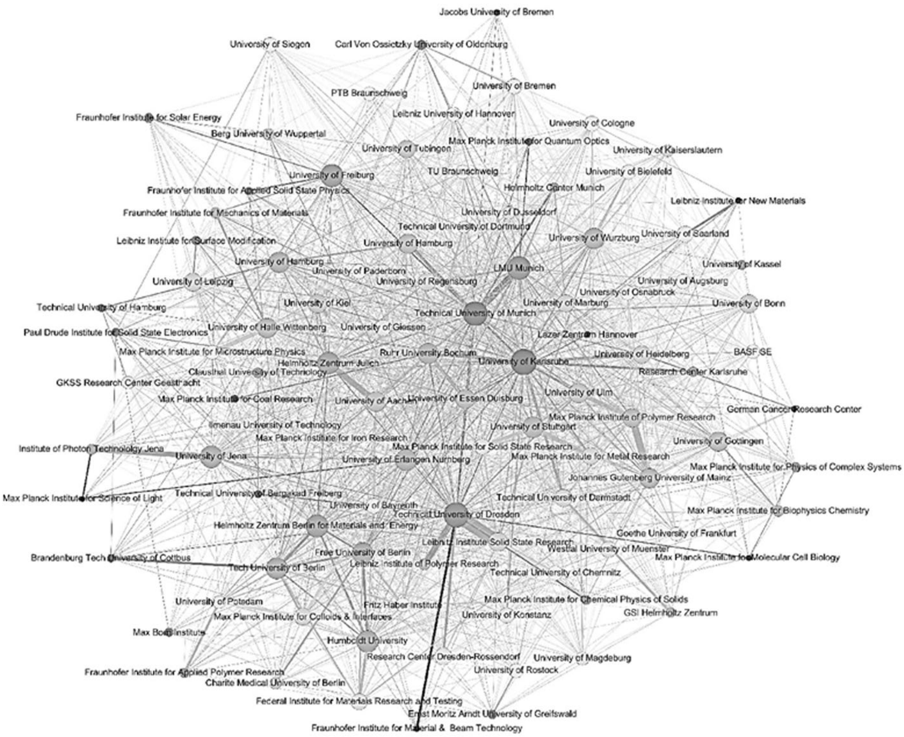

Fig. 2 German network of nanotechnology organizations

The scientific network of German nanotechnology mainly consists of universities and publicly funded research organizations, such as institutes of the Max-Planck Society, the Fraunhofer Society and the Leibnitz Association, as well as the Helmholtz Research Centres. Only one firm, BASF, appeared in our analysis. This is not surprising, as with publications we primarily depict the scientific part of the German nanotechnology network. As a rule, firms do not aim at publishing their results in academic journals (Nelson et al. 2014). Between 2010 and 2012, 38.2% of inter-organizational collaborations took place between universities, 14.2% between 'non-universities' organizations, as well as 47.6% between universities on the one hand and non-universities on the other hand. Among the top ten organizations accounting for a quarter of German nanotechnology publications, we find three publicly funded research organizations. It is notable that there is a representative of every major research association with the exception of the Fraunhofer Society, which ranks on the 84th place here. This is not surprising, as the focus of their research lies in applied research, which does not lead to publications in the first place but to patents, innovations etc. (Nelson 2009). A striking feature of the German innovation system in general and of the nanotechnology system in particular is the large share of publicly funded research outside the universities and in the research associations (Heinze and Kuhlmann 2008).

4 Proximity and collaboration in German nanotechnology: Variables and regression models

4.1 Dependent variables and the regression models

In order to account for the two stages of collaboration investigated here (see also Fig. 1 in Section 2.2), we define two different dependent variables namely the formation and the output of collaboration. Accordingly, we apply two different regression models capturing the influence of proximity on the formation (model A) and the output (model B) of collaboration in German nanotechnology. The independent variables (see Section 4.2) are the same for models A and B.

In the first model (model A), the dependent variable is the likelihood of two organizations in the network actually collaborating. Model A specifically tests the influence of different kinds of proximity on the formation of collaborations, i.e. it tests hypotheses 1, 3, and 5. Model A is a binary logistic regression capturing the influence of independent variables on a dependent dichotomous variable. Particularly, in our model A, we show the likelihood of organizations forming links governed by cognitive, organizational, physical and systemic proximity. Accordingly, the equation of model A is specified as follows

$$Y(X_1, ..., X_n) = \frac{e^{(\alpha+\beta_1 X_1+...+\beta_n X_n)}}{e^{(\alpha+\beta_1 X_1+...+\beta_n X_n)} + 1} \quad (1)$$

with Y being the binary dependent variable, α the intercept, β the coefficient for independent variable and X_i being the independent variables. The dependent variable is binary indicating either the existence or the absence of a link between two organizations. If the number of publications between two organizations is zero, the variable is also zero, indicating the absence of collaboration links between the two organizations. If there is at least one publication with authors affiliated with both organizations, the variable scores 1, indicating the existence of a collaboration between the two. We take all 4950 potential links between the one hundred German organizations most productive in nanotechnology into account here.

The second model (model B) specifically tests the influence of different kinds of proximity on the output of existing collaborations. Output, in terms of total publications, is the dependent variable in model B. This means that model B tests hypotheses 2, 4, and 6. Model B, a negative binomial regression, is specified as follows

$$Y(X_1, ..., X_n) = \alpha + \beta_1 X_1 + ... + \beta_n X_n \tag{2}$$

with Y being the dependent variable, α an intercept, β the coefficient of independent variable and X_i the independent variables. The dependent variable is ratio scaled. It was calculated by adding up the fractionated publications of each collaboration (for the method of fractionation see Section 3.3). In total we found 1994 collaborations in the scientific network of German nanotechnology.

To appropriately credit collaboration, there are several options for fractionating publications. In this paper we first divide the credit equally across all authors, and then award the respective organizations according to the affiliations of the authors. A comparable scheme for fractionating co-patenting activities is used in Maggioni et al. (2007). We use a similar scheme to consider the collaborative efforts embodied in a paper. If there are n authors in a paper, where $n > 1$, then there are n!/(n - 2)!2! bilateral collaborations present in the scientific network.

Both models as presented create an estimation and inference challenge. Specifically, there is a feedback loop whereby the joint production of papers results in a heighted capability to produce nanotechnology. This enhanced capability enables the researchers to produce more papers in the future. There is, therefore, an uncontrolled confounder that affects both dependent and independent variables in the regression equation, resulting in model endogeneity. This challenge is addressed by employing a form of instrumental regression. An instrumental variable representing the epistemic resources of one hundred leading German organizations is constructed. Most importantly the similarity and differences between the knowledge of German organizations is captured in the model. The variable must be carefully constructed to disentangle epistemic effects from other forms of proximity. This model remedy is described more thoroughly below.

4.2 Independent variables: Data and indicators

The independent variables comprise those representing physical, systemic, organizational and cognitive proximity as well as a control variable and a number of interaction variables. For building the indicators representing the independent variables we used publication data, the NUTS classification system and geographical information from Google Earth.

Physical proximity is the part of geographical proximity stemming from pure bodily closeness between collaborators (for details see Section 2.1). The geographical information we obtained by collecting the latitude and longitude data of the affiliation addresses given, for more information see Appendix 1. The data stems from Google

Maps (Google 2013) and contains a ratio scaled variable which is the logarithm of the distance between collaborating organizations. The formula used for the calculation of the physical distance is as follows:

$$D = \arccos\left[\sin\left(\frac{Lat1}{180^o}^{*}\pi\right)^{*}\sin\left(\frac{Lat2}{180^o}^{*}\pi\right) + \cos\left(\frac{Lat1}{180^o}^{*}\pi\right)^{*}\cos\left(\frac{Lat1}{180^o}^{*}\pi\right)^{*}\cos\left(\frac{Lon1}{180^o}^{*}\pi - \frac{Lon2}{180^o}^{*}\pi\right)^{*}R\right]$$

with D as distance, *Lat* and *Lon* as latitude and longitude data of pairs of collaborators and R as radius of the earth. This is simply the mathematical formulation of the Great Circle distance between two points on a sphere.

Systemic proximity is the part of geographical proximity mirroring that collaborators belong to the same or neighbouring innovation systems (For details, see Section 2.1). We use the Nomenclature of Territorial Units for Statistics (NUTS) classifications system to mirror systemic proximity as it indicate geographical entities systemically cohesive. This classification is a hierarchical system for dividing up the economic territory of the European Union using the three levels NUTS 1, NUTS 2, and NUTS 3 (Eurostat 2011; European Commission 2014). NUTS 1 relates to major socio-economic regions, e.g. the German Länder, whose governments are in charge of most research and education policies. NUTS 2 comprises more disaggregated units, e.g. mostly the German (former) Regierungsbezirke, often used for implementing specific regional measures. NUTS 3 are small regions that are used for specific diagnosis, e.g. the German *(Land)kreise* and *kreisfreie Städte*. NUTS 2 and 3 regions often cover local/ regional research communities. Researchers in NUTS regions are connected more closely because they are subject to a joint institutional structure and policy measures aiming at strengthening the system by bringing different innovative agents together. Therefore, we consider them a reasonable proxy for systemic proximity.

Organizational proximity is based on publication data. Two dummy variables represent organizational proximity. These variables in combination are used to show whether organizational proximity influences the formation or output of collaborations. We included one dummy variable indicating whether both of the collaborators are universities (*University*) and another one indicating whether both of them are 'non-universities' (*Non-University*). The two dummy variables represent three possible kinds of collaboration: first, only university partners collaborating (1 for the dummy *University* and 0 for the dummy *Non-University*); second, only non-universities collaborating (0 for the dummy *University* and 1 for the dummy Non-University); and third, a mix of both organizational types (0 for both dummies). As the dummies only score in cases of university or non-university collaborations,the mixed case is our reference.

In addition to organizational proximity, we look into the interaction between organizational type and cognitive proximity with the help of the terms *Cognitive proximity * University* and *Cognitive Proximity * Non-University*. Non-university organization does not only mean researchers from firms, but in particular also contains the institutes of the Max-Planck Society, the Fraunhofer Society and the Leibnitz Association as well as the Helmholtz Research Centres (For more details see introduction).

The variables representing *cognitive proximity* rely on publication data. In order to measure cognitive proximity, we constructed a research profile for each of one hundred leading German organizations as well as for the 4950 possible collaborations amongst them. We did so by using the science categories of Web of Science. The query used here provided us with six main categories for nanotechnology, namely Materials Science, Multidisciplinary Chemistry, Physical Physics, Applied Chemistry, Multidisciplinary Nanoscience & Nanotechnology Physics, Condensed Matter (Arora et al. 2013) to which we added an" everything else" category capturing the non-nanotechnology publications. In order to identify the research profile of the one hundred leading German organizations, we calculated the share of publications of an organization falling into these seven categories (cf. a similar approach Cunningham and Werker 2012). We did this by including all papers published by an organization, fractionally weighted by that organization's contribution (For the method of fractionation, see also Section 3.3). In order to identify technological closeness between collaborators, we calculated the research profiles for each of the 4950 possible collaborations between the one hundred leading German organizations. These were based on the separate and joint publications falling in each of seven subject categories, as mentioned above. By comparing the individual technological profile of an organization to the collaborative profile, we can identify the degree of cognitive proximity. Cognitive proximity is calculated as follows:

$$INFO(x,y) = \sum_{i \in X} \sum_{j \in Y} p\left(x_i, y_j\right) \log\left(\frac{p\left(x_i, y_j\right)}{p(x_i)p\left(y_j\right)}\right) \quad (3)$$

With INFO (x, y) we combine both relational information, i.e. the collaborative output, as well as non-relational information, i.e. the typical output of each of the partners. This formula is well-known and builds on the mathematical theory of communication (Shannon 1948), which has been widely discussed in information theory (MacKay 2003). When calculating the joint profiles of organization x and y, we consider each subject category i (see Appendix 2). We include both the profile of research done individually, p(x) and p(y), as well as the one done jointly, p(x,y). If organizations share exactly the same profile, cognitive distance between them is zero. While in principle the value of the variable could climb to infinity, here we ensure some minimum amount of cognitive proximity because of the category of 'everything else'. In the following, we use the unit of cognitive proximity in terms of quantities information. The correct unit for information using log(10) units is known as the Hartley; these can be easily converted to the more familiar bit of computer science, which is measured in log(2) units.

In Table 1, you find all independent variables, instrumental variables, and their descriptions.

In addition to the independent variables representing the cognitive, organizational, physical and systemic proximity we add a control variable and a number of interaction terms. We include the total number of publications of a pair of organizations as a control variable in the regression models. The purpose of the variable is to control for the output of organizations. On top of the control variable we include three interaction variables. As first interaction variable, we take the square of cognitive proximity. This variable controls for the possible non-linear effect expected for cognitive proximity (see Section 2.1). For the two other interaction variables, we multiply organizational by cognitive proximity. These interaction variables account for how universities as well as other organizations mediate cognitive proximity.

Table 1 Regression models' variables

Name	Description
Pure physical proximity	
Physical proximity	Logarithm of km distance between collaborators
Systemic proximity	
Shared NUTS1	Shared NUTS1 region
Shared NUTS2	Shared NUTS2 region
Shared NUTS3	Shared NUTS3 region
Bordered1	Bordering NUTS1 regions
Bordered2	Bordering NUTS2 regions
Bordered3	Bordering NUTS3 regions
Organizational proximity	
University (Univ)	Both of the collaborators are affiliated with a university
Non-University (NUniv)	Both of the collaborators are not affiliated with a university
Cognitive Proximity	
Cognitive proximity INFO(x,y)	Overlap of research specialisations of collaborators: 0 means complete overlap and 1 none at all
Interaction variables	
Square of Cognitive proximity	Square of Cognitive distance
Cognitive proximity * University	Interaction of University and Cognitive distance
Cognitive proximity * Non-University	Interaction of Non-University and Cognitive distance
Control Variable	
Publication	The average of the logarithm of the total number of publications

5 Proximity and collaboration in German nanotechnology: Results and implications

5.1 Proximity and collaboration in German nanotechnology: The results

We use two different model specifications and therefore we need two distinct approaches to generalize and interpret the parameters. Model A explains the formation of collaborations. For model A, we provide the beta coefficients with the corresponding odds ratios, i.e., Exp (B), as the coefficients alone just show the power of an exponent in the regression model and are hard to interpret. Model B explains the output of collaboration. For Model B, we provide the B both unstandardized and standardized. In Table 2 you find an overview of all variables' coefficients, their significance and their standard errors.

The analysis of the control variable, publication, shows four important results. First, the more publications an organization produces the more often it collaborates (model A). Second the more the partner organizations produce, the higher the expected output of any given collaboration, all things considered (model B). This effect is expected, because the more an organization publishes, the higher its academic success and reputation. This means that the more it publishes, the more desirable it is for future collaborations. Furthermore, a positive association between prior publication and

Table 2 Regression models' coefficient

Independent variables	Model A: Formation of Collaboration Logistic regression		Model B: Output of Collaboration Multi-linear regression	
	Hypotheses: 1, 3, 5, 7		Hypotheses: 2, 4, 6, 8	
	B	Exp(B) Odds ratio	Beta Unstandardized	Beta Standardized
Constant	2.608* (.147)	13.569	−.404* (.048)	–
Physical Proximity				
Physical proximity	−.231* (.120)	1.261	−.042 (.040)	−.041
Systemic Proximity				
Shared NUTS1	.341 (.333)	1.407	−.013 (.106)	−.004
Shared NUTS2	.853 (.653)	2.347	.168 (.194)	.036
Shared NUTS3	−.176 (.709)	.838	.639** (.207)	.113
Bordered NUTS1	.282 (.157)	1.326	−.022 (.052)	−.010
Bordered NUTS2	.091 (.279)	1.095	.287** (.089)	.087
Bordered NUTS3	−.342 (.568)	.710	.041 (.186)	.005
Control Variable				
Publication	2.369* (.131)	10.685	.430* (.044)	.197
Organizational Proximity				
University (Univ)	3.172* (.375)	23.857	−.074 (.060)	−.035
Non-University (NUniv)	−1.120* (.240)	.326	−.313** (.105)	−.082
Cognitive proximity				
cognitive proximity	−2.777* (.234)	0.062	.831* (.079)	.264
Interaction Variables				
Square of cognitive proximity	−10.197* (.471)	.000	.717* (.153)	.139
Cognitive proximity * Univ	−6.549* (.746)	.001	.602** (.210)	.095
Cognitive proximity *NUniv	2.258* (.583)	9.567	.000 (.319)	.000

(* the level of significance of the coefficient at 0.01 and ** at 0.05)

publication output in collaboration would be expected only by chance. As this effect was expected, we controlled for it in order to avoid it being captured by any other variable. The resultant model shows the incremental publication above expected output for any collaboration pair. Third, German publications on nanotechnology are mainly the result of collaborative research. This is reflected in the high odds ratio for the publication variable in Model A. If it would be done mainly internally, the odds ratio for this variable would be much smaller. Fourth, organizations not only look for new research partners but actively involve smaller parties to participate in existing collaborations. Prior institutional publication is introduced as a control variable in this model. If collaboration is in proportion to existing publication, the coefficient would be 0.50. Here the publication coefficient is less than 0.50, indicating the network is disassortative – large publishers actively seek and incorporate less active publishing organizations into the network.

By distinguishing *physical from systemic proximity*, we open the black box of geographical proximity providing nuanced results. Our outcomes reveal that, while physical proximity affects the formation of collaborations, systemic proximity partly affects the output of collaborations. Pure physical proximity goes hand in hand with the formation of collaborations. This result supports hypothesis 1. As suggested physical proximity does not influence collaborative output. Systemic proximity partly influences the output of collaborations: belonging to the same NUTS3 region or being located in bordering NUTS2 regions positively affects collaborative output. So, we do not reject hypothesis 2. The positive influence of belonging to the same NUTS3 region indicates that our results are in line with former analyses. Their results also indicate that on local levels organizations successfully form small regional innovation systems using established links, thereby exploiting the benefits of sharing common knowledge and institutions (Cooke et al. 1997). The outcomes obtained for the systemic proximity show that it has no influence on the formation of collaborations.

Our results on physical and systemic proximity give more nuances to geographical proximity, which has been investigated very thoroughly in the past. Obviously it helps forming a collaboration if scholars are working physically close to each other. The output of a collaboration remains unaffected though. However, working in the same NUTS3 region, the level of *Kreise*, as well as neighbouring NUTS2 regions within the same *Land*, positively influences the output of a collaboration but not its formation. Either systemic proximity on the district level captures the fact that people working within the same or neighbouring districts can use established links as well as share common knowledge and institutions.

Organizational proximity shows clear effects on the formation of collaborations and some effects on their output. Given the characteristics of the German non-university sector, collaborations with only university partners are organizationally closest, because the partners are subject to similar goals and incentives. In contrast, collaborations with only non-university partners are organizationally most distant, because the partners have to meet the goals and incentives of publicly funded research which differ substantially (see Section 3.2). Collaborations with university and non-university partners are in between, because universities employ scholars doing basic or applied research or a mixture of both. So, scholars in the various publicly funded research organizations can more easily find a fitting partner in the university than in the non-university sector. Collaborations containing both university and non-university partners are our reference point to which we compare the collaborations containing only university partners and the ones containing only non-university partners. According to hypotheses 3 and 4, collaborations containing only university partners would do best, while collaborations containing only non-university partners would do worst. The mixed collaborations serving as our reference point would be in the middle. Our results confirm hypothesis 3, as forming a collaboration is easiest with only university partners, while it is most difficult with only non-university partners. Thereby, our results confirm that organizations from the publicly funded non-university sector have not traditionally collaborated with each other (Heinze and Kuhlmann 2008). Moreover, we do not reject hypothesis 4, as interestingly mixed collaborations produce the highest collaborative output. We suggest that this result partly reflects the specific set-up of the German innovation system: while German universities usually span a broad spectrum of disciplines relevant for nanotechnology research. The publicly funded non-university sector is extremely specialised. The combination of the extreme specialisation of the non-university research institutes and the broadly embedded knowledge of university partners turns out to be particularly productive in terms of publication output.

Looking at the interaction terms between technological and organizational proximity we see the particular situation of the German non-university sector reflected as well. When the cognitive proximity decreases, the formation of a collaboration becomes more unlikely between university partners and more likely between non-university partners - again compared to mixed collaborations between university and non-university organizations. As the organizations of the German non-university sector of publicly funded organizations so profoundly specialized, they are often from the very outset cognitively distant. Interestingly, if collaborations between university partners exist, their output is the higher the more cognitively distant. Moreover, collaborations between the highly specialized publicly funded research institutes and broadly embedded university scholars turn out to be particular fruitful as well.

Regarding cognitive proximity and collaboration, we nuance former findings. These suggest that cognitive proximity positively influence output if partners are close but not too close (Broekel and Boschma 2012; Cunningham and Werker 2012; Ter Wal 2013). While our results confirm this inverted U-shaped relationship for cognitive proximity and the formation of collaboration, they show that, for existing collaborations, the partners produce more output the more cognitively distant they are. It is a rather small effect but significant. This indicates that too low a cognitive proximity affects a collaboration already in the formation phase, i.e. the partners do not embark on joint research project. However, in those cases where collaboration has been successfully established this collaboration produces more output the more different the partners are in cognitive terms. Thus, we neither reject hypothesis 5 nor 6.

While our results provide deeper and more detailed insights of the dynamics of collaborations, we acknowledge some limitations. Our results augment former findings on proximity and collaboration by pointing to the effects of different forms of proximity on the two stages of collaboration as well as to how specific features of an innovation system shape the scientific network. As noted, there are potential sources of endogeneity between the production of knowledge of organizations (as measured in papers) and the knowledge capabilities of the organization. Here, we addressed this endogeneity by creating and using an instrumental variable – the knowledge profile of the organization. This variable helps in the unbiased estimation of other model parameters, but the estimated effects of cognitive proximity may themselves be biased. A two-stage regression procedure for unbiased estimation, or a full-fledged instrumental regression procedure may be needed for more accurate estimates of cognitive proximity.

5.2 Implications for university management and research policy

Our results highlight the fact that proximity affects the formation of collaboration and output differently, thereby indicating a number of promising routes for university management and research policy. Regarding *physical and systemic proximity*, we suggest carefully considering the aim of policy and management measures. For example, if policy implements measures aimed at improving transport infrastructure measures, then they may achieve a reduction in commuting time between potential partners. This would enhance the likelihood of forming collaborations. However, the output of existing collaborations would not change. If policy makers intend an increase in output, they might consider investing in local knowledge infrastructure, thereby enhancing systemic proximity. Existing collaborations would benefit from knowledge and information in the local innovation system and therefore produce more publication output.

Our results on *organizational proximity* and collaboration hint at tailor-making research policy and university management. Particularly, non-university organizations, such as the institutes of the Max-Planck Society, the Fraunhofer Society, the Leibniz Association as well as the Helmholtz Centres, would benefit from overcoming a lack of organizational proximity. As these organizations are extremely specialised, research policy and university management might help overcoming a lack of organizational proximity. According to interviews with various stakeholders in German nanotechnology, there are three kinds of barriers to overcome (Heinze and Kuhlmann 2008). First, there are a number of stereotypes and prejudices that suggest that scholars from specific organizations are slower or less productive than others. Second, due to different missions and set-ups the working routines of the organizations are not compatible. Third, there is a lack of interface management amongst the headquarters of the different societies in place. The German Ministry for Education and Research already has established such projects for university-industry projects. To give an example, since 2003 it has funded several value-chain oriented collaborative projects aimed at connecting the scientific community with the commercial world (Zweck et al. 2008). So, policy could use this experience to bring together organizations from the non-university sector as well. Management of universities and research organizations could help collaborations by offering flexible solutions for partnerships with other kinds of organizations.

Our results point at *cognitive proximity* as one of the most important starting points for making policy and management decisions, because it has by far the strongest magnitude of effect on both the formation and the output of collaborations.[1] While cognitive proximity in terms of tapping into diverse knowledge bases has such positive effects on both the formation and even more on the output of collaborations, interdisciplinary collaborations form a substantial challenge. They require dealing with emerging integrated fields of knowledge that stem from different disciplines and domains (Etzkowitz and Viale 2010). When looking at our results, it becomes clear that forming a collaboration might be hampered by too much cognitive diversity, whereas collaborations' output thrive on it. This indicates that potential partners stay away from collaborations where lack of cognitive proximity obstructs its success. As this seems

[1] Particularly, it has the highest marginal effect in our models: This means that it has the highest contribution to the variations in the independent variable which can be seen by removing and adding this variable in our models.

to be a good self-regulating mechanism, university management and policy makers should stay away from the formation of new collaborations involving cognitively distant partners. However, if cognitively distant partners have already an ongoing relationship – according to our results – they are the more productive the more cognitively distant. So, policy might find it worthwhile supporting these collaborations. Existing German policy measures, such as The Initiative Networks of Competence Germany, which includes more than 9000 members from different technological fields (BMBF 2012), might be a useful starting point in this context. On top of that, one could think of web-based cluster portals and matching sites giving access to information about potential partners and various research initiatives. This would give potential partners sufficient information to decide whether or not to initiate a collaboration based on their expertise.

6 Conclusions

With our analysis, we illuminate how differently proximity affects the two stages of collaboration, i.e. formation and output. This becomes particularly obvious when opening the black box of geographical proximity by splitting it into pure physical and systemic proximity. Our results show that while pure physical proximity plays a role early on as it positively influences the formation of collaborations, systemic proximity affects collaborations later on by inducing higher output. Moreover, the specific features of publicly funded German research organizations influence the formation and output of collaborations via organizational proximity or a lack thereof. We find clear proof of the institutional set-up of innovation systems shaping collaboration networks. In addition, as cognitive proximity has by far the strongest magnitude of effect on both the formation and the output of collaborations, this might be an interesting starting point for successful university management and research policy. Particularly, existing collaborations with cognitively diverse partners have a lot of potential. Therefore, research policy and university management might consider designing specific measures stimulating current partnerships being cognitively different.

Our results provide the basis for two further research lines. First, because of our use of publication analysis, we focused on the scientific network of nanotechnology, i.e. scholars working at universities and publicly funded non-university organizations. In further research, we would like to complement publication with patent and other data - often found on the internet. That would enable us to include the industrial network. Second, we found that organizational and systemic proximity also captures the nature of the German innovation system. Including more countries in our analysis would enable us to investigate these effects more thoroughly. Further investigations of regional and national innovation systems, in particular their role for nanotechnology collaborations, might be fruitful in this context. Particularly, comparative analyses of the scientific networks of European nanotechnology with those of other leading countries, such as the US, Japan or China, might be promising.

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Appendix 1

Determining the exact geographical position of an organization

The network constructed in our paper is inter-organizational but based on co-authorships in publication. Following this approach and trying to calculate a distance between organizations we encounter a problem of defining the exact geographical position since usually organizations are located in several buildings. We can see it harvesting the addresses of individual researchers provided by the Web of Science database. In addition, these exact addresses are missing sometimes. We solve this problem by taking the addresses of headquarters checking in parallel that all authors from this organization are located at least within the same city.

Appendix 2

Table 3 Science Categories used in the calculation of technological proximity

Materials Science, Multidisciplinary
Chemistry, Physical
Physics, Applied
Chemistry, Multidisciplinary
Nanoscience & Nanotechnology
Physics, Condensed Matter
Everything else

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Affiliations

Claudia Werker [1,2] · Vladimir Korzinov [3] · Scott Cunningham [1]

[1] Department Technology Policy and Management, Delft University of Technology, Jaffalaan 5, 2628BX, Delft, The Netherlands

[2] TIME, RWTH Aachen University, Kackertstraße 7, 52072 Aachen, Germany

[3] Department of Economics and Management: Chair of Economic Policy, Karlsruhe Institute of Technology, KIT Campus Süd, Building 01.87, Rüppurger Str. 1a. Haus B, D-76131 Karlsruhe, Germany