Series A: Discussion Paper 2006-W02

Team diversity and research collaboration in life sciences teams: Does a combination of research cultures pay off?

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June 2006

ISBN 3-03724-090-3

Publication Series

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Acknowledgements

Some of the work on this paper was performed as part of the NetReAct project funded by the Institute for Prospective Technological Studies of the European Commission under contract 22540-2004-12 F1ED SEV DE. I thank the NetReAct partners Simon Robinson, Alexander Mentrup, Wolfgang Glänzel, Xuemei Li and Mike Thelwall for their contributions to this project. Moreover, the technical assistance from Gordon Wiegand with realising the survey is acknowledged.

Abstract

The combination of knowledge and skills from different backgrounds or research cultures is often considered good for science. This paper describes the extent to which academic research teams in the life sciences draw on knowledge from different research cultures and how this is related to their research performance. We distinguish between team diversity, where scientists with a background in another research discipline or country are members of the team, and collaboration between research teams. Summarising the results, we can state that the most successful teams have a moderate level of team diversity: 20-25% of the team members are from a different country or research discipline. These teams are involved in extensive collaboration activities, benefit from the positive influence of international collaborations and experience a mixed influence (increased productivity but lower impact) with regard to industry collaborations. Research team leaders and policy makers should take the ideal level of team diversity, i.e. moderate, into account in their recruitment practices and in relation to providing support for the professional integration of new team members from a different background.

Key words

Research teams, team diversity, research collaboration, research productivity

Table of Contents

1 Introduction

It is well-known that the origin of scientific revolutions and rapid progress lies at the intersections of different knowledge corpora (Bordons & Gomez, 2000; Gibbons et al., 1994; Nissani, 1997). When knowledge and skills from various backgrounds or research cultures are combined and applied, new problem solutions can emerge.

These research cultures can have their roots in *research disciplines* with distinct social organisation, ways of describing and delineating tasks or a specific set of approaches and methods (Becher, 1989; Whitley, 2000). The interdisciplinary composition of research teams has been proposed several times as one of the major features of modern research (Gibbons et al., 1994; Ziman, 1994). Ziman (ibid.) argues that interdisciplinarity is fundamental in modern science as the scale of research has grown, problems require broad knowledge from different disciplines and because cognitive lock-ins must be overcome. The supposed advantages of interdisciplinary research are numerous (Nissani, 1997). However, some authors also state possible disadvantages, in particular practical barriers (Younglove-Webb, Gray, Abdalla, & Thurow, 1999).

Differences in research cultures might also originate in specific *national cultures* as a result of the education system responsible for the socialisation as a professional scientist. The conviction that this kind of diversity is "beautiful" and beneficial for research teams is spreading among policy-makers in particular. For instance the European Commission states in its Communication on the Mobility Strategy:

> *"It [mobility, FB] permits the creation and operation of multi-national teams and networks of researchers, which enhance Europe's competitiveness and prospective exploitation of results." (European Commission, 2001, p. 4)*

Increasing the mobility of researchers has become a prominent goal in European research policy (European Commission, 2000, 2001, 2005). Geographical mobility may specifically lead to the combination of contextualised practices of knowledge production and fertilise the intellectual exchange (Jöns, 2003, 2006), foster international research collaboration and disseminate research excellence (European Commission, 2005).

Last but not least, diversity might also be the result of socialisation in an academic or *business environment* with different codes of conduct, norms and standards. Whereas scientists work according to a set of norms that has been described as CUDOS (communalism, universalism, disinterestedness, originality and scepticism), industry refers to a PLACE (proprietary, local, authoritarian, commissioned and expert) logic (Ziman, 1994).

As a diversity of research cultures is supposed to be very important for scientific advancement, we would expect that many studies would have investigated this in order to evaluate its effect on the performance of research teams, laboratories, institutes and other organizational units in science. However, this is not the case. Existing typologies of research laboratories tend to focus on their relationship with industry and other funding bodies and the products produced by the labs. Furthermore, the body of literature on the diversity of research teams is generally very limited. Only the issue of research collaborations has been investigated to any real extent, but to the best of our knowledge never in relation to the structures of the teams.

Our first goal is therefore to identify which strategies research teams apply in order to obtain knowledge from a different research culture: interdisciplinary, international or industry background. We distinguish between two generic approaches which can be employed:

1) The integration of such knowledge and skills into the team by recruiting staff who (supposedly) possess it.

2) Collaborating with other research teams which can make skills and knowledge available for a specific project and on a temporary basis.

In addition, our second goal is to obtain some insight into the relationship between different strategies of knowledge sourcing and a team's research performance. Research performance, however, is narrowly defined from a peer perspective: as research productivity, which is measured through the production of scientific papers in internationally recognised journals (the Thomson ISI Web of Science), and as research quality, which is measured according to the citations of these research papers.

The paper first presents a discussion of the state of knowledge on team diversity and collaboration in Chapter 1. Hypotheses are then formulated in Chapter 2 for the empirical analysis. Chapter 3 describes the data and methods employed. A typology of research teams using cluster analyses is presented in Chapter 4. In Chapter 5 we show and discuss the results of multivariate regressions on indicators representing the sourcing of knowledge from the research cultures considered as well as some control variables. The final chapter draws some conclusions and makes recommendations for team leaders and science policy makers.

2 The role of knowledge from other research cultures and its effects on research performance

2.1 Typologies or research teams

Our first objective is to produce a typology of university-based research teams in relation to the sourcing of knowledge from other cultural traditions. Firstly we look at the extent to which existing typologies take these issues into account. We found that with one exception these typologies are largely restricted to the relationship between research laboratories and the market, commercial interests or private enterprises:[1]

- The typology in Crow and Bozeman (1987) is based on two variables: the extent to which a laboratory performs public work, measured as the percentage of R&D financed by governmental funds, and the market influence on the lab, which is assessed on the basis of the type of products that the lab produces (public or private goods). In the process of collecting data by means of a survey and site visits at case study labs it became apparent that the laboratories differ in relation to several additional characteristics, such as the research scope, how far removed they are from the research frontier, their organizational stability and organizational structure.
- Another typology, developed on the basis of interviews with 20 French labs in the plant breeding and biochemistry fields, uses three dimensions: the fundamental or applied character of the scientific publications produced by the lab, the degree of dependence on industry funding and the bilateral or multilateral nature of their contracts (Joly & Mangematin, 1996). Four different types of laboratories were distinguished: Research centres for the profession, designers of generic tools and methods, basic and specialised laboratories and mutating laboratories. Each of these types acquires its research funds and interacts with industry according to a different logic.
- A distinct approach was followed by Larédo and his co-authors (Larédo, 2001; Larédo & Mustar, 2000). They constructed what they called a “research compass card” based on the activity profiles of French labs. These profiles consist of indicators on the labs’ relationship with different stakeholders (from scientific research, the education system, industry, public authorities plus the general public and other institutions such as media or museums). Larédo and Mustar (2000) identified various strategies for meeting the demands of these stakeholders and they drew the conclusion that these strategies and the

[1] These research laboratories are not exactly the same unit of analysis as research teams. Sometimes one team might equate to such a laboratory, in other cases two, three or more teams might equate to one. As Larédo (1999) shows, significant differences exist between countries in this respect. Previous classifications predominantly used French research laboratories and the results are also informative for the present purpose.

resulting activity profiles should be taken into account when evaluating the performance of labs.

- Finally, a recent classification of 83 labs in different disciplines at a large French university also addressed some of the issues which form the focus of this paper, namely the team structure according to subdiscipline and collaboration at international level and with industry (Carayol & Matt, 2004). The analysis uses lab size, research intensity, publication performance and openness (towards industry or internationally) of the labs to differentiate between five types. Type 1, the standard research-intensive labs, publish more than the average lab, are very interdisciplinary and have below-average industry relations. Type 2 are teaching-oriented labs in the social sciences and humanities with below-average publications and few co-authors from industry or from abroad. The labs of type 3 are not research intensive or industry oriented, but they collaborate frequently at international level and with industry. The top-performing labs in terms of publications (type 4) are small, are the most collaborative both internationally and with industry and are very interdisciplinary. Type 5, termed large laboratories, have average publication output, below-average industry relations and above-average international co-authorships. We can conclude that the types of laboratories with a high publication output (1 and 4) are rather small, but interdisciplinary; their links to industry and to international collaborators are either high (type 4) or low (type 1).

The scope of our analysis is somewhat broader, as it goes beyond the science-industry debate and addresses team structure as well as collaboration relationships. However, our set of industry-related variables and research performance variables used to assess the units is somewhat limited compared to the typologies listed above.

What do we know about how different cultural traditions and the differing approaches to obtaining those (i.e. recruitment or collaboration) affect the results of scientific research?

2.2 Team diversity and research performance

Research into the effects of work group diversity on group process and performance has shown that diversity may have negative as well as positive effects, depending mainly on the origin and degree of diversity and moderating influences such as task interdependence and organizational culture (Williams & O'Reilly, 1998). The positive effects are attributed to a broader range of knowledge, skills and contacts in diverse groups, and the negative effects are attributed to reduced and less efficient communication, less cooperation and more conflict (Bunderson & Sutcliffe, 2002; Williams & O'Reilly, 1998). They propose an overall curvilinear team diversity effect:

> *“Taken together, the overall effect of increasing diversity is likely to have a u-shaped form with some increments of diversity having large positive increases in group problem-solving capability with comparatively small*

> *negative effects on group functioning. Large amounts of diversity in groups may offer little in the way of added value from unique information and make group cohesion and functioning difficult." (Williams & O'Reilly, 1998, p. 90)*

Research into the diversity of R&D teams has focused on three particular issues: organizational tenure diversity, communication relations and functional diversity. It has been shown that R&D teams which maintain intensive communication relations with a simultaneous high degree of (organizational tenure) heterogeneity are more productive than more homogeneous and less communicative teams (Ancona & Caldwell, 1992; Reagans & Zuckerman, 2001). Functional or background diversity is due to differences in the education or functional specialty of the group members. Both, positive and negative effects on group performance have been found (Bunderson & Sutcliffe, 2002; Williams & O'Reilly, 1998). This was explained with the operationalisation of functional diversity (Bunderson & Sutcliffe, 2002) and with a trade off between internal network density and external network range (Reagans, Zuckerman, & McEvily, 2004). Few empirical studies have investigated the importance of disciplinary, country or sectoral (industry) diversity which could be the sources for such functional diversity.

Discipline diversity: Carayol and Matt (2004) indicate in their typology that research-intensive labs which have above-average publication rates per scientist are also very interdisciplinary. However, in their subsequent regression analyses, this indicator is no longer used. Younglove-Webb et al. explain a negative effect of disciplinary diversity on team performance due to the high costs of removing barriers to communication and coordination (Younglove-Webb, Gray, Abdalla, & Thurow, 1999). Such barriers may be the result of disciplinary chauvinism, differing goals, styles, attitudes and values, status differences, gender differences, or simply physical distance. A strong argument in favour of interdisciplinarity is made by Hollingsworth and Hollingsworth (Hollingsworth & Hollingsworth, 2000): when analysing two case studies of globally leading biomedical research organisations, they suggest that diverse but scientifically integrated staff capable of communicating and bridging the disciplinary boundaries were conducive to making major biomedical discoveries during the entire 20th century. However, they also warn against the danger of "hyperdiversity" which can lead to ineffective communication (Hollingsworth, 2002); such hyperdiversity represents a serious challenge to building common ground (Younglove-Webb et al., 1999). Previous studies have corroborated the finding that interdisciplinarity is particularly common and important in the life sciences (Carayol & Nguyen Thi, 2004; Quin, Lancaster, & Allen, 1997; Sanz-Menendez, Bordons, & Zulueta, 2001). Based on these results we expect a non-linear relationship between the level of disciplinary diversity and the research performance of a team and propose the following hypothesis:

> *H1: Interdisciplinary research teams perform better than disciplinary teams and teams with very little interdisciplinarity. For very interdisciplinary research teams, however, the performance measures are lower than for moderately interdisciplinary teams.*

Country diversity: Empirical studies into the influence of people with a background in a different national, ethnic or religious culture and education system on a team's research performance are even scarcer. An investigation into the Rockefeller Institute's scientific success stresses the contribution of foreign permanent staff as well as visiting scientists (Hollingsworth & Hollingsworth, 2000). However, this contribution might also have been due to scientific eminence. For the US it has been shown that foreign-born and foreign-educated scientists make more exceptional contributions to scientific output than would be expected from their proportion of the scientific workforce (Stephan & Levin, 2001). Jöns argued that cross-border scientific interactions might lead to inspiration and cooperation but also irritation and confrontation, depending on the degree of heterogeneity between the involved parties (Jöns, 2003). We summarise that a certain level of country diversity in research teams might be beneficial to their performance, but above this level communication and cooperation is reduced and conflict increased thereby preventing cross-fertilisation among the team members. This is expressed in the following hypothesis:

> *H2: The more diverse the country composition of research teams, the better their research performance. For very international research teams, however, the performance measures are lower than for moderately international teams.*

Industry diversity: Studies of academics' mobility between science and industry can provide some insight into the results of the interaction between both sectors. A recent study (Dietz & Bozeman, 2005) obtained the result that movers between academia and industry increased their productivity for the five-year period after the move, regardless of the direction in which it occurred. Excessive movement ("low homogeny") is correlated with a lower publication output. A different aspect of mobility was investigated by Adams et al. (Adams, Black, Clemmons, & Stephan, 2005) in relation to top-level US American research institutions. These collaborate more with other research institutions, private firms and foreign research institutions if their research staff were formerly PhD students at these organisations. We propose the following hypothesis:

> *H3: The establishment of personnel connections with industry improves the research performance of research teams.*

2.3 Research collaboration and research performance

The internal diversity is only one possible channel for a team to combine knowledge and technical skills from different cultural backgrounds - in the sense of academic, industrial or national cultures. Another channel is the acquisition of knowledge through research collaboration. Katz and Martin conclude that the empirical evidence supports the concept of a positive relationship between collaboration and research productivity (Katz & Martin, 1997). It is not only collaboration which is important, but also *who* the collaboration partners are. This determines what type of advantage the collaboration generates. The characteristics that receive the most attention in the scientific discussion of research collaborations are: (1) disciplinary versus interdisciplinary collaborations, (2) local versus global collaborations, and (3) public versus private collaborations.

Disciplinary versus interdisciplinary collaborations: Hinze has shown that in autoimmune diseases – a specific life science field – a large percentage of publications may be classified as cross-disciplinary (Hinze, 1999). Analysing Spanish research teams in two biomedical fields and in material science, Sanz-Menendez et al. (Sanz-Menendez, Bordons, & Zulueta, 2001) have shown that collaboration between teams from different disciplines is more common if the research teams consist of scientists from a single discipline. Hence, interdisciplinary collaborations within and between research teams are in a way substitutes. We do not know of any analysis that attempted to measure the effects on publication productivity of interdisciplinary research collaboration between teams. In a recent analysis of 62 multi-institutional and multidisciplinary NSF projects, Cummings and Kiesler found no significant relationship between the number of disciplines in a project and the number of new ideas and tools produced by these projects (Cummings & Kiesler, 2004). In parallel to H1 above, we therefore propose:

> *H4: Research teams involved in interdisciplinary collaborations perform better than teams without interdisciplinary collaborations.*

Local versus global collaborations: Various reports show that the importance of scientific collaboration at international level has increased over the past 25 years (European Commission, 2003; Narin, Stevens, & Whitlow, 1991; National Science Board, 2002, 2004). However, the level of collaboration varies according to scientific specialty and country. Within the life sciences, notable differences exist. For instance, US American zoologists have been found to have many collaboration partners and to collaborate intensively at international level, whereas the collaboration networks of general biologists and biochemists overall, and at international level in particular, are rather small (Bozeman & Corley, 2004).

In principle, the benefits quoted for international research collaborations are of the same nature as those listed for collaboration in general, see e.g. the benefits listed by Georghiou (1998); but international collaboration clearly gives rise to additional costs, for instance due to the necessity of bridging linguistic and cultural differences or finding suitable contractual arrangements. However, it is clear that international collaboration must bring additional benefits which outweigh higher transaction costs; otherwise it would be hard to explain its impressive growth rate. Such benefits might be access to equipment, local resources, data or other objects of study, or to eminent scientists and groups (Georghiou, 1998; Thorsteinsdóttir, 2000; Wagner, 2005).

Empirical evidence of the impact of international research collaborations on research productivity is mainly positive. Several studies have confirmed this for the life sciences. A study of Spanish biomedical research shows that international collaboration increased the productivity of the team leaders and the impact of the published work (Bordons, Gomez, Fernandez, Zulueta, & Mendez, 1996). Italian studies found a positive effect of the number of research collaborations with foreign non-profit institutions on the productivity of molecular biology and genetics research groups (Arora, David, & Gambardella, 1998; Cesaroni & Gambardella, 2003).

According to Narin et al. (1991) their finding that biomedical papers with international co-authors have greater impact than single author papers and nationally co-authored papers can be generalised to other disciplines. This is shown by Glänzel (2001) for a range of countries. He also found that co-publications of several country pairs may attract fewer citations than expected on the basis of the corresponding domestic reference standards and termed this type of co-publication links “cool links” (Glänzel & Schubert, 2001). In contrast to biomedical research, where the observed citation impact of most analysed countries was higher than the domestic impact of at least one of the involved partners, and often also higher than the world standard, the impact of joint papers of some countries was unambiguously low in chemistry and mathematics. It may therefore be the case that international co-authorship is not always beneficial for all partners. Other studies have shown that international collaboration generally has a more pronounced positive effect on citation impact than local or domestic collaboration (Adams, Black, Clemmons, & Stephan, 2005; Persson, Glänzel, & Dannell, 2004). However, this might also be caused by a self selection effect – only the best scientists collaborate at international level (Bordons & Gomez, 2000) – and increased self-citations (Herbertz, 1995). Adams et al. (2005) find a trade-off between quantity and quality, i.e. international collaboration had a negative effect on the number of publications but a positive effect on citations. Contrary to their own expectations, Carayol and Matt (2004) find that the proportion of internationally co-authored publications and research productivity are not correlated.

> *H5: Research teams collaborating internationally perform better than teams without international collaborations.*

Public versus private collaborations: The literature on collaborations between public research organisations and private firms is far too broad to be reviewed here in its entirety. The topic has been discussed for instance in the economics of innovation literature (W. M. Cohen, Nelson, & Walsh, 2002; Mansfield, 1991; Salter & Martin, 2001); in the interdisciplinary literature on technology transfer (Bozeman, 2000; Charles & Howells, 1992; Rogers, 2002); and in different strands of sociological and interdisciplinary science studies (Gibbons et al., 1994; Leydesdorff & Etzkowitz, 1997). This list is certainly only the tip of the iceberg and often focuses on the social and economic consequences of scientific research. Also, it discusses a wealth of channels or carriers through which the exchange of knowledge is realised. However, here we are dealing with a narrower problem and almost from the opposite direction: What is the influence of research collaborations between science and industry on the research performance of the scientific partners in particular research teams?

Brooks (Brooks, 1994) and others have pointed out that industry benefits from science, but science also benefits from industry. For instance, scientists may obtain new research questions or instrumentation and techniques from the exchange with private firms. Private firms provide funding for scientific research projects and open their doors to students at all levels to apply their knowledge and practice their skills. However, concerns have also been raised (Hicks & Hamilton, 1999; Joly & Mangematin, 1996; Landry, Traore, & Godin, 1996): because of private funding, public research may be diverted from the more fundamental type of research problem to the more applied type; firms might introduce restrictions on the disclosure and publication of research results because they want to exploit them first; private funding might be more volatile than public funding. This raised concerns regarding negative long-term effects on the speed of scientific progress. Do the benefits or the costs prevail? Hicks and Hamilton show that papers with co-authors from science and industry are more often cited than single-university papers (Hicks & Hamilton, 1999) and Landry et al. point to the higher productivity of Canadian scientists who collaborate with industry (Landry, Traore, & Godin, 1996). Van Looy et al. find higher productivity for scientists linked to industry (Van Looy, Ranga, Callaert, Debackere, & Zimmermann, 2004). A positive correlation between links with industry and research productivity is found for French labs, but only in bivariate correlations and not in a multivariate regression (Carayol & Matt, 2004). Moreover, some of the above-mentioned concerns are also confirmed (Hicks & Hamilton, 1999; Landry, Traore, & Godin, 1996).

> *H6: Research teams involved in collaborations with scientists from industry perform better than teams not involved in such collaborations.*

2.4 Research teams

Before providing further details on the data and methods that we used, we will first elaborate our understanding of research teams, the unit of analysis of this paper. Research teams or research groups have been considered as one of the basic social entities in the sciences since the early works on the social organisation of science (Hagstrom, 1965; Price & Beaver, 1966). The identification of research teams is not a trivial issue, as no clear institutionalised delimitation exists. Previous analyses used different approaches for defining research groups:

- The institutional definition considers all researchers in the same unit of an organisation (J. E. Cohen, 1981; Hagstrom, 1965). This definition requires particular treatment of technicians and administrative staff, PhD students, guests and visitors and of multi-organisation teams.
- The functional definition of research teams is based on joint research activities. It can result in teams limited to one single organisation or teams drawing membership from several separate organisations (UNESCO study see Andrews, 1979). The functional definition must specify what joint research actually means – the UNESCO research team, for instance, specified this temporally with a minimum of eight hours of team-related work per week and scientist and a minimum group size of three scientists.
- The definition of research groups based on co-authorships (e.g. Adams et al., 2005; Bordons & Zulueta, 1997; Seglen & Aksnes, 2000) identifies methods and thresholds for adding co-authors to a particular group. It does not include unproductive scientists and is therefore somewhat problematic when it comes to assessing the relationship between group size and research productivity (Stankiewicz, 1979).

A common link for the definitions is that they all view teams as entities in which scientists work together to produce new knowledge. They differ in regard to how they assess this joint work and whom they count as a scientific worker. For the present study, a functional definition was considered to be the most appropriate. The institutional definition would have forced us to ignore the open organisational approach to research groups adopted in some countries, where mixed teams are very common (e.g. France). The definition based on co-authorships tends to underrepresent certain staff groups which were deemed important in this analysis, in particular PhD students. *Hence, we understand as a research team or research group a group of people, scientists and non-scientists, which works in the same location for a certain time period to produce new scientific knowledge. The group of people is part of a larger organisation (university, department, school etc.) and at least some of its members are employed by a university. Also, the team is recognized from the outside as a separate entity.*

The definition includes certain restrictions in regard to location, time and people. The geographical restriction may be somewhat counterintuitive in view of the growing trend towards virtual collaboration facilitated by the internet. However, this is necessary in order to clearly meet one of the main objectives of the study: juxtaposing the effects of group structures with inter-group collaboration. The inclusion of non-collocated and virtual members in the groups would have made this difficult if not impossible. For the same reason, visiting scientists and guest workers were not included in the research teams. Furthermore, such people might be attracted to a team by its good research performance, though in this case they are a consequence of high productivity rather than its source (J. E. Cohen, 1981). To exclude short-term guests and visitors we set a minimum residence with the group of twelve months.

3 Data and methods

3.1 The data set

The analysis uses data on research teams in the life sciences defined according to the ISCED 1997 category 42 and affiliated to universities in 10 different European countries. Through internet research an overall population of 7,732 teams was identified (see Table 1). A stratified, random sampling process was used to draw a sample of 1,773 teams. The stratification variable was the number of hyperlinks pointing to the team's internet homepage (inlinks) according to Google (teams without a homepage were included in the lowest stratum). This indicator was chosen as a readily available proxy indicator for the research performance of the team, as previous research has shown that for academic organisations, the number of hyperlinks is related to research performance (Thelwall & Harries, 2003). For the sample teams we identified the names and email addresses of the team leaders via the internet; for the majority of the teams we were also able to obtain some staff information about the total scientific and non-scientific staff (77.5% of the teams), the PhD students (53.8%) and the post-docs (39.3%).

Table 1: Dataset of life sciences research teams by country

Country	Research population	Sample	Usable questionnaires				
			Number	In % of sample	Mean no. of inlinks	Mean team size	% of female heads
CZ	173	119	30	25.2%	1.6	12.8	23.3%
DE	1,447	271	60	22.1%	9.5	16.6	20.0%
ES	896	164	37	22.6%	1.9	14.8	8.1%
FR	1,384	225	56	24.9%	4.4	16.8	12.5%
HU	214	108	34	31.5%	5.8	22.3	17.6%
IT	952	186	52	28.0%	1.5	8.8	21.2%
NO	199	122	37	30.3%	7.8	11.0	18.9%
PT	229	123	44	35.8%	11.4	12.6	50.0%
SE	650	148	41	27.7%	7.3	12.3	26.8%
UK	1,588	307	77	25.1%	8.7	13.1	13.0%
Total	**7,732**	**1,773**	**468**	**26.4%**	**6.4**	**14.3**	**20.5%**

Source: NetReAct (FHSO).

The team leaders of the sample teams then received an electronic questionnaire (either as an email attachment or as a personalised link to an online questionnaire). This questionnaire contained questions on the team, its structure and team members and its collaboration activities with reference to the year 2003. The questionnaire was accessed by 811 respondents leading to 468 usable questionnaires (26.4% of the sample teams, see Table 1). The number of inlinks, team size (according to the internet) and gender of the team leader were verified for the sample to check whether the responses were representative. The only limitations to representativeness are: the Italian teams that responded tended to have fewer hyperlinks (= worse research performance) than the Italian teams which did not respond. Among the responding German teams, those with female team leaders are overrepresented and among Spanish teams they are underrepresented. These limitations will be taken into account in the interpretations.

Using the information obtained from the internet and the survey it was possible to retrieve bibliographic data for the responding teams from the Thomson ISI Web of Science. The publication data collected was for the year 2001 and the citation data for the years 2001-2003. The mismatch between survey data (for 2003) and publication data (for 2001) is one of the major weaknesses of the analysis. It would have been preferable to collect publication data on two or more years starting in 2003.

3.2 Operationalisation of the hypotheses

The teams' research performance was measured according to three different variables built on bibliographic data extracted from the Science Citation Index Expanded (SCIE) of Thomson ISI: 1) the total number of papers recorded in the 2001 SCIE volume as article, letter, note, or review (TOTPAP); 2) the TOTPAP variable was normalised by team size to obtain a productivity indicator (ZTOTPAP); 3) citations received by these papers in the years 2001-2003 were counted and divided by the number of papers obtaining the Mean Observed Citation Rate (TOTMOCR) per team which can be considered as an indicator of the quality of these publications. Of course, these indicators and the SCIE database have several well documented weaknesses: not necessarily all co-authors of a publication really contribute intellectually, a bias towards English language publications might give an advantage to native speakers, self-citations inflate citation scores, citations might be created for other reasons than the quality of a paper etc. (Borgman & Furner, 2002; Cronin, 1984; Herbertz, 1995; Leeuwen, Moed, Tijssen, Visser, & Raan, 2001; Raan, 2003). Notwithstanding these weaknesses, publications and citations are generally accepted measures for assessing research performance.

The hypotheses relate to three dimensions of internal structures and collaborations: the importance of interdisciplinary work (H1, H4), their international orientation (H2, H5), and relationships with industry (H3, H6).

- H1: In response to different survey questions, the team leaders indicated the fields in which they themselves and their post-docs had written their PhDs, as well as the fields in which their PhD students were currently writing their theses. The responses listed 35 different fields in the life sciences and adjoining disciplines as well as an additional "other fields" alternative. Using an approach similar to (Carayol & Nguyen Thi, 2004) a Shannon Diversity Index of PhD fields was calculated for measuring the diversity of fields present in each team:

$$\mathrm{FDIVALL} = \sum_{i=1}^{C} (p_i * \ln p_i)$$

with	FDIVALL	Field diversity index
	C	Total number of different fields *i* of the team members' PhD theses
	p_i	Proportion of C made up of the *i*th field

- H2: The country diversity of the team was measured using similar diversity indices. Separate indices were calculated for the PhD students (CDIVPHD) and post-docs (CDIVPDOC) of each team based on the information about the countries in which they obtained their most recent degrees. Each country listed in the responses received a separate coding.

- H3: In order to analyse the effect of industry training on a team's research performance, it would have been necessary to obtain data on the previous employment of team members in industry. This information was not collected, as the survey focussed on the situation of PhD students and post-docs. H3 cannot therefore be investigated further.

- H4: Data for the role of interdisciplinary collaboration was also assessed in the survey. Team leaders were asked to list the number of research teams in fields other than their own with which they collaborated. As the team size was positively correlated with the number of collaboration partners, we calculated a ratio of collaborating teams from other fields per team member (INTDISCO).

- H5: The significance of international collaborations was analysed with data retrieved from the Thomson ISI database. Co-authors on the teams' publications in 2001 were assigned to categories. The analysis makes use of three binary indicators on these co-authors: the first indicator takes the value of one if the team has published one or more papers with co-authors from any foreign country, otherwise it is zero (ICPAP01); the second indicator EUCPAP01 is constructed similarly, becoming one if a paper has been published with co-authors from another EU member state (and zero otherwise), and the third indicator is one if the team has published papers with co-authors affiliated to organisations in the US (USCPAP01).

- H6: For industry relationships we also used an indicator based on the bibliometric data, namely if teams had published with co-authors from industry the indicator was assigned the value one and otherwise it was zero (BCPAP01). In addition, we included another indicator based on the survey which used the information on the funding of PhD students and post-docs. Teams that had at least one PhD student or post-doc funded by industry were assigned the value one and all other teams were set to zero (INDUFUND).

Some words of caution are necessary regarding the last two publication-based indicators: it is well known that co-authorship often reflects an intense interaction of the collaborators (Harsanyi, 1993; Laudel, 2001). At the same time, co-authors might be included for totally different reasons, e.g. because they secured the resources for a project and participated during its conception. However, as our level of analysis is the research group, we presume that the latter factors do not introduce a significant bias in the collaboration counts and we take the collaboration data as a conservative estimate of the teams' actual collaborative research activities at international level and with industry.

In addition to these variables, the baseline analyses included a set of control variables. The variables were included on a case-by-case basis if they improved the estimation results. These control variables took into account different team characteristics which were found to be influential in previous work (see the review above): the country in which the team was located, the principal research discipline of the team, time since the team's foundation (age), team size and the proportion of different types of staff (principal investigators (PI), PhD students etc.). They also referred to the particular characteristics of the team leaders which might affect their research performance: their gender, experience (measured as the number of years they have been leading a research team) or recognition assessed through questions on the professional attention that they received since 2000.[2]

3.3 Methods of data analysis

Cluster analyses

The first analytical task was a classification of the research teams according to their internal structures and collaboration activities. This task was achieved by means of hierarchic cluster analyses of the teams using survey data and bibliometric data. The baseline model of the cluster analyses used the squared Euclidean distance as the distance measure and the Ward algorithm for the cluster identification, a method that has proven its validity in previous studies (Bacher, 1996). In order to analyse the sensitivity of the results in relation to this method, a control cluster analysis with a different distance measure and clustering algorithm was performed (Euclidean distance and Complete Linkage clustering). The cluster analyses were carried out with the SPSS software package, version 14.0.

As the results of a cluster analysis might be influenced by high correlations among included variables and outliers in the dataset, both issues had to be verified first. Correlation coefficients among the included variables indicated that correlations were not a particular problem – the largest Pearson correlation coefficient was only 0.25 between the diversity indices for the countries of PhD students and post-docs. Seven outliers were identified by means of a process described by Buttler (Buttler, 1996). These seven cases were excluded from the initial hierarchic clustering. The results of the hierarchic cluster analysis were then subjected to a k-means cluster analysis using the arithmetic means of each cluster as the initial cluster centres. In the k-means analysis, all outliers and cases with one missing value were then added to a cluster and the results from the hierarchical cluster analysis were re-classified.

[2] This was assessed through five related questions: "Since 2000, has your work been recognised in any of the following ways? Have you (a) won a scientific award, (b) been invited to serve on a major professional committee, (c) been invited to serve on the editorial board of a scientific journal, (d) organised an international conference, (e) been invited to serve on a national or international advisory committee."

Regression analyses

The second analytical task was the identification of those factors which influence the performance of research teams or are at least related to it. Different forms of regression models were estimated to perform this task.

The first dependent variable of total number of papers listed in the SCIE database in 2001 (TOTPAP) is a non-negative integer. Count data models can efficiently deal with such variables. The baseline approach of count data models is a Poisson regression model. If the dependent variable is subject to overdispersion – the variance exceeds the mean – the negative binomial regression model (NEGBIN) is preferable, as it permits this difference (Cameron & Trivedi, 1998). We tested for overdispersion as described in Cameron and Trivedi and include the alpha values from the NEGBIN estimation in the results tables – significant alphas indicate overdispersion. Moreover, if the dataset contains many zeros ("zero inflated" or ZI) either Zero Inflated models or Hurdle models can deal with this. The Vuong statistic is proposed as a test statistic for zero inflation (Greene, 2000). Zero inflation was not a problem with our dependent variable according to the results for the Vuong Statistic (not shown). Because count data models do not have simple quality measures such as the adjusted R^2 of regular regressions, the difference between the Log-L and the restricted Log-L – in this case the NEGBIN versus the Poisson model – can be used as a quality measure of the estimations.

The second and third dependent variables were both non-negative metrics. We used simple Ordinary Least Squares (OLS) regressions for these variables. The adjusted R^2 indicated the percentage of the variance of the dependent variable which is explained in the estimations. A particular problem of regressions is heteroscedasticity of the residuals, meaning that their variances are not constant across observations. Heteroscedasticity which is dependent on a particular explanatory variable can be evaluated using the Goldfeld-Quandt test. We used this test to identify heteroscedasticity which is dependent on the team size and adjusted the estimations accordingly by using the White estimator or, alternatively, including team size as a weighting variable as described by Greene (Greene, 2000). The estimations were carried out with LIMDEP, Version 7.

4 Typology of research teams based on cluster analyses

4.1 Results

The baseline hierarchical cluster analysis produced a four-cluster solution. 35 cases (9.4%) were regrouped in the k-means clustering. The control cluster analyses with a different distance measure and linking algorithm also produced four clusters; however, 101 out of 438 cases (21.6%) were classified differently. This indicates that the borders between the clusters are not sharp and about one fifth of the teams could belong with equal probability to at least two different clusters. Excluding these 101 teams from the clusters does not change the cluster profiles in any way relevant to the following interpretations and the results are therefore not shown.

Clusters A, B, C and D consist of 230, 133, 56 and 19 teams. 30 cases (6.4%) had to be excluded because the dataset was incomplete in a way that did not permit their inclusion. In the following tables these four clusters are described according to the three dimensions included in the analysis as well as several additional variables.

In order to analyse the practice of *interdisciplinary work and the sourcing of interdisciplinary knowledge*, we investigated the degree of collaboration with teams in other fields (INTDISCO) and the field diversity of the teams (FDIVALL). The clusters exhibit differing profiles (see Table 2). Cluster A has below-average interdisciplinarity values for both team structure and collaboration with other teams. Cluster B is composed of teams with a particularly high team member field diversity, whereas interdisciplinary collaboration with other teams is low. Cluster C exhibits a degree of interdisciplinarity that is very close to the overall average for all indicators. The teams in cluster D differ from the rest in particular on the basis of their very high number of collaborating teams from other fields per team member.

The five different clusters also have clearly distinguishable profiles for the variables used to indicate the degree, type and direction of the teams' *international orientation*.

- Cluster A, the largest cluster, is made up of the least international teams in the sample. They very rarely published with international co-authors (ICPAP, EUCPAP, USCPAP, see Table 2) and have very few PhD students or post-docs who obtained their most recent degree abroad (see Table 3): only 10% of teams have a PhD student or post-doc with a degree from another EU country or a country outside the EU and US. These teams have almost no PhD students or post-docs with degrees obtained in the US.
- Cluster B is also somewhat below average in relation to internationally co-authored papers. However, this cluster has the highest staff diversity. The large diversity (by country of most recent degree) of the teams' PhD students (CDIVPHD) is remarkable. More than half of the teams have a PhD student from

another EU country (PHD_EU), more than 60% have a PhD student from a foreign country outside the EU and the US (PHD_INT) and 12% have PhD students from the US (PHD_US). Similar country diversity values were obtained for post-docs.

- Cluster C is characterised by very high numbers of internationally co-authored papers (ICPAP) and papers with co-authors from the EU (EUCPAP) or the US (USCPAP) per team member. The country diversity of PhD students is close to the overall average, whereas for post-docs it is just above the average.
- Cluster D is characterised by average numbers of internationally co-authored papers and low degrees of internationality for the teams' PhD students and post-docs. An exception is the large percentage of teams with post-docs who obtained their PhD in the US (PDOC_US). However, it should be borne in mind that the cluster consists of only 19 teams and that this figure might not be representative.

The final issue of team classification is the extent to which teams were *involved with industry*. Two types of relationships are considered: the joint publication of papers with co-authors from industry (BCPAP01) and the funding of team members (PhD students or post-docs) by industry (INDUFUND). Both variables are dummy variables and Table 3 shows the percentage of teams per cluster that has either published with industry partners or received funding from them. Strikingly, industry funding and joint publishing are not very well correlated: Nearly one third of the teams in cluster C published with industry in 2001, but only 4 out of the 56 teams (7.1%) had either PhD students or post-docs funded through industry contracts. The cluster A and B teams both published with industry and received some staff funding, whereas the teams in cluster D had negligible industry contacts.

Table 2: Cluster profiles 1 (means and standard errors)

	Cluster A		Cluster B		Cluster C		Cluster D		All teams		ANOVA F-Value
	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	
Interdisciplinary work											
INTDISCO	0.18	0.01	0.19	0.02	0.25	0.04	2.11	0.46	0.27	0.03	109.36**
FDIVALL	0.46	0.03	0.96	0.04	0.55	0.06	0.49	0.12	0.62	0.02	33.84**
International orientation											
ICPAP (all countries)	0.07	0.01	0.10	0.01	0.60	0.07	0.14	0.06	0.15	0.01	100.30**
EUCPAP	0.04	0.00	0.05	0.01	0.33	0.04	0.09	0.04	0.08	0.01	80.62**
USCPAP	0.01	0.00	0.03	0.01	0.15	0.03	0.03	0.02	0.04	0.01	32.40**
CDIVPHD	0.14	0.02	0.81	0.03	0.33	0.05	0.15	0.07	0.37	0.02	126.58**
CDIVPDOC	0.06	0.01	0.66	0.04	0.44	0.07	0.14	0.08	0.31	0.02	69.60**
Team members											
Principal investigators	2.3	0.1	2.8	0.3	1.6	0.2	1.3	0.2	2.3	0.1	4.11*
Post-doctoral researchers	1.9	0.2	3.0	0.3	2.0	0.2	1.0	0.2	2.2	0.1	6.29**
Other res.	1.4	0.2	1.7	0.4	0.7	0.2	0.4	0.1	1.4	0.1	2.10
PhD students	4.1	0.3	5.7	0.5	3.9	0.3	1.7	0.3	4.5	0.2	7.46**
Other res. students	3.0	0.3	2.8	0.4	2.0	0.3	0.8	0.2	2.7	0.2	2.33
Tech. staff	2.1	0.2	2.3	0.4	1.4	0.3	1.4	0.4	2.1	0.2	1.16
Other staff	1.1	0.5	0.7	0.1	0.4	0.1	0.0	0.0	0.9	0.3	0.45
Total size	15.9	1.1	19.0	1.7	12.0	1.0	6.6	0.9	15.9	0.8	4.65**
Visitors											
Short-term visitors/team	2.1	0.13	2.8	0.27	2.3	0.27	1.1	0.32	2.3	0.11	4.14**
Short-term visitors/staff	0.17	0.02	0.18	0.01	0.26	0.04	0.17	0.05	0.19	0.01	2.02
Gender of PhD students and post-docs											
Male PhD stud.	1.6	0.08	2.2	0.10	1.9	0.17	1.4	0.31	1.8	0.06	7.29**
Female PhD stud.	2.1	0.09	2.2	0.10	1.9	0.17	1.3	0.32	2.0	0.06	3.06*
Male post-docs	1.0	0.09	1.7	0.12	1.5	0.16	1.5	0.31	1.4	0.07	8.85**
Female post-docs	1.1	0.09	1.3	0.10	1.4	0.17	0.3	0.15	1.2	0.06	3.60*
Publications and impact of the publications											
TOTPAP	3.17	0.26	3.98	0.40	12.55	0.97	2.11	1.00	4.57	0.27	63.59**
ZTOTPAP	0.23	0.02	0.26	0.02	1.29	0.13	0.32	0.13	0.38	0.03	90.95**
TOTMOCR	6.15	0.57	8.80	1.29	7.31	0.92	7.37	2.38	7.25	0.53	1.61

** significance level p < 0.01, * significance level p < 0.05

As a next step we investigated how these types of research teams can be further characterised. We considered the following variables:

- Team age
- Overall team size, numbers of different staff categories and short-term visitors
- Gender of the team leader, PhD students and post-docs
- Publications and impact of the publications.

Table 3 shows that the younger a team, the more likely it will be in cluster A and the less likely in cluster B. The older a team gets, the higher its internal diversity, as this is the main difference between clusters A and B. In cluster C, characterised by teams with many collaborations and a diverse set of post-docs, the representation of teams firstly increases then decreases with maturity; the turning point is a team age of 11-15 years. The pattern in cluster D is somewhat irregular.

Table 3: Cluster profiles 2 (percentages)

	Cluster A	Cluster B	Cluster C	Cluster D	All teams	Chi-Square
International orientation						
PHD_EU	9.5%	53.1%	27.8%	5.3%	25.1%	86.71**
PHD_US	1.8%	11.5%	7.4%	5.3%	5.7%	14.77**
PHD_INT	13.6%	60.8%	20.4%	21.1%	29.3%	90.88**
PDOC_EU	9.3%	52.7%	38.9%	11.8%	27.3%	81.39**
PDOC_US	1.0%	13.7%	7.4%	17.6%	6.7%	24.53**
PDOC_INT	10.3%	46.6%	33.3%	17.6%	25.4%	57.92**
Industry relationships						
BCPAP01	8.3%	11.3%	30.4%	5.3%	11.9%	57.92**
INDUFUND	16.1%	15.0%	7.1%	5.3%	14.2%	4.29
Age of the team						
Up to 5 years	67.8%	20.0%	6.7%	5.6%	100.0%	–
6-10 years	51.3%	27.4%	15.0%	6.2%	100.0%	–
11-15 years	48.4%	33.0%	18.7%	0.0%	100.0%	–
16-25 years	40.2%	38.0%	15.2%	6.5%	100.0%	–
More than 25 years	44.1%	47.1%	5.9%	2.9%	100.0%	–
Unknown	78.6%	21.4%	0.0%	0.0%	100.0%	–
Total	52.1%	30.6%	12.9%	4.4%	100.0%	34.00**

** significance level $p < 0.01$, * significance level $p < 0.05$

The clusters differ significantly in regard to overall team size and the number of principal investigators, post-docs and PhD students (see Table 2). The teams of cluster B are the largest with the most PIs, post-docs and PhD students. Cluster D is characterised by small teams with an average of only 6.6 team members, roughly one PI, one post-doc, two PhD students and some support staff. Cluster A has staff numbers close to the average for all teams, which is probably a consequence of its size. Teams in cluster C are somewhat smaller than those in clusters A and B, both overall and for each of the included staff categories.

It is also interesting to consider the number of short-term visitors in this context, as this type of visit usually takes place in ongoing research collaborations in order to exploit research infrastructure or compounds or to learn specific techniques. Overall, the teams in cluster B hosted the most short-term visitors per team. However, if we take the team size into account and divide the number of visitors by the staff total, the picture changes. Then only the teams in cluster C exhibited above-average visitors per staff member.

Another dimension of team diversity which has not been taken into account in the classification of the teams is gender. Differentiating the four clusters by the gender of the PhD students and post-docs gives the following results (see Table 2). As the groups differ in size, absolute numbers of male and female personnel should not be compared, but rather their proportions.

- With reference to PhD students, cluster A has more female than male PhD students, whereas the gender structure is more balanced in the other three clusters.
- With reference to post-docs, clusters A and C are balanced whereas male post-docs are overrepresented in the teams of clusters B and D.

Last but not least, Table 2 also provides an overview of the publications differentiated by cluster. It shows the total number of publications (TOTPAP), the number of publications per team member (ZTOTPAP) and the mean observed citation rate of all publications (TOTMOCR). The results are quite clear: with an average of more than twelve publications or 1.3 publications per team member, the teams of cluster C are by far the most prolific writers. This is consistent with the large number of their papers with international or industry co-authors (see above). However, in regard to the quality indicator TOTMOCR, the teams in cluster C do not perform better than the teams in other clusters.[3] The cluster differences for this indicator do not meet the significance threshold. Only teams in cluster A clearly achieve lower impact; the papers of the teams in cluster B appear to be cited more often, but the standard error is quite large and points to significant variations between the teams in this cluster.

4.2 Discussion of the results

The analysis showed that the research teams in the life sciences indeed pursued differing approaches to sourcing knowledge from a different research culture. Table 4 gives an overview of clusters in regard to the team structure, collaborations and the other variables discussed in the previous chapter.

Table 4: Overview of the clusters

	Cluster A	Cluster B	Cluster C	Cluster D
International orientation	Not international	Very international teams	International publishing and post-docs	Low degree of internationality
Interdiscipli-nary work	Little interdisciplinarity	Interdisciplinary teams but few collaborations	Average interdisciplinarity	Many interdisciplinary collaborations

[3] This, however, is slightly different if we only include the 32 “core teams” which were grouped into cluster C by both clustering methods and exclude the remainder. Then the TOTMORC value for cluster C increases to 8.8 and the inter-cluster differences become significant at $p < 0.05$.

	Cluster A	Cluster B	Cluster C	Cluster D
Industry relationships	Average industry publications and funding	Average industry publications and funding	Many industry publications but little funding	Few industry publications and little funding
Collabora-tions – team structures	Few collabo-rations, homogeneous structure	Average collabo-rations, very diverse team structure	Many collaborations, diverse set of post-docs	Many collaborations (but few productive), little team diversity
Overrepre-sented team age group	Up to 5 years	16-25 years, more than 25 years	6-10 years, 11-15 years, 16-25 years	-
Total team size	Average size	Large teams	Slightly smaller than average	Small teams
Short-term visitors	Average	Average	Many	Average
Gender	More female PhD students	More male post-docs	Very balanced	More male post-docs
Total publications	Few publications, low impact	Few publications, but high impact (not all teams)	Many publi-cations, average impact	Average publi-cations and impact

Cluster A contains teams with little internal diversity, few external collaboration activities and a very limited international orientation. They produce few publications – only 0.25 papers per year and team member – with little impact. Of course, research teams which are not successful according to this measure of research productivity might produce a different type of added-value such as specific tools, methods or solutions to applied problems for industry (Joly & Mangematin, 1996). However, the measure of a team's proximity to industry in this cluster is likewise not particularly encouraging. It is disconcerting that cluster A is the largest cluster with approx. 50% of the classified teams. The weak position of these teams might be partially explained by their relative youth – young teams founded in 2000 or later are overrepresented in this cluster.

Cluster B is the opposite to cluster A in terms of team diversity as it contains teams with a high internal diversity. In contrast, external collaboration activities are only average. The teams are rather large, mature and multi-disciplinary. However, any expectations that these diverse teams are also outperformers are unfounded: the publication output per staff member is also low. The Mean Observed Citation Rate as a quality measure is high, but its variation across the teams is also quite high. We conclude that diversity, size and maturity are clearly not sufficient conditions for being a successful research team. "The more, the better" does not hold for PhD students or post-docs or other staff categories. We assume that some of these teams have grown beyond the optimal structure and size. However, we should not forget that some – but not all – of the teams in the cluster have a very high citation impact. These teams might prefer quality to quantity and produce fewer but better publications. Due to their maturity they might be more established and not need to participate in the "publish or perish" race to the same extent as younger and less established teams. Interestingly, this can be related to previous findings: for a set of labs from a French university it has also been shown that large labs are rather heterogeneous in regard to their scientific performance (Carayol & Matt, 2004).

Cluster C contains the teams with significant collaboration activities and highly diverse post-docs. The teams are interdisciplinary, but not significantly: small teams have scientists from two different fields whereas larger teams have scientists from three different fields, though in the latter case one field usually dominates. We find that young and old teams are underrepresented in this cluster. The teams are slightly smaller than average and more balanced than the other teams in relation to gender. This cluster contains the top producers of publications among our teams and interestingly also the most visited teams (in terms of visitors per team member). It seems that the role of productive collaborations, i.e. collaborations leading to scientific articles, is somewhat more important than the role of diverse team structures, though at least for post-docs the diversity measure is also above the overall team average. However, the impact of these teams' publications is only average. This reinforces the idea that teams might opt for a quantity or quality approach in regard to their scientific work and output.

As cluster D is the smallest cluster with only 19 teams, interpretation must be made with caution as the cluster values are heavily influenced by individual team values. The teams in cluster D are small, their diversity is below average and they do not have extensive international links. Their common characteristic is that they have many collaboration partners per team member. However, the teams had low publication rates and we therefore call these collaborations unproductive.[4] The profile of this cluster indicates, somewhat analogously to cluster B, that sourcing external knowledge through collaborations as in this case is not sufficient to achieve good research performance. Moreover, the very small average size of less than seven team members (4.4 scientific staff, 2.2 administrative and technical staff) is striking.

[4] This is, of course, a simplification, as the collaboration might have produced other forms of output than the scientific papers counted for this study.

5 Explaining the performance of research teams

In addition to the cluster analyses, we used regression models to relate the team performance indicators – total number of papers, number of papers per team member, Mean Observed Citation Rate – to the team's approach to knowledge sourcing. Moreover, several structural characteristics of the teams and their leaders were included as control variables.

5.1 Results

Model 1 in Table 5 shows the results of the baseline estimation for the total number of publications in 2001. Significant positive relationships can be confirmed between publication output and the size of the research team (TEAMSIZE) and the recognition of the team leader (RECOG). As with team size, the experience of the team leaders – measured as the number of years since attaining leadership of a team for the first time – has a non-linear but positive effect on the team's publication output: the more experienced the team leader, the higher the output. Only for higher values of experience – team leaders with many years of leadership and probably close to the end of their careers, expressed in the squared experience variable (EXPRNCE2) – does the curve slope downward again, i.e. the publication output is smaller. In the first models we also included a control variable for the gender of the team leader that was not significant in any of the estimations, either for TOTPAP or the other dependent variables. Moreover, all models included controls for countries and sub-disciplines (not shown).

In model 2 we added to the baseline model a set of variables reflecting the different dimensions of internal structures and collaborations, the international orientation, the importance of interdisciplinary work and industry relationships.[5] We obtain a curvilinear relationship for the country diversity of the PhD students in the teams (CDIVPHD). The magnitude of the coefficients for the upward and downward slopes (squared variable CDIVPHD2) is similar. Hence, we can conclude that the optimum level of country diversity for maximised output is rather low. The coefficients for field diversity (FDIVALL) and interdisciplinary collaboration partners (INTDISCO) are not significant. The dummy variable for papers published with industry partners (BCPAP01) is positive and highly significant: teams which had co-authors from industry published more papers than teams which did not have co-authors from industry.

Models 3 and 4 used a different dependent variable, namely the number of papers published in 2001 and listed in the Thomson ISI database divided by the number of

[5] Note that the variables for research collaborations with foreign partners – at global level, from the EU or from the US – had to be excluded due to estimation problems.

staff in the team (ZTOTPAP). The normalised publication output is a continuous variable and we therefore changed the estimation method to OLS regressions. The results consequently differ to those using models 1 and 2. In model 3 – without the variables on team diversity and collaboration – only variables on team size yield significant effects. Now the effect is exactly the opposite of that found with models 1 and 2: the larger the team size, the smaller the number of published articles per team member. The squared variable (TEAMSIZE2) points to a curvilinear effect.

If we add the variables on international orientation, the importance of interdisciplinary work and industry relationships, the quality of the model improves considerably: the adjusted R-squared increases to 0.360. We also see that the effect of collaboration with scientists from both other EU countries (EUCPAP01) and the US (USCPAP01) is positive and highly significant. As for the non-normalised total number of papers, the relationship between normalised output and the country diversity of PhD students is curvilinear with a low level optimum (CDIVPHD and CDIVPHD2 are of similar magnitude). This indicates that low country diversity of PhD students is conducive to research output. We again find a positive relationship for collaboration with industry (BCPAP01). The variables on interdisciplinary collaboration partners and the field diversity of the team are insignificant.

The last models use the Mean Observed Citation Rate MOCR as the explained variable. The MOCR can be considered as an indicator of the quality of publications. The estimation with the restricted variable set (Model 5) also shows a negative effect – in this case linear – of the team size. Papers of large teams are less often cited than papers of smaller teams. Moreover, the estimation produces significant coefficients for different types of staff (we also included these variables in the other estimations, but because of their weak performance they are excluded from the final models displayed here): teams with high proportions of principal investigators (PI) and other researchers are cited less often (OTHRES), whereas teams with high proportions of post-docs are cited more often. These coefficients are partially corroborated in the augmented model 6. In addition, we obtain positive coefficients for the variable assessing international collaborations (INTDISCO). The fact that a team had PhD students or post-docs funded by industry exerts a negative influence on the citation rate of its papers (INDUFUND).

Table 5: Explanation of the teams' research performance with team characteristics

	Model 1 TOTPAP		Model 2 TOTPAP		Model 3 ZTOTPAP		Model 4 ZTOTPAP		Model 5 TOTMOCR		Model 6 TOTMOCR	
Variable	**b**	**t-ratio**	**b**	**t-ratio**	**b**	**t-ratio**	**b**	**t-ratio**	**b**	**t-ratio**	**b**	**t-ratio**
Constant	0.862	3.936**	0.895	3.186**	0.529	5.301**	0.400	2.995**	7.665	4.814**	7.780	3.739**
TEAMAGE	0.005	0.822	0.011	1.484	0.003	1.676+	0.002	0.803	0.011	0.385	0.028	0.964
TEAMSIZE	0.023	3.469**	0.019	2.419*	-0.012	-5.749**	-0.013	-5.127**	-0.021	-2.641**	-0.015	-1.741+
TEAMSIZE2	-1.1E-04	-1.983*	-8.4E-05	-1.404	6.1E-05	4.932**	6.1E-05	4.478**	–	–	–	–
PI	–	–	–	–	–	–	–	–	-11.107	-3.776**	-12.521	-3.406**
POSTDOC	–	–	–	–	–	–	–	–	10.182	2.081*	5.270	1.121
OTHRES	–	–	–	–	–	–	–	–	-5.112	-1.851+	-7.937	-2.188*
RECOG	0.106	3.256**	0.137	3.403**	0.024	1.504	0.015	0.839	–	–	–	–
EXPRNCE	0.038	2.318*	0.014	0.699	0.005	0.746	-4.9E-04	-0.071	0.076	1.665+	0.068	1.355
EXPRNCE2	-0.001	-2.771**	-0.001	-1.238	-2.7E-04	-1.529	-1.0E-04	-0.491	–	–	–	–
ICPAP01	–	–	–	–	–	–			–	–	3.292	4.013**
EUCPAP01	–	–	–	–	–	–	0.230	7.028**	–	–	–	–
USCPAP01	–	–	–	–	–	–	0.190	3.768**	–	–	–	–
CDIVPHD	–	–	0.674	1.930+	–	–	0.378	2.633**	–	–	-1.390	-1.528
CDIVPHD2	–	–	-0.581	-2.002*	–	–	-0.307	-2.444*	–	–	–	–
CDIVPDOC	–	–	0.122	0.362	–	–	0.106	0.664	–	–	1.084	1.172
CDIVPDOC2	–	–	-0.127	-0.486	–	–	-0.123	-1.118	–	–	–	–
INTDISCO	–	–	-0.018	-0.154	–	–	0.126	0.956	–	–	0.672	0.508
FDIVALL	–	–	0.174	0.536	–	–	0.035	0.219	–	–	-2.746	-1.092
FDIVALL2	–	–	-0.243	-1.144	–	–	-0.058	-0.699	–	–	2.105	1.334
BCPAP01	–	–	0.722	4.846**	–	–	0.212	2.434*	–	–	-0.130	-0.119
INDUFUND	–	–	0.059	0.392	–	–	-0.033	-0.589	–	–	-3.641	-4.505**
Model type		NEGBIN		NEGBIN		OLS		OLS		OLS		OLS
Alpha	0.534	7.571**	0.461	4.560**		–		–		–		–
Log-L		-1037.516		-770.4513		–		–		–		–
Rest. Log-L		-1334.189		-939.0459		–		–		–		–
F		–		–		4.11**		6.40**		4.76**		4.35**
Adjusted R2		–		–		0.136		0.362		0.176		0.242
Gold.-Quandt		–		–		1.682**		–		2.755**		–
Cases		395		296		395		296		395		296

b: estimated coefficient; t-ratio: quotient of estimated coefficients and standard errors; Significance levels ** < 0.01, * < 0.05, + < 0.1.

5.2 Discussion of the results

The estimated models provide a variety of results which corroborate some of the above-formulated hypotheses and contradict others:

- H1 on interdisciplinarity is not confirmed at all: we do not find the expected curvilinear relationship between interdisciplinary team composition and performance. Even the estimated signs of the coefficients are only in line with our expectation for publications, but not for citations.
- The second hypothesis H2 was estimated using indicators on the country diversity of the teams' PhD students and post-docs. We find that only the country diversity of PhD students exhibits a quantifiable relationship to the number of publications. The relationship is curvilinear as expected: with other factors kept constant, the publication output is highest for teams with moderate PhD student country diversity and lower for teams with high, low or zero diversity. H2 is therefore partially confirmed.
- H3 could not be investigated using the available empirical data.
- H4 was largely tentative as previous empirical evidence was scarce. As with Cummings and Kiesler (2004) we did not identify any relationship between interdisciplinary collaborations and the performance of research teams.
- H5 is generally confirmed. As with previous studies (Arora, David, & Gambardella, 1998; Bordons et al., 1996; Cesaroni & Gambardella, 2003), we find a positive relationship between international collaborations and research productivity. We also confirmed other work in regard to the effect of international collaborations on the impact of research papers (Adams et al., 2005; Glänzel, 2001; Narin et al., 1991; Persson et al., 2004).
- In regard to H6 the results point to a complex relationship between industry contacts and research performance. Firstly, teams who published jointly with co-authors from industry published significantly more papers in total, and per team member, than teams who did not have co-authors from industry. However, industry funding of either PhD students or post-docs has a large and negative effect on the citation rate of the papers. This complexity is in line with previous results (Carayol & Matt, 2004; Hicks & Hamilton, 1999; Landry et al., 1996). The main consequence of public-private collaboration does indeed seem to be the more applied nature of the topics and findings rather than a problem with restrictions on the publication of results. The findings of joint university-industry projects can still be published, but their impact is lower and they are less well recognised in the scientific community.

If we combine the findings, we see that interdisciplinarity is common for the internal composition of life sciences teams and their external collaborations: On average, we find that only one third of the teams are mono-disciplinary. Two thirds of the teams employ scientists with degrees from different fields, usually two fields in smaller teams and three fields in larger teams. Three quarters of the teams have at least one external collaboration partner in another field, on average the groups have 2-3 partners from other fields. Hence, we consider interdisciplinarity in the life sciences as a general feature that does not provide any additional advantage and is not related to the team performance. The most marked relationship to team performance is visible for the indicators on international orientation: international collaboration and a moderate degree of staff internationality, in particular among the PhD students, are conducive to success. The role of science-industry relationships is positive in terms of quantity, but negative in terms of quality of output.

A further remark on team size is appropriate: this was included as a control variable and has been discussed controversially in previous research (see the reviews in Bonaccorsi & Daraio, 2005; von Tunzelmann, Ranga, Martin, & Geuna, 2003). We found an inverse relationship between size and performance and an optimum team size of only a few team members (the maximum average publication per capita is reached for teams with 7 members). This contradicts the expectation voiced by Bonaccorsi and Daraio (2005) that increasing returns of size might apply at the team level, as they themselves could not find them at the level of institutes.

6 Conclusions

If we compare the results of the cluster and regression analyses, we see that neither the most diverse teams nor the most active collaborators are producing the most output and obtaining the most citations. Should we therefore conclude that combining different research cultures is not a promising approach to becoming a successful and outperforming team? No, this is not supported by the results either. Though hyperdiversity is not conducive to becoming a successful research team, a total lack of access to knowledge from different research cultures is also detrimental. But what is a desirable level of diversity and where does hyperdiversity start? Looking at the life sciences research teams we obtain the following answer: Overall, the outperforming teams have 20-25% of team members (PhD students, post-docs, team leaders) who obtained their most recent degree in a different country. For the very international – and less successful – teams the figures are 40-45%. Moreover, international collaboration is practised a lot by successful teams. In relation to field diversity, the successful teams are composed of members from just 2 different fields (smaller teams) or 3 fields (larger teams). The proportion of team members from a different field was also approx. 25%. This degree of diversity seems to be “sustainable”. Teams with scientists from 5 or more different fields do not seem to integrate the diverse knowledge cultures with success. Collaboration with private businesses is positively related to productivity, but negatively to the impact of these publications.

Team leaders, research directors and research policy makers at all levels should be aware of the curvilinear relationship between diversity and team performance. They should also adjust their HR practices and policies.

- *Research directors and team leaders:* Team composition matters. A well-balanced team is characterised by some heterogeneity, but this should not be excessive. It is indeed beneficial to integrate researchers with other backgrounds outside of the mainstream of a team. We presume – but did not directly investigate in this paper – that the diversity provides a team with different skills, work practices, cognitive frameworks of interpretation and association, and more. The positive effect is manifested in enhanced productivity. However, at the same time diversity also gives rise to additional costs, as people from other cultural backgrounds speak different languages – not necessarily literally but in many other respects: they attach other meanings to concepts; they have been taught other standards of “proper” research; they have received different practical training, how to carry out a proper experiment, measurement etc. These differences may place a burden on communication and they certainly require additional efforts on all sides to be accommodated. If these efforts are not undertaken or sufficient resources are not made available, the effects of increased diversity will be negative. It is therefore very important when selecting new personnel that great care is used to identify cultural differences and their possible consequences.

- *Research policy makers:* One comment also seems justified in relation to mobility measures. Increasing the mobility of scientists between countries, disciplines or sectors and thus raising the heterogeneity of research organisations may not be beneficial to research performance. This is particularly the case if the capacity of research teams and institutions to accommodate this diversity is not taken into account and, when necessary increased. How can this be achieved? Firstly it might be appropriate to place a restriction on the number of guest scientists, PhD students or post-docs supported by stipends that a team and its leader can take on board. In particular if there are more applications than available mobility grants, the grants should be spread over different recipients and concentrated as little as possible. Secondly, in addition to supporting the mobile scientist, some supplementary support for the host institution can be helpful. Mentoring schemes with appointed mentors and defined responsibilities for facilitating the integration into the new team could be a useful approach to reducing communication barriers. This goes beyond the type of assistance given to mobile researchers and their families regarding matters of daily life provided by science foundations, ministries etc. The assistance that we have in mind is targeted at enhancing professional communication and collaboration of scientists from different research cultures within research organizations, and it can only be provided by the organizations themselves. It is very much in line with the EC's intentions and objectives and it clearly pursues one of the objectives of the Mobility Strategy: *"The objective is to encourage host organisations to take more responsibility for their foreign staff and visiting researchers."* (European Commission, 2001, p. 11)

We generally have confidence in our results and employed due care in the construction of the dataset, and its analysis and interpretation. However, there are clear limitations which should be overcome in future investigations of this issue. One major limitation is related to the performance indicators. The time gap between the survey data and the bibliometric data has already been discussed above, and though we think that the analysis is nevertheless valid, it is probably the key reason for the low explanatory value of the regression models. Another weakness is that the paper considers only the research performance of teams through indicators on their research output and the impact of this output according to one database, the Thomson ISI SCIE. Other products of scientific work are well-educated and trained graduates, private goods for firms, or collective goods and expertise for public authorities and the general public (Larédo & Mustar, 2000). Team structures and collaborations certainly also affect these other forms of output and there may even be a trade-off between high research productivity and training: high diversity in a research team may serve to integrate new scientists into the research community and produce added-value for the community as a whole, though the research productivity of the individual team is lowered. Last but not least, diversity not only influences output but also job satisfaction and thus tenure/turnover of team members (Williams & O'Reilly, 1998). This has consequences for the long-term team performance. However, we lack the data to include these other output forms and influences in this analysis. Another limitation is related to the transformation of diversity into research output. Due to the format of the study we could only presume that different backgrounds, whether national, disciplinary or sectoral, also generate differing ideas, perceptions, behaviours, practices etc. in research. It was not possible to assess whether this assumption is true, and if so, what is particularly beneficial or detrimental to the production of new knowledge. Future work on research teams should attempt to address these issues more appropriately.

Appendix

Acronym	Variable	Mean	S. Dev.
Dependent Variables			
TOTPAP	Total number of papers published in the Thomson ISI SCIE database in 2001	5.350	5.833
ZTOTPAP	Total number of papers published in the Thomson ISI SCIE database in 2001 per team member	0.417	0.526
TOTMOCR	Mean Observed Citation Rate 2001-2003 of the 2001 papers	6.253	7.076
Independent Variables			
TEAMAGE	Team age	9.803	8.526
TEAMSIZE	Team size (total staff)	16.196	16.514
TEAMSIZE2	Team size (total staff) (squared)	534.433	1854.060
PI	Proportion of principal researchers	0.168	0.110
POSTDOC	Proportion of post-docs	0.147	0.121
OTHRES	Proportion of other researchers	0.067	0.099
RECOG	Recognition of the team head (Scale 1 “very low” to 5 “very high”)	2.771	1.549
GENDER	Gender of the team head	–	–
EXPRNCE	Experience of the team head: years leading a research team	10.419	8.504
EXPRNCE2	Experience of the team head (squared)	180.713	246.062
ICPAP	Papers with foreign co-authors published in the Thomson ISI SCIE database in 2001 per team member (binary-coded in the regressions)	0.147	0.268
EUCPAP	Papers with co-authors from the EU published in the Thomson ISI SCIE database in 2001 per team member (binary-coded in the regressions)	0.083	0.162
USCPAP	Papers with co-authors from the US published in the Thomson ISI SCIE database in 2001 per team member (binary-coded in the regressions)	0.036	0.103
CDIVPHD	Country diversity of PhD students	0.369	0.438
CDIVPHD2	Country diversity of PhD students (squared)	0.327	0.500
CDIVPDOC	Country diversity of post-docs	0.310	0.465
CDIVPDOC2	Country diversity of post-docs (squared)	0.312	0.568
PHD_EU	Team has at least one PhD student with the most recent degree from another EU country (binary-coded)	–	–
PHD_US	Team has at least one PhD student with the most recent degree from the US (binary-coded)	–	–
PHD_INT	Team has at least one PhD student with the most recent degree from another country worldwide (outside EU & US) (binary-coded)	–	–
PDOC_EU	Team has at least one post-doc with the most recent degree from another EU country (binary-coded)	–	–
PDOC_US	Team has at least one post-doc with the most recent degree from the US (binary-coded)	–	–
PDOC_INT	Team has at least one post-doc with the most recent degree from another country worldwide (outside EU & US) (binary-coded)	–	–

Acronym	Variable	Mean	S. Dev.
INTDISCO	Interdisciplinary collaboration partners per team member	0.266	0.584
FDIVALL	Field diversity of the entire team	0.605	0.513
FDIVALL2	Field diversity of the entire team (squared)	0.629	0.734
BCPAP01	Papers with co-authors from industry published in the Thomson ISI SCIE database in 2001 per team member (binary-coded in the regressions)	0.025	0.123
INDUFUND	Industrial funding of PhD students or post-docs	–	–

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