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Organizational and institutional influences on creativity in scientific research

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ABSTRACT

This paper explores institutional and organizational influences on creativity in scientific research. Using a method for identifying creative scientific research accomplishments in two fields of science (nanotechnology and human genetics) in Europe and the US, the paper summarizes results derived from twenty case studies of highly creative research accomplishments, focusing on contextual patterns at the group, organizational, and institutional levels. We find that creative accomplishments are associated with small group size, organizational contexts with sufficient access to a complementary variety of technical skills, stable research sponsorship, timely access to extramural skills and resources, and facilitating leadership. A potential institutional threat to creative science is the increase in competitive research council funding at the expense of flexible institutional sponsorship. Implications for research management and research policy are considered.

1. Introduction

Scientific creativity is a key driver for scientific and technological progress, and also a precondition for advances in other societal domains. Yet, our knowledge and understanding of how research organizations and institutional environments, and changes in both, impinge upon capabilities of research groups to conduct creative research is fragmented. The complex relationships between productivity, social stratification, reward structures, and organizational context in scientific research were frequently studied until the mid-1970s within the institutional paradigm of the sociology of science (see, for example, Shepard, 1956; Meltzer, 1956; Merton, 1957; Meltzer and Salter, 1962; Stein, 1962; Pelz, 1964; Crane, 1965; Pelz and Andrews, 1966; Cole and Cole, 1967; Reskin, 1977; Zuckermann, 1977; Andrews, 1979; Long and McGinnis, 1981). Since then science studies have been dominated by a social-constructivist paradigm that focuses on the micro-conditions of knowledge production in laboratory settings and epistemic cultures (Latour and Woolgar, 1979; Knorr-Cetina, 1981, 1999; Knorr-Cetina and Mulkay, 1983). At the same time, the study of creativity has become popular in psychology, although organizational and institutional questions play only a marginal, if any role (Dunbar, 1997; Amabile, 1996; Sternberg, 2003; Simonton, 1999, 2004). It was only recently that new attempts were undertaken to re-establish an organizational and institutional perspective in the study of scientific accomplishments. For example, Hollingsworth (2000, 2002) and Hage (2006) have published on organizational structures that foster breakthrough research. Hemlin et al. (2004) have explored various institutional factors that are associated with what they call "creative knowledge environments". Yet, in their book on serendipity in science, Merton and Barber (2004) conclude that the institutional analysis of discoveries in science is still in its infancy. Many important questions remain about what creative scientific accomplishments are, how we can identify them, in which organizations they occur most often, and which institutional factors are influential in shaping cutting-edge research environments.

The desire to know more about the factors that contribute to scientific creativity is given further impetus by the substantial changes seen over the last few decades in the institutional and organizational conditions under which scientific research is conducted (Jansen, 2007; Laudel, 2006; Schimank, 2005; Etzkowitz, 2003; Owen-Smith, 2003; Langfeldt, 2001; Bourke and Butler, 1999). Public research funding is now increasingly allocated through competitive processes, rather than long-term institutional block-grants; increased research collaboration is encouraged through a variety of measures including through organized research centers, networks, centers of excellence, and interdisciplinary teams, to address diverse challenges of complexity, convergence, knowledge exchange, scale, scope, and internationalization in contemporary science; and evaluation systems for research performance are increasingly implemented as a supplement to peer review (Münch, 2008; Thèves et al., 2007; Lepori et al., 2007; Corley et al., 2006;

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Shapira and Kuhlmann, 2003; Chompalov et al., 2002; van Leeuwen and Tijssen, 2000; Henkel, 1999). In the context of heightened competitive pressures to foster science-driven business development and the rise of new global locations for research (especially China), research policymakers in developed economies hope that adjustments to research organizations and broader institutional environments for scientific research will not only promote more efficiency but also boost scientific excellence and creativity (Blau, 2005). There is an increasing need for recommendations about the design of science policy to support highly creative researchers and their groups.

This paper explores factors which influence the ways in which research groups conduct their work. Besides features of the research group itself, such as size and career stage of group leaders, our main analytical and empirical focus is on organizational variables and the institutional environment in which these groups operate, such as leadership, funding structures, or competitive pressures. Our study is built on a longitudinal multi-method research design based on survey, interview, archive and bibliometric data, and uses both quantitative and qualitative research methods including as network and regression techniques, and in-depth interviews and case studies (Heinze et al., 2007; Heinze and Bauer, 2007). We identified creative research accomplishments in two broad fields of science, analyzed why certain research groups are more creative than others, and investigated which factors in their work environment were influential for their accomplishments.

We begin the paper by reviewing contributions to the literature on scientific creativity and by highlighting selected key issues important for further research (Section 2). Second, we introduce our methodology (Section 3). Third, we discuss in more detail the results from our case studies of highly creative research accomplishments, focusing particularly on findings related to organizational and institutional influences on scientific creativity including work group factors, such as size of research groups or communication patterns, and organizational features, such as sponsorship or disciplinary variety (Section 4). Then, we discuss our findings in the light of previous results, and we demonstrate how our findings improve our understanding of creative knowledge environments (Section 5). Finally, we consider the implications for research management and research policy (Section 6).

2. Literature review: definitions, approaches and findings on scientific creativity

The importance of creativity in numerous areas of society has resulted in studies of creativity from diverse fields, including management and business (Sutton, 2002), arts (Maritain, 1977; Berka et al., 2003), politics (Otten, 2001; Nagel, 2002), and urban and regional development (Florida, 2002). However, there is a convergence in characterizing creativity as encompassing capabilities to do things that are new and useful (see Ochse, 1990 and Amabile, 1996, for a summary of definitions).

In the world of science, creativity is similarly defined in terms of knowledge and capabilities that are new, original, surprising, and useful (Hollingsworth, 2004; Simonton, 2004). As in other fields, standards and norms are established in science against which claims for innovative contributions are assessed, although science, more than other fields, has evolved procedures, disciplines, and institutions to accredit new knowledge (Whitley, 2000). In making judgments about scientific creativity, scientific peers use criteria such as plausibility, validity, and originality. There are well-recognized tensions here, since criteria of plausibility and validity tend to encourage conformity, while originality draws upon and encourages dissent. The history of science is replete with examples of path-breaking research achievements that were initially rejected by the scientific establishment because they challenged existing paradigms (Kuhn, 1962; Polanyi, 1969; Hessenbruch, 2004). In other cases, work that was initially proclaimed publicly to be highly creative was found, following more considered scientific review, to be flawed (Lewenstein, 1992). In short, the scientific community must be persuaded that novel and unexpected contributions have value, and claims that research is highly creative need validation over time and by other scientists.

There are varied approaches to examining and empirically measuring creativity. These include examining creative individuals, the products or outcomes of creative work, creative processes and creative knowledge environments (Stumpf, 1995; Hemlin et al., 2004). At the individual level, there has been much discussion – not necessarily with consensus – about the relationship between intelligence and creativity (Mansfield and Busse, 1981; Sternberg, 2003). There has also been a focus on the behavioral traits of creative individuals, including their level of curiosity, risk tolerance, motivation, and willingness to overcome failure, leading to arguments that creative people typically tolerate higher levels of contradiction, ambiguity, and uncertainty in their work (Sternberg et al., 1997; Weinert, 2000). Still, such individual characteristics are neither easily measured nor uniformly correlated with creative accomplishments, leading others to concentrate on tangible scientific publication outcomes and citations to identify highly creative researchers.

A prominent attempt to assess scientific creativity through outcomes is publication and citation analysis within an evolutionary-probability theoretical frame (Simonton, 1999, 2004). Simonton argues that scientists who are highly productive in publishing papers encounter a greater likelihood that one or more of their papers will come to the attention of other scientists, be cited, and recognized as creative. In other words, the more contributions to knowledge that a scientist produces, the higher his or her chances are that one of these contributions resonates well in the scientific community. This approach is not without criticism because, for example, some highly creative scientists publish only a few papers, while citation counts typically consider only journal publications and not books or other contributions, such as new scientific instrumentation. Another outcome approach is based on studying prestigious prize winners in science (Zuckermann, 1977; Hollingsworth, 2002). Of course, such prizes are highly selective – and there are surely more creative research accomplishments than Nobel committees can recognize. Hollingsworth (2002) addresses this problem by obtaining access to short-listed Nobel Prize nominees until the 1940s.

Creative processes, including the selection of problems, methods, partners and knowledge sources, have been another area of inquiry. Rather than focusing on innate individual traits, work on creative processes has highlighted the opportunity structures in collaboration networks that facilitate the generation and diffusion of novel ideas. Proponents of network brokerage argue that people who are placed at the intersection of heterogeneous social groups have an increased likelihood of drawing upon multiple knowledge sources, leading to the generation of new ideas. For example, managers who occupy brokerage positions are more often than others the source of good ideas (Burt, 2004; Rodan and Galunic, 2004). In contrast, proponents of cohesive collaborative networks argue for the benefits of trust, shared risk taking and easy mobilization in facilitating information and knowledge transfer. According to these studies, individuals with cohesive social ties are more likely to be involved in innovations (Uzzi and Spiro, 2005; Obstfeld, 2005). In reference to this ongoing debate, Fleming et al. (2007) argue that although brokering inventors are more likely to generate new ideas, the brokered network structure itself is less suited to diffusing these ideas. Therefore, network structures that enhance the generation of novel ideas may inherently diminish the likelihood of their diffusion.

Considerations of the research environment add a series of further elements – including organizational and institutional features – to the examination of scientific creativity. Research environments influence opportunities for research collaboration and multidisciplinarity, which may in turn affect processes of knowledge discovery. But once we contemplate the role of organizational and institutional aspects, a range of other factors may come into play in stimulating creative research situations, including autonomy for researchers, adequate facilities and funding, development of complementary disciplines and fields, staff selection, management structures, and leadership. Less conducive factors include: insufficient basic funding, limited time for research, bureaucratic management, narrow range of disciplinary expertise, and excessive evaluation and accountability pressures (Hemlin et al., 2004, pp. 16–17, 195–196).

Perhaps the first comprehensive effort to empirically examine modern research environments was a study of 17 research facilities in the United States across various types of fields and laboratories by Pelz and Andrews (1966).[1] Another major effort to analyze research organizations in a comparative fashion was the UNESCO study by Andrews (1979) on more than 1200 research groups across six countries.[2] Again other studies have investigated university departments and their role in setting research goals and influencing scientists' productivity (Long and McGinnis, 1981; Baird, 1986; Allison and Long, 1990), More recently, Hollingsworth (2002) examined a large number of research breakthroughs in the biomedical sciences across 128 research organizations in the United States, of which 28 had two or more major discoveries in the first half of the twentieth century.[3] There are also historical accounts of exceptionally successful institutes in the biomedical sciences, such as Rockefeller University, California Institute of Technology (Hollingsworth, 2000, 2004) or Institut Pasteur (Hage, 2006). These studies differ in methodology, for example, with respect to the identification of research groups, by key outcome variable (productivity, recognition or research breakthroughs), and by level of analysis (group, department, institute, or project). Significantly, although some are published recently, they all examine research organizations and institutional environments from earlier periods. For example, Hollingsworth (2002) and Hage (2006) study breakthroughs in the first half of the 20th century; Pelz and Andrews (1966) report on research organizations of the 1950s; and Andrews (1979) capture the situation before 1975. Research organizations and institutional environments have changed extensively in the last three decades following periods of post-Second World War expansion (Windolf, 1997), 1970s stabilization (Ziman, 1994), and more recent restructuring (as noted in Section 1 of this paper). While our emphasis is on recent research organizations and institutional environments, it is insightful to consider the findings from studies focusing on earlier scientific generations. In particular, this literature raises three important themes still relevant today, namely: specialization, communication, and research autonomy; group size and departmental effects; and resources, recruitment and leadership, as discussed in the following sections.[4]

2.1. Specialization, communication, and research autonomy

Pelz and Andrews (1966, pp. 22–27, 35) find that scientists are most productive when they both interact vigorously with and involve their colleagues in setting up their research goals. Research productivity is correlated with high frequency of intra-organizational communication. Hollingsworth (2000, 2004) argues that research breakthroughs are typical for research organizations where scientists communicate across disciplinary and thematic borders, and where research leaders provide strategies for integrating scientific diversity with rigorous standards of scientific excellence. For example, because the Rockefeller University was organized around laboratories rather than scientific disciplines and fields, it had a greater capacity to adapt quickly to research strategies and to allow effective communication across cognitive boundaries (Hollingsworth, 2004, pp. 34–35). Further strategies for intellectual integration within the boundaries of an organization are mobility of researchers and teamwork between departments (Hage, 2006). However, the way in which the individual and organizational levels interpenetrate is somewhat contested in the literature. Hollingsworth (2000) emphasizes scientific excellence and depth of domain-specific knowledge at the individual level in combination with intellectual integration at the organizational level. In contrast, Pelz and Andrews show that high-performance scientists are often not in agreement with their organization in terms of research agenda and strategy. The authors argue that "a laboratory remains vigorous when it encourages a certain tension between what the members want, and what they think the organization wants" (Pelz and Andrews, 1966, p. 139).[5] Such tension, however, is only bearable if scientists share the same motivation for their work: "It seemed helpful if sets of close colleagues shared a common enthusiasm for similar kinds of problems and preferred social relations" (Pelz and Andrews, 1966, p. 146). Pelz and Andrews found thematic breadth to be most effective when combined with freedom in goal setting and research strategy, whereas coordinated research settings were better suited to more specialized researchers (Pelz and Andrews, 1966, pp. 29–31, 158–173).

2.2. Group size and departmental effects

There is considerable evidence in the literature that research performance initially tends to rise as group size increases, but that above a certain group size threshold, this effect tails off or becomes negative, i.e. either no increase or even a decrease in performance (for a review, see von Tunzelmann et al., 2003). For example, analyses based on the large dataset of Andrews (1979) show that above a threshold of 4–6 team members, per capita performance decreases markedly, particularly in academic natural science groups. Also, in order for groups larger than 5–7 scientists to reach the performance levels of smaller groups, both coherent research programs and group leaders with strong time commitments to research activities are needed. Although the curvilinear relationship between group size and performance is evident both for quantity and quality of research across various countries and fields, quality seems to be affected more negatively from large group size than per capita research quantity (Andrews, 1979, pp. 55–94, 192–222). In addition, the department level has been found influential. Long and McGinnis

[1] Pelz and Andrews analyzed industrial, government and university labs which spanned the following R&D fields: pharmaceuticals, glass and ceramics, electronics, electrical equipment, weapons guidance, animal diseases, commercial uses of agricultural products, basic research in several physical sciences, biological and social sciences (Pelz and Andrews, 1966, p. 2).

[2] Andrews and colleagues studied within the fields of mathematics, astronomy, physics, chemistry, life sciences, earth and space sciences, agricultural sciences, medical sciences, technological sciences, and social sciences the following types of research organizations: academic organizations, academies, cooperative organizations, productive enterprises, and private institutions (Andrews, 1979, pp. 17–52).

[3] Hollingsworth (2002) examined universities, medical centers, free standing research institutes, and industrial research laboratories in the biomedical sciences.

[4] See also Bland and Ruffin (1992) for a more detailed literature review on productive research environments.

[5] On a more general level, March (1991) argues that organizations learn more effectively from individuals who are slow (rather than fast) in acquiring what is known and taken for granted by the organization.

(1981) and Allison and Long (1990) find for the fields of physics, chemistry, mathematics and biology that scientists with growing departmental prestige tend to show an increase in both the number of publications and the number of citations. Again other studies find that university departments with clear research goals show higher productivity levels than those without such goals (Baird, 1986), and that flat and decentralized structures in research organizations correlate with higher productivity at the level of organizational units (Birnbaum, 1983).

2.3. Resources, recruitment and leadership

Other important variables for productive research climate are human resources, instrumentation and funding. Pelz and Andrews (1966) report that actual resources are associated less highly with productivity than the resources researchers perceived they could access. Similarly, Andrews (1979) finds that the perceived accessibility of human resources but not the de facto level of human resources explains the largest amount of variance in a research unit's performance. Recruiting outstanding scientists in a research team is another important variable. For example, Dill (1985) shows that highly productive research units can be distinguished by the significance they attach to hiring talent. The importance of recruitment also points to the influence of leadership. Hage (2006) argues that plural organizational leadership ensures diversity of research strategies and richness in ideas. The three directors of Institute Pasteur operated with diverse recruitment patterns but all three kept a look-out for creative people in their fields and then attempted to convince them to come to the Institute. However, leadership is crucial not only for recruitment, but also for directing research groups. Andrews (1979, p. 68, 102, 219) finds that effective leaders are involved in ongoing research. Active participation in the praxis of scientific work is important for leaders to understand the problems of the group, to motivate group members and to organize a coherent research program. This finding is also reflected in the literature review by Mumford et al. (2002) who suggest that leadership in creative environments requires predominantly technical and scientific expertise.

In summary, the available literature provides several ideas which informed the development of our interview protocol (Section 4). However, opportunities abound for new work that probes. Much of the extant literature is based on historical analyses of science prior to recent developments in the structure and dynamics of scientific research in the advanced economies. Moreover, while there has been a significant focus on intra-organizational communication and the balancing of individual and institutional research goals, inter-organizational and institutional aspects have been somewhat less studied. For example, there has been little discussion of the role of research councils in sponsoring new research fields; there is little emphasis on how basic research activities are framed differently in public sector research organizations and private laboratories; and most studies are concerned with understanding productivity and recognition, but less with scientific creativity. In these respects, our study of creative scientific events and the research groups responsible for them seeks to generate new insights, particularly since we are embedding our cases in current organizational and institutional contexts. In the next section we introduce the methodology for identifying highly creative research accomplishments and the case study approach for examining work environments of highly creative scientists and their groups.

3. Methodology: identification of creative accomplishments and case study design

The exploration of the features of the organizational and institutional context that have an effect on scientific creativity was carried

Table 1
Typology of scientific creativity.

Type of scientific creativity		Examples
1	Formulation of new ideas (or set of new ideas) that open up a new cognitive frame or brings theoretical claims to a new level of sophistication.	Theory of specific relativity in physics (EINSTEIN, 1905)
2	Discovery of new empirical phenomena that stimulated new theorizing	Biodiversity → Theory of evolution (Biology), DARWIN (1859)
3	Development of a new methodology, by means of which theoretical problems could be empirically tested.	Factor analysis → Theory on mental abilities (Psychology), SPEARMAN (1904a, 1904b, 1927)
4	Invention of novel instruments that opened up new search perspectives and research domains.	Scanning tunneling microscopy → Nanotechnology (Physics), BINNIG & ROHRER (1982)
5	New synthesis of formerly dispersed existing ideas into general theoretical laws enabling analyses of diverse phenomena within a common cognitive frame.	General systems theory (Biology, Cybernetics, Sociology), BERTALANFFY (1949), ASHBY (1956), LUHMANN (1984)

Source: Heinze et al. (2007). See source for full references to and discussion of examples.

out by means of a set of case studies anchored around selected individuals and their groups identified as highly creative in a new nomination method, previously reported in Heinze et al. (2007). Since the highly creative researchers were identified by independent experts and prize review panels, our work is based on ex post, external attributions of creativity by others rather than by modeling creative mechanisms at the individual level.

3.1. Identification of highly creative research accomplishments

First of all, we conducted a survey that obtained more than 400 European and US nominations from 185 experts in two fields of research, human genetics and nanoscience/nantechnology (referred to as nanotechnology), across five categories of prominence: highly cited researchers, active academic researchers, active industry researchers, journal editors, and research program managers.[6] The two research fields were chosen to offer a comparison between a more established, disciplined-embedded field (human genetics) and an emerging interdisciplinary field (nanotechnology). Furthermore, both fields have undergone substantial growth in recent years (see Heinze, 2004 and Youtie et al., 2008 for nanotechnology; Sulston and Ferry, 2002 for human genetics), while the science system as a whole is in a steadier state (Ziman, 1994). Field growth is an important variable for the development of creative ideas, because more novel ideas are produced, and the forces of sorting out original ideas are relatively weak (March, 2007, pp. 16–17). Therefore, it is especially fruitful to study the organizational context of creative research in growing research fields. In order to account for creative activity of several sorts, we introduced a typology of scientific creativity, with five stipulated categories and one open category for respondents to include types not included in the original list (Heinze et al., 2007; Table 1).[7]

In parallel with the nomination survey, we identified relevant prizes in the two fields, drawing on respondent nominations, other expert input, and our own knowledge. It should be noted that few prizes are specifically dedicated to nanotechnology, an

[6] For details of the sample frame and operationalization of the categories, see Heinze et al. (2007).

[7] The scientific creativity typology is discussed in detail in Heinze et al. (2007).

Table 2
Distribution of creative scientists, combining nominations and prize winners.

	Nanotechnology		Human genetics	
	Europe	US	Europe	US
Multiple prize winners	9	5	10	1
Multiple nominations	7	21	0	3
Prize winner and nomination	16	17	5	9
Multiple prize winners and multiple nominations	3	4	0	0
Total highly creative scientists	22	29	14	11
Total scientists in database	224	204	150	111

Source: CREA database, 2005 (Heinze et al., 2007). There is overlap between the four categories, so the total number of highly creative scientists is smaller than the sum of the rows 1–4.

exception being the Feynman Prize. Prizes for nanotechnology accomplishments are usually associated with a discipline (such as physics or materials research) or an organization (such as the Max-Planck-Society in Germany or the Centre National de la Recherche Scientifique in France). Our approach was therefore to identify relevant prizes broadly, then to carefully review all awards and laudations to explicitly identify relevant prize winners. We merged the nomination and prize winner data so as to offer a consolidated basis for studying creative research accomplishments (Table 2). Supplemented by additional web-based research, this provides us with a unique data source of information about creative research accomplishments in our two target science domains. We are particularly interested in scientists with multiple nominations, since recognition of their research is derived from more than one source.

3.2. Case study methodology

Our database of highly creative scientists offers a foundation from which to develop case studies, since we can identify scientists by the number and type of creativity nominations, by field, and the character and timing of their creative research accomplishment.[8] Hence, drawing on the subset of multiply-nominated creative scientists (i.e. those with most nominations from different sources), we undertook case studies of creative events of twenty research groups across Europe and the United States in the two fields of nanotechnology and human genetics. These cases explored the organizational and institutional dimensions of work environments in which creative research has been conducted.

The theoretical framework for the case studies addresses the relationship between features of the context of research work and the occurrence of a creative event that has already happened and has been recognized by colleagues and other experts who participated in the nomination process. The theoretical question for the case study design is whether there is a predominant contextual pattern for creative events in scientific research. Since creativity is surely also a matter of individual talent, our approach cannot completely isolate the contextual factors from the individual abilities of the researchers as causes of the creative event. Rather, our exploration addresses a set of necessary conditions for a creative event to come to fruition given that the researchers in our cases are already regarded as highly talented. Moreover, the span of an individual's research career is generally long enough for the same person to have worked in changing contextual conditions and it is therefore likely that the pursuit of research goals involves strategic calculations for the researcher in which an assessment of contextual factors is inherent in choosing alternative paths of action. Therefore, it is possible to compare the effects of contextual factors at different times in the career of the same researcher. In order to obtain reliable data about the context from our informants, we used information from the nomination process, including publications, citations, prize citations, among other external indicators, to identify a specific creative event so that the features of the context could be related to actual conditions of work at a determined time and place. This significantly reduced the potential for recall problems, ambiguous statements and generic opinions in response to our interview questions because the creative events were prominent occurrences in the lives of our respondents, the circumstances of which they are likely to remember in detail.

The cases were selected using parameters most relevant to features of the context, such as the research field (nanotechnology and human genetics), organizational affiliation (universities, medical facilities, industry R&D labs), geographical location which also provided diversity in various institutional and cultural dimensions (different regions of the United States and several European countries with their different funding mechanisms, academic styles, promotion rules, among other things), and different sorts of creative event as identified by nominators using our proposed typology. By conducting case studies under all these conditions we aimed at establishing whether there were emergent patterns that could confirm the presence of essentially the same sort of phenomenon across cases. In other words, and as a brief reminder, the logic of multiple case studies is not based on a representative sample for generalizing to a large population, as statistical inference does. Rather, cases are selected to elucidate the mechanism of a phenomenon for generalization to theory and concepts (George and Bennett, 2005; Eisenhardt, 1989).

Each case included a fairly complete account, both historically and technically, of the creative event obtained from the key researcher (or researchers) associated with the accomplishment and validated by others familiar with the event (colleagues, collaborators, competitors or external observers). A comprehensive file with information on publications, co-authors, and citations, research themes, and the organizational context of the research group was also compiled. Then, in-depth interviews were conducted with the group leader, and follow-up interviews with colleagues and associates, group members, and other scientists who were knowledgeable about the circumstances under which the creative event materialized. In total, we conducted 44 interviews between November 2005 and February 2007 (see List of interviews).

The interview protocol included questions related to the preparation phase prior to the creative accomplishment, the creative accomplishment phase, and factors related to research group, organizational and institutional levels. The main variables about which data is gathered are derived from the literature review above (Section 2). At the group level, variables include the size and composition of research team, communication patterns, quality of research leadership, and need and access to outside resources such as specialized equipment. At the organizational level, the variable set comprises (all variables at the time of the accomplishment): structure and size of the organization, centralization of decision-making, clarity of research goals, features of the funding arrangement, accountability burden, reputation and visibility of the organization. Finally, the institutional level variables include job mobility opportunities, competitiveness within the research field, and munificence of the funding environment. The case study method enables an in-depth analysis, capturing more of the texture and detail of behavior than is possible in conventional aggregate data-oriented methods. In addition, the case study method is "non-linear" in the sense that the researcher learns from the case and, if appropriate, adjusts the focus of the research during the course of the project. Hence, there is no need to hold fast to hypotheses if they are clearly being discredited in favor of more accurate and

[8] Although not reported here, we also know their names and current institutions.

Table 3
Creativity case summaries.

	Case number									
	1	2	3	4	5	6	7	8	9	10
Type of multiple expert and prize nominations	MultPrizNom	MultNom	MultNom	MultPrizNom	MultNom	MultPrizNom	PrizNom	MultPrizNom	PrizNom	MultNom
Type(s) of CE	2	2, 3	3	1, 2, 3	3, 5	3, 5	1, 5	2, 3	2, 3	3
Multiple CEs	Yes	Yes	Yes	Yes		Yes		Yes	Yes	Yes
CE preparation phase	1988–1997	1985–1992	1983–1990	1990–1996	1993–1996	1997–1998	1995–2000	1993–1997	1995–1999	1988–1992
CE accomplishment phase	1997–1998	1995–2000	1990–1999	1997–2002	1997–2002	1998–2000	2000–2004	1997–1998	2000–2005	1993–2000
Career stage	Mid	Early	Early	Mid	Early	Early	Early	Mid	Mid	Early
Field	Nano	Nano	Nano	Nano	Nano	Nano	Nano	Nano	Nano	Nano
CE accomplishment institution	Basic Ind. Lab.	Basic Ind. Lab.	Basic Ind. Lab.	Basic Ind. Lab.	Univ.	Univ./Gov. Lab.	Univ./Gov. Lab.	Univ.	Univ.	Univ.
CE accomplishment country	JP, US	US	US	US	US	DE, FR	DE	NL	US	US
Current institution	Univ.	Univ.	Univ.	Ind. Lab	Univ.	Univ./Gov. Lab.	Univ./Gov. Lab.	Univ.	Univ.	Univ.
Current country	D	S	S	S	D	S	S	S	S	S

	Case number									
	11	12	13	14	15	16	17	18	19	20
Type of multiple expert and prize nominations	MultPrizNom	MultNom	MultNom	MultPriz	MultNom	PrizNom	MultPriz	PrizNom	MultPriz	PrizNom
Type(s) of CE	2	3, 5	1, 3, 5	1, 3	3, 4, 5	2	1, 3	3	2	1, 2
Multiple CEs		Yes	Yes	Yes			Yes		Yes	Yes
CE preparation phase	1974–1983	1993–1997	1980–1992	1970–1990s	1990–1996	1986–1991	1988–1994	1975–1990	1981–1985	1985–1992
CE accomplishment phase	1983–1988	1998–2002	1993–1999	Mid 1990s	1996–1997	1991–1996	1994–1995	1990–2000	1985–1993	1993–2002
Career stage	Mid	Early	Mid	Mid	Mid	Early	Early	Mid	Mid	Early
Field	Nano	Nano	Nano	Nano	Nano	HG	HG	HG	HG	HG
CE accomplishment institution	Univ.	Univ	Univ	Univ.	Univ.	Gov. Lab.	Univ./Gov. Lab.	Hosp./Gov. Lab.	Univ.	Univ.
CE accomplishment country	UK	US	US	US	US	UK	DE	FR	NL	US
Current institution	Univ.	Univ.	Univ.	Univ.	Univ.	Hosp./Gov. Lab.	Univ.	Hosp./Gov. Lab.	Univ.	Univ.
Current country	S	S	S	S	S	S	S	S	S	S

Notes: MultPriz = multiple prizes, MultNom = multiple nominations, PrizNom = nomination and prize, MultPrizNom = multiple nominations and prizes; CE type abbreviations: 1 = New theoretical concepts, 2 = New empirical discovery, 3 = New methodology, 4 = New instruments, 5 = New synthesis; Country abbreviations: JP = Japan, FR = France, US = United States, DE = Germany, UK = United Kingdom, NL = Netherlands. Current country: D = different; and S = same.

valid explanations. Thus, the case study provides flexibility for the researcher to follow the most fruitful path.

3.3. Case description

Of the twenty cases, ten were undertaken with researchers currently located in Europe, and ten with creative researchers currently located in the US. Fifteen cases were undertaken in nanotechnology, five in human genetics. There is some concentration in the creativity types 3 (new methodology) and 2 (empirical discoveries), followed by type 1 (theoretical concepts) and 5 (new synthesis). Thirteen out of twenty accomplishments can be characterized by more than one creativity type, and 1&3, 2&3 and 3&5 are the most frequent combinations in this regard. Five scientists/groups fall in the most select category: multiple nominations and multiple prizes. Seven cases are in the multiple nomination category, five in the prize and nomination category, and three cases in the multiple prizes category (Table 3).

Fourteen cases appear as "serial" producers of creative accomplishments, indicating some institutionalization of effective practices for creative research. About half of the accomplishments have their roots in the mid-1980s, and three cases even in the late 1970s, indicating the substantial time necessary to move from idea generation to accomplishment. This time lag was due to resistance within the research community to accept these novel results and to incorporate them in the collective stock of knowledge. In one case, the group leader worked for about one decade solely on the problem until the research community accepted the novelty and usefulness of his work. In another case it took about nine years until an experimental result, that contradicted an established theory, could be matched with a new theoretical explanation provided by a collaboration partner. However, there are also several cases with rapid advancement from the preparation to the accomplishment phase, particularly when groups were involved in "priority races".

The creative events were accomplished across a wide range of institutional environments, predominantly in universities ($N = 11$), followed by basic research labs in industry ($N = 4$), settings in the public research sector spanning both a university and a government lab ($N = 3$), government labs ($N = 1$), and settings spanning government labs and hospitals ($N = 1$). The institutions in which our target scientists/groups work today are mostly universities ($N = 15$), but also mixed settings including hospitals and government labs ($N = 4$). Only one group with a creative accomplishment in an industrial basic research lab has remained in this institutional context. It should also be noted that US cases have some geographical concentration in areas which are already known to have a large share of R&D, such as the San Francisco Bay area and the greater Boston area. In contrast, we are not able to identify such concentration for Europe (Table 3). In the next section we report on the organizational and institutional factors that were obtained by systematic cross-case analysis.

4. Organizational and institutional factors influencing scientific creativity

This section discusses key results from the twenty case studies with an emphasis on factors that support creative scientists and groups in their research, but also with findings regarding barriers to scientific creativity. The two levels: organizational and institutional are clearly intertwined, but we discuss them separately for analytical clarity. As noted above, our unit of analysis is the research group. The group is embedded in both an organizational and broader institutional environment which contributes to or constrains the capability of group leaders and group members to conduct research in a way that seems most fruitful to them.

The comparison of the dimensions and variables from the case study protocol with the emerging dimensions demonstrates the learning process we underwent as we were exposed to the case study material. It shows how some of our initial expectations about the basic elements of the context of creativity were enriched and corrected by it. For example, spatial arrangements and infrastructure emerged as somewhat more important influences than anticipated. Furthermore, larger institutional developments, such as the severe budget cuts in (if not breakdown of) the former Soviet Union research system, and the increasing international mobility of scientists, figured more prominently in our data than initially expected. Finally, the comparatively strong representation of industrial R&D laboratories as organizational environments for scientific creativity, particularly until the early 1990s, corrected our initial expectation that the academic heartland is exclusively institutionalized in universities and government laboratories. In our policy conclusions, we will return to these and other issues.

4.1. Organizational level

The cases indicate that creative researchers have a number of distinctive ways in which they manage their research groups. This includes highly effective supervisor–student relationships, the careful selection of new group members for complementary skills and attributes, and the flexibility to address new problems or ideas that arise. We also find that groups in our sample are relatively small at the time of the main creative event: typically around six to eight researchers, including juniors and students, and sometimes with only 2–3 researchers, but they benefit from organizational contexts that provide sufficient access to a relatively large variety of technical skills. A frequent factor associated with scientific accomplishments is stable research sponsorship, provided either through some kind of basic institutional funding or dedicated funding schemes for junior scientists.

4.1.1. Research autonomy

First of all, among the prerequisites for a productive scientific atmosphere is a context in which there is a set of broadly defined problems or long term targets and carefully selected individuals are brought in as group members. They are then given freedom to pursue a more focused problem within the larger set of problems as a step toward the broad target. Freedom to define and pursue individual scientific interests within or beyond a broadly defined thematic area is central to understanding why scientists and their groups are highly creative. Individual scientific freedom is made even more productive when group members are conducting their work in units with many other bright and curious scientific minds who stimulate each other. Mutual curiosity and interest is a strong norm in all groups under consideration. For example, one group leader reported that one of his PhD students got upset because he expected the group leader to approach him about the ongoing experiment more frequently than just twice a week. Subsequently, the group leader communicated more frequently with his students.

4.1.2. Small group size

Second, we identified small group size as important organizational dimension for the development of creative work. This confirms findings previously reported (Section 2). In fifteen of our twenty case studies, small group size was highly influential for the creative accomplishment; in another four case studies this variable had some influence. The analysis of the case studies indicates that research groups responsible for creative events often start with two people, the group leader and a PhD student or a post-doc. Later on, leaders deliberately limited their groups to no more than six to eight researchers (excluding technicians and other support staff). Small group size has a number of advantages. It allows the group leader to be actively involved in research and to stimulate effective scientific exchanges within the group. This is corroborated by the majority of our cases. In contrast, we have reason to believe that large research groups are less able than small groups to unleash the creative potential of their group members, because group leaders are forced to spend more time on administration than science which weakens the crucial link between group members and group leaders. In addition, small groups typically show a lack of hierarchical decision-making in relation to research activities. The flat structure of communication, with no difference in communication between formal hierarchical levels, fuelled the dynamics regarding creative research accomplishments. Furthermore, small group size fosters productive mentor–student relationships that larger groups have difficulty to establish and to maintain.

However, several groups (although not all) did grow significantly in the period following the main creative event. This growth seems to be associated with following up and capitalizing on the opportunities that the creative event opened up. This raises an interesting question of the value of the research activities in each period, since the later ones would be deemed less creative but are critical for actually realizing the potential of the creative event itself. Also, it seems that group growth as a particular reward mechanism in science produces unintended negative effects, such as more hierarchical decision-making and reduced group leader involvement in research activities.

4.1.3. Complementary variety

Third, the small groups were typically embedded in an organizational context that had a complementary variety of scientific skills and instrumentation. For example, one scientist reported his experience within an industry lab: "We were going to have lunch and of course if you come back from lunch with a thousand ideas because everybody is in a slightly different field but not so far from you so you can talk – it's close enough." We also found collaboration within a university between theoreticians and experimentalists in physics that had enabled a highly recognized creative event in one of our cases. This type of environment provides numerous opportunities for stimulation, collaboration, the acquisition of new knowledge and research techniques or access to instrumentation. The combination of small work units in rich research contexts with requisite scientific variety allows for rapid elimination of dead ends when pursuing high-risk ideas. Researchers saw this as a critical factor since it allowed them to quickly test many of the possible paths to a solution for their problem and discard the ones that did not seem promising. Our case studies provided numerous examples of the importance to scientific creativity of a large, well-endowed organizational environment, with a good intellectual and technical infrastructure and access to a large diversity of skills and interdisciplinary knowledge across the organization.

However, we found that the scientific diversity of an organizational environment alone may not foster creativity unless it is also linked to organizational arrangements that support multidisciplinary contact. These include spatial arrangements, such as the organization of laboratory facilities or office space, but also staircases or coffee bars designed to promote interaction. Social arrangements, such as lunchtime patterns, can also play an important role in fostering communication opportunities across departmental borders. In university contexts, for example, these interactions take place mostly across department boundaries. In our cases, some laboratories were more adept than others at facilitating these exchanges by cultivating a culture of shared resources and reduced bureaucratic requirements. For example, one group leader described the physical infrastructure of the university where the creative event materialized, as one in which all disciplines are united "under one roof". Walking along the corridors initiated acquaintanceships and discussion between scientists from various disciplines. "Within three minutes I change from chemistry to physics to biology. When I walk to the electron microscope, I went through the faculties of physics and biology. These contact points are very important."

4.1.4. Communication with groups in external organizations

Fourth, effective communication with other groups that have complementary knowledge and expertise are an important factor for accomplishing creative events. For example, several theory groups depended on data from experimental groups in other research institutes, often abroad, or measurement groups needed access to sophisticated materials which they could neither produce in their own labs nor acquire from specialized companies. Interestingly, the emergent communication pattern showed that most of the in depth communication on matters close to the problem of interest to the group occurred with groups that were outside the organization; sometimes they were collaborators and on others competitors. On the other hand, the most important type of communication with groups within the organization was of a broader multidisciplinary nature and related to key skills the group itself did not possess. In other words, there is somewhat of an inverse relationship between cognitive distance and physical distance in the typical patterns of scientific communication.

In addition to our case-study findings on communication across organizational boundaries, we examined the collaboration patterns of creative scientists in a quantitative way. Drawing on our database of multiply-nominated highly creative nanotechnology scientists, Heinze and Bauer (2007) find that these scientists collaborate much more frequently with other peers than scientists from a comparison group of similarly productive researchers; they have larger collaboration networks and more often link disconnected peers. Because of this particular communication pattern, creative scientists also publish in a wide range of academic journals, and thus they are capable of speaking to different audiences and specialties. Although, for technical reasons, Heinze and Bauer (2007) do not distinguish between intramural and extramural communication, the increasing gap in the volume of collaborations between the two types of scientists (i.e. creative researchers versus comparison group) demonstrates that getting timely access to complementary expertise, skills and instrumentation from other groups is important to achieving creative events.

4.1.5. Facilitating leadership

Fifth, as we had anticipated from the literature review, both group and organizational leadership are important for the development of creative work. Effective group leaders perform many important roles. They bridge otherwise disconnected knowledge domains, carefully select new group members for their complementary skills and attributes, have the flexibility to address new problems or ideas that arise, help post-docs with a good idea both to attract funds so they can become self-sustaining and develop good intuition about the right measure of risk to take on with their new idea, and provide a protected area under which group members conduct their research. We also identified two types of mentor-student relationships. In the first type, mentors provide a research avenue where their students can develop their particular research interests. For instance, mentors provide ideas and directions, but students arrange the experimental setting. In the second type, mentors recruit highly talented students in their group but do not set them on a particular research track. Their role is more responsive to the needs of the students.

In addition to group leadership, we also witnessed the importance of directing research organizations through active leadership. In more than half of the cases, the director's research vision at the R&D management level of the organization was influential in shaping the creative accomplishment. This vision is not so much about goal clarity as it is about goal-fruitfulness in generating more focused problems that are tractable and significant. Typical visions are "finding the highest possible storage density for computer memory" or "explain the Fragile-X syndrome" which are more fruitful than clear, since the actual initial goal may undergo significant metamorphosis in the process of its pursuit. Perhaps most importantly, these leaders gave their junior staff freedom. Half of the creative events in our case studies are based on the research of junior scientists, highlighting the importance of providing independent research support to outstanding individuals at an early stage of their careers (see career stage in Table 3). As the focus of research missions is on the solution of a major problem and not on advancing disciplinary knowledge, this factor also has the attribute of encouraging interdisciplinary work because research teams were typically composed of people from a variety of disciplinary backgrounds that contributed to meeting the goals of the mission.

4.1.6. Flexible research funding

Sixth, flexible research funds were found pivotal in several research breakthroughs in our set of cases. Flexibility means that funds are not earmarked for specific purposes; that group leaders have discretion about when and how to spend them; and that funds can be used for high risk/high potential investments. In this regard, flexibility allows scientists to shift research funds in the research direction that seems most fruitful to them. One group leader argued: "When someone has to invest or wants to invest unexpectedly much more money in a project, you need the flexibility. You need a good funding level in order to be able to afford flexibility."In particular, core institutional funds, which are independent from success in attracting external grant money from research councils, have been found highly important to supporting scientific accomplishments in eight out of twenty cases, and in seven other cases these funds had some influence. Surprisingly, the four industrial research laboratory groups in our sample received high levels of such institutional core funding. For example, one group leader recalled that staff scientists in the industrial laboratory were not encouraged to write grant proposals, but to communicate directly with management about their demands for new resources. The interviewee argued that research managers who recruited him used to say: "I did not hire you to be a manager, I hired you because you are a scientist. I want you to do science. I want you to be in the lab." In contrast, group leaders in universities were sometimes forced to raise funds for their research with small grants from many different agencies, and progress was achieved only because these group leaders used grants from research councils imaginatively.

Another category of flexible funds are large, multi-year research awards provided to scientists in an ascending stage of their career. In total, six junior scientists were awarded prestigious and well-endowed individual awards. They were either supported by the Förderpreis of the Krupp von Bohlen und Halbach Foundation, the European Commission's Young Investigator Award, the National Science Foundation's Young Investigator Award, the James McDonnell Foundation's Centennial Fellowship, or the Howard Hughes Institute's Investigator Award. An in-depth study of these (and other) award schemes shows that they differ considerably with respect to target group and field, selection process and criteria, budget size, and funding duration; and that several of these schemes are powerful tools to support junior scientists (Heinze, 2008). In addition, we find unanimous consensus among our interviewees that too few such awards are currently available.

4.2. Institutional level

So far, our findings suggest that there are several organizational factors that support the capabilities of research groups to accomplish creative scientific results. In addition, however, we have identified features in the institutional environment which facilitate or constrain the creative capabilities of research groups. In this section, we will report on such institutional factors. In brief, our cases indicate that job mobility is a necessary condition for creativity in science, because when scientists accept a new job, they tend to move to research units that offer an opportunity to change field or to address intrinsically risky research problems. Also, although competition is believed to be an important institutional mechanism in science, we observe several cases with little or no influence of competitive pressures in the institutional environment on the preparation or accomplishment phase of a creative event. Finally, we find that whilst the conservative procedures adopted by research funding agencies for allocating grants may be appropriate for "normal science" in established disciplines, they create many problems for scientists with original research ideas.

4.2.1. Job mobility

We did not find that job mobility is as unidirectional a factor as one might assume. Several group leaders spent many years in the same place and either had been in one main institution their entire career or had made one major change in their career. The university setting has absorbed many researchers who moved away from industry labs when the attractive conditions in the latter deteriorated. But we did not find evidence of competitive recruiting mid-career as a mechanism to encourage creative research. Resources for hosting visitors or spending periods of time with other groups working on the same problem area had a greater effect on the success of the creative pursuits of our interviewees.

We found that when they move, creative scientists tend to move to research units that offer an opportunity to change field or to address intrinsically risky research problems. Fundamental research labs of large, leading industrial companies were a magnet for such scientists, at least until the early 1990s. Other cases demonstrate that the United States has the most open academic job market in this regard and offers ample opportunities not only for scientists from Western European countries, but particularly for researchers from the former Soviet Union where the public research sector underwent severe budget cuts in the early 1990s. In eight of our cases "immigrant scientists" moved to different countries (including the United States, France, Japan, and Germany) permanently or for a long period in order to pursue their research. These researchers reported that they had to work much harder than native scientists in order to receive recognition, but all described their moves as pivotal for the development of their scientific skills, their success in accomplishing the creative event, and future career options. We conclude from these observations that job mobility is an important condition for an institutional environment that is conducive to creative research.

4.2.2. Reputational competition in the intellectual field

Competition for reputation in the intellectual field seems to work in different ways depending on the phase of the creative work. In seven cases, competition was highly influential in either the creative event preparation or accomplishment phase. During the preparation phase, friendly competition within an organization is an important motivator. At the cusp, when an important result seems within grasp, chances are that groups in different organizations are also close to a significant achievement and the race to be first with important results will carry over even into the accomplishment phase, where important derivative results are pursued in a competitive fashion. For example, several groups were involved in "priority races" between competing scientists/groups. One group received materials for analysis and characterization from another group, but these materials were given, at the same time, to a rival group. In another case the priority race took place quite fiercely and without any mutual communication. In both cases, priority was given informally to the groups in our sample, but their publications appeared around the same time and even in the same journal as those of their rival peers.

Yet, we also observed cases where competitive pressures in the institutional environment had little or no influence on the preparation or accomplishment phase. Most of these were found in the field of nanotechnology. One reason may be that the field of nanotechnology is still emerging: the new opportunities in nanotechnology have made possible many new research paths, such that several of our creative cases developed these with little initial competition, although still with substantial risk. Some of these paths have attracted considerable attention over time. One interviewee argued that in the preparation phase of the accomplishment, this new path was met with enthusiasm by the research community: "People liked it, right away. When engineers first saw it, it was immediately a hit, there was ecstatic enthusiasm, it provided understanding, and we got inundated by request for talks and presentations." Today, there are more than 50 groups worldwide working in this new area.

4.2.3. Funding agency behavior

The manner in which responsibility for a certain field of research is allocated to a specific division of the funding agency and advised by experts in the area is a significant barrier for creative research because each division tends to award funds to scientists who have a record of publications in the area. Several group leaders had achieved their creative event on the basis of moving to a new field, or integrating new fields with their area of expertise. But one university group leader said her group "had no chance" to get money from a funding agency for their "wild ideas". The group leader recalled that one always needs preliminary results in order to compete for external funds. Therefore, getting into a new field without having preliminary results is regarded as "almost impossible". Another group leader argued that "field-hopping is bad for research grant income because it takes five years to build up credibility to get research funding". The current research system does not appear flexible enough to accept that a scientist with an excellent track record in a given field can have the capability to investigate a phenomenon that involves moving into a new field and that there are synergies in funding such research.

A second problem is connected to funding agencies jumping onto the bandwagon once the results of breakthroughs in research generate attention. Research councils and other funding agencies allocate funds for a program in the field and often set goals for work that is either already done, or unrealistic. Although programme officers in funding agencies may have a scientific background, they are perceived by several of our group leaders to have been out of research for too long to understand how research works. In consequence, the guidelines in calls for research proposals, according to one group leader, "tend to be wrong, and they do not present the actual priorities in the field".

Furthermore, many funding agencies require research proposals to set targets, or give exact details of the likely results, but this is often not possible with exploratory, open-ended research, characterized by one group leader as "a meandering path, you're branching out, making new things all the time and closing up other things and so you're moving through a difficult landscape to find your way to interesting things". We also found evidence that renewal funding is jeopardised if the expected results are not achieved. Several group leaders argued that a substantial portion of their research had not been described in any way in the research proposal. So, when it comes to grant renewals, funding agencies might argue that this research did not achieve its goals. Funding agencies also now require more accountability by scientists, and have increased the administrative burden on them. They require scientists to provide frequent progress reports, show they have worked the proposed hours or carried out the working steps according to the original proposal. Our case study results suggest that creativity would be promoted by having more flexibility in the use of grant income and less demands for constant progress reports.

4.3. Factor combinations

The variables at the organizational and institutional level must be understood as interrelated contributing influences rather than as independent, cumulative factors. Set in its context, the creative research process that we were able to detect from interviews and supporting documents of the cases has mechanisms that combine many of the influences mentioned above in ways that are more than their simple aggregation. One of these mechanisms is found in large R&D laboratories in industry. Several of our highly creative researchers were recruited to these labs at an early stage in their careers, either as post-docs or junior staff researchers. They were then integrated into a mission-oriented research program while also allowed significant freedom to pursue an aspect of the overall program that most interested or excited them. This work environment was characterized by organizations that provided significant job stability for their staff scientists, a base level of funding, and access to a large diversity of skills and multidisciplinary knowledge across the organization. These research laboratories were well equipped with instruments and experimental capabilities that allowed the pursuit of empirical research in any direction the problem might suggest and had in-house, expert technicians to provide reliable experimental results in a relatively short period of time.

The second mechanism is the university setting which is rather different from the industrial labs described above. We found that scientists that experienced their main creative events in a university context made efforts to create a setting as close as possible to the one described above while preserving the broader mission of academic work. The central difference between the main model described above and the academic setting, in the words of one of our interviewees, is that "industry labs are equipment rich and labour poor while universities are labour rich and equipment poor." Therefore, university scientists must devote considerable efforts to gain access to the necessary equipment and compensate for the time demanded by graduate students, who are "in training mode" by selecting problems that are not too time sensitive. Three other important areas in which the academic setting departs from the fundamental research laboratory in industry mechanism are the conspicuous lack of core funding to protect against interruptions of the work, the burden of non-research academic obligations such as committee work and other service activities of the university, but also the strong individual freedom associated with a group leader's position in the academic setting. In the next section, we review our findings in the light of the literature reviewed above, and we point to future directions for research.

5. Discussion

Previous studies reported that intra-organizational communication across disciplinary or departmental boundaries is associated with a productive research climate (Andrews, 1979; Pelz and Andrews, 1966). Although in some cases this view is confirmed, we also found that extramural collaborations have a much greater benefit for scientific progress than was previously assumed. The changes in institutional and organizational conditions mentioned in Section 1, especially the encouragement of research collaboration, may explain the growing importance of extramural collaborations to scientific progress. However, timely access to skills and partners are not necessarily available within the boundaries of the research organization in which the focal group is embedded. As mentioned, there is an inverse relationship between cognitive and physical distance in the typical patterns of communication that facilitate the accomplishment of creative events. While accessibility to outside skills and resources tends to expand the capabilities of research teams to make rapid progress on matters close to the problem of interest to the group, other teams and resources within organizational boundaries provide a scientific reservoir for serendipitous observations generated through effective intramural communication.

However, the opinion that deep knowledge and specialization at the individual level is integrated at the organizational level (Hollingsworth, 2002) is not fully supported. Creative scientists in our sample typically possess a rather broad scientific profile that distinguishes them from more specialized normal scientists—a finding that is also corroborated by Heinze and Bauer (2007) with respect to the nanotechnology domain. In addition, several group leaders have accomplished creative events because they had changed their research field, for example from chemistry to optics, or from semiconductor physics to biophysics. In these cases, intellectual variety is integrated at the individual level rather than at the level of the entire research organization.

However, our results do confirm previous findings regarding the strong correlation between small group size and per capita performance (von Tunzelmann et al., 2003). This is noteworthy because previous studies usually examined productivity and recognition, but not creative scientific accomplishments or research breakthroughs. Compared to the entire populations of researchers in the two fields, our twenty cases represent a very small fraction only, so the clear impact of small team size can be interpreted both as strong confirmation but also as an extension of previous evidence (because our dependent variable is creativity and not productivity).

Interestingly, we obtained mixed findings with respect to departmental effects as identified by Long and McGinnis (1981) or Allison and Long (1990). Whereas the authors argue that once scientists have joined departments, their productivity level matches that of the department, in several cases of our immigrant group leaders the causality seemed to point in the opposite direction. Typically, these immigrant scientists had to prove their scientific capabilities by working much harder and by contributing substantially higher performance than native scientists before they were invited to join prestigious departments. On the other hand, group leaders in industry reported that the dynamics and pace within these fundamental laboratories was an important driver and an inspiration for their own creativity.

Perhaps the two (strongly interconnected) variables where our findings diverge most sharply from previous evidence are funding and organizational leadership. Most importantly, in the public research sector the predominance of institutional block-grant funds (1st stream funding) has been replaced by a new regime based on competitive research council grants (2nd stream) and private foundation or industry sponsorship (3rd stream). Whereas previous studies were concerned with the relationship between perceived or actual resource levels and performance (Andrews, 1979; Pelz and Andrews, 1966), our findings suggest that the continued expansion of peer-reviewed funding, in particular at early stages of the research process, may eliminate ideas that are judged by peers as speculative, unorthodox, or transdisciplinary. Peer-review criteria, such as plausibility and validity tend to encourage conformity, while originality draws upon and encourages dissent. For this reason, funding arrangements based on peer review tend to discriminate against the early stages of exploratory research, as they have an inherent tendency to support conventional mainstream research and scientific work that follows established research lines while ignoring visionary and high-risk approaches.

Apart from a conservative bias, the double trend of decreasing institutional funding and increasing external sponsorship has at least two other consequences. First of all, winning funding competitions and reviewing increasing amounts of research proposals requires substantial time investment by scientists, time that they can neither spend on laboratory work and group interaction, nor for reading and contemplation. Since style and content of research proposals are different from presenting arguments and evidence in journal articles, these activities have reduced the precious time of the group leaders studied. Second, increasing extramural sponsorship requires a new type of organizational leadership. While research directors are expected to articulate a research vision, to recruit outstanding personnel, and to motivate scientists (as argued in previous literature), a new type of expectation has emerged: they need the capability to equip research organizations with appropriate funding from diverse sponsors and balance research budgets. Organizational leaders need to be successful in acquiring new grants and opening up additional funding channels. They must be competent in continuously monitoring the complex landscape of funding agencies and sponsorship programs. These new leadership role requirements are non-voluntary because organizations usually cannot afford to neglect their funding environment.[9] Our case studies demonstrate, however, that not only university provosts and institute directors but increasingly group leaders are confronted with meeting these new roles. The consequences were described by one group leader, who had formerly worked in a fundamental industry laboratory, as follows: "When I came [to this university], I thought I would still do research. I haven't done just one experiment in the seven years since I've been here, in the lab myself. Of course, I direct experiments but I don't carry them out myself. (...) People do most of my ideas but I'm a manager".

The discussion shows that while the institutional literature in science studies (mostly from the 1950s to the 1970s) offers useful starting point with respect to group and organizational variables, new themes have emerged that reflect the broader institutional changes in the research system since the 1970s. There are several examples where we believe our exploratory results could be fruitfully extended: (1) to understand the institutional forces that led to the marked decline of industrial companies funding exploratory and basic research (for an introduction see, for example, Chesbrough, 2003); (2) to explore the changed relationship between industry and public sector research in generating and diffusing knowledge (for an introduction see, for example, Evans, 2004); (3) to analyze quantitatively career trajectories of creative (entrepreneurial) group leaders (for an introduction see, for example, Levin and Stephan, 1991). More generally, it would be highly desirable to learn more about the differences between creativity in the natural and technical sciences on the one hand, and in the humanities and the social sciences on the other hand (for an introduction see, for example, Guetzkow et al., 2004). Also, we need more general theoretical propositions that serve as a framework for generalization and for stating cumulative hypotheses. Clearly, the renewed interest in organizational and institutional questions about the governance of research is an opportunity for more systematic theorizing. Several colleagues have started to investigate contingent variables at the group, organization and institutional level with organizational research outcomes (see, for example, Jordan, 2006; and the contributions in Jansen, 2007). Although a *governance theory of research organizations* does not yet exist, its development is underway. In the next and final section of this paper, we discuss conclusions for research management and research policy.

[9] There are exceptions, such as the German Max-Planck-Society whose institutes receive permanent institutional funding. However, many Max-Planck institutes are actively seeking external funding in the 2nd and 3rd stream (for an overview of the German research landscape see Heinze and Arnold, 2008 and Heinze and Kuhlmann, 2008).

6. Policy conclusions

This paper uses the results of a new nomination method to select a set of highly creative scientific accomplishments in Europe and the United States in two scientific fields, nanotechnology and human genetics, in order to explore organizational and institutional factors associated with creative research. We employ a multiple-case study approach of twenty highly creative research accomplishments encompassing diverse types of scientific creativity. In these cases, we did not find remarkable differences by scientific field or creativity type; rather, the principal findings relate to mechanisms at the group, organizational, and institutional level. Several of these mechanisms are relevant for current policy making. In this section, we explore some of the lessons for research management and research policy.

We collected evidence that a stimulating work context offers ample opportunities for fruitful scientific exchange, often across established cognitive domains. In contrast, the exploration mode is weakened when research groups are large and organized hierarchically. Despite this finding, large hierarchical groups can be found almost in every university and in every government laboratory. Large groups are either valued by research cultures (for example in Germany), or they emerge systematically because the predominant funding mechanism produces large structure after initial scientific successes (for example in the United Kingdom and the United States). Several of our case studies demonstrate that successful groups can grow substantially in a short time period (the Matthew effect, see Merton, 1957). Clearly, this mechanism is in conflict with the fact that breakthroughs are typically accomplished by small groups. Therefore, senior research management should be aware that highly creative research can be more difficult to undertake in large research groups, and that path-opening solutions in science seem to emerge more readily from small research units. The size of research groups should be considered an important management objective for effective research governance, particularly in new and frontier research areas. Policy makers also need to think about new mechanisms that relieve successful scientists from managing too many projects and too large groups, because large groups and hierarchical structures are barriers for creative research.

Well-endowed research institutes with a good intellectual and material facilities infrastructure and access to a large diversity of skills and multidisciplinary knowledge provide numerous internal and external opportunities for stimulation, collaboration, the acquisition of new knowledge and research techniques, or access to instrumentation. Interactions within and across such organizational contexts are particularly fruitful when groups work in related and complementary fields of expertise and when research institutes have the requisite variety of skills and knowledge. Those involved in the planning of periodic reorganizations of research institutions should ensure that changes maintain and increase the breadth of disciplinary expertise available. Furthermore, the scientific diversity of research organizations may be more likely to support creativity if linked to organizational, social and spatial arrangements that support planned and unplanned multidisciplinary contact. Organizational opportunities may include multi-disciplinary or cross-unit seed research awards, lab staff rotations, cross-training and inter-unit seminars and exchanges. Spatial arrangements, such as the allocation of offices, junior research space, hallways, coffee bars or laboratory facilities, and social arrangements, such as lunchtime patterns, may also be organized so as to encourage the opportunities for communication across departmental borders, between staff, regardless of their status, and between disciplines.

For more than three decades, the science system has been operating under "steady state" conditions (Ziman, 1994). Steady-state science has been accompanied by a decreasing lifespan for research projects, and this trend has given strength to the forces that eliminate unorthodox and original ideas. In several of our cases a certain kind of funding helped to reap the fruits of novel ideas: funding based on trust that scientists will do their work as well as they can. However, for many years, scientific research activity has been confronted with a high level of distrust, and this distrust is visible in the widespread use of performance indicators and by growth in measures such as evaluation, progress reports, management reports, audit certificates and the like. Permissive, trust-based funding does not appear to play the central role that it should play in the budgets of funding agencies. Therefore, policy makers should now be ready to accept that there is a clear need to provide appropriate funding for exploratory and high-risk research, even under the regime of steady-state science.

When considering the institutional landscape that fosters creative research, it should be noted that a conspicuously favorable environment was found in a set of fundamental R&D labs in industry that, due to changes in market conditions and industry strategies, has been drastically reduced in size over the last decade. Many of the industrial labs mentioned by our interviewees no longer exist and some that do no longer allow the sort of work that resulted in the creative events that earned them the recognition reflected in our nomination process. This raises another sort of policy question that is not limited to lessons for R&D management and grant mechanisms aimed at stimulating individual choices by researchers. Rather, it points to the overall direction of the innovation system and whether this change in research arrangements will have an effect on its capacity to be as creative as it has been to date.

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Appendix A. List of interviews

	Country	Interview dates
Cambridge University	UK	5.4.2006*, 16.7.2006
Columbia University	US	22.1.2007*, 29.1.2007
Eidgenössische Technische Hochschule Zürich	CH	7.3.2006
Emory University	US	22.11.2005
Erasmus-MC, Rotterdam University	NL	14.2.2006
Forschungszentrum Karlsruhe/Universität Karlsruhe	DE	14.7.2006
Georgia Institute of Technology	US	19.1.2007, 30.1.2007*, 6.3.2006, 13.7.2006
Harvard University	US	6.5.2006
Hopital Necker, Paris	FR	17.3.2006
Howard Hughes Foundation	US	8.1.2007*
IBM Watson Lab	US	5.12.2005
Instituut voor Atoom-en Molecuulfysica, Amsterdam	NL	11.7.2006
Massachusetts Institute of Technology	US	4.4.2006, 6.4.2006*

Appendix A (*Continued*)

	Country	Interview dates
Max-Planck-Institut, Dresden	DE	5.5.2006
Max-Planck-Institut, Stuttgart	DE	27.2.2006
McDonnell Foundation	US	20.11.2006*
New York University	US	8.8.2006*
Purdue University	US	9.2.2007*
Rheinisch-Westfälische Hochschule Aachen	DE	20.4.2006
Rice University	US	31.1.2007*
Stanford University	US	22.3.2006
Technische Universität München	DE	11.1.2007
Technische Universiteit Delft	NL	1.6.2006
UC Santa Barbara	US	28.2.2007*
Universität Bayreuth	DE	22.5.2006*, 10.11.2006
Universität Heidelberg	DE	6.2.2006
Universität Karlsruhe	DE	11.12.2005, 9.2.2006
Université Louis Pasteur, Strasbourg	FR	2.6.2006
University Illinois, Urbana-Champaign	US	20.3.2006
University of Connecticut	US	23.2.2007
University of Iowa	US	11.9.2006
Volkswagen-Stiftung	DE	14.11.2006*
Wellcome Trust	UK	2.5.2006*
Western General Hospital, Edinburgh	UK	28.11.2005, 24.8.2006*
Western Michigan University	US	9.1.2007*

Notes: *Interview by telephone, all other interviews in-person. Interview date in Day, Month, Year format.

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