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How do collaborations with universities affect firms' innovative performance? The role of "Pasteur scientists" in the advanced materials field

Yasunori Baba[a,*], Naohiro Shichijo[b,1], Silvia Rita Sedita[c,2]

[a] *Research Center for Advanced Science and Technology, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan*
[b] *Interfaculty Initiative in Information Studies, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[c] *Department of Economics and Management, University of Padua, via del Santo 33, 35123 Padova, Italy*

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ABSTRACT

This article aimed to identify the effect of university–industry (U–I) collaborations on the innovative performance of firms operating in the advanced materials field, and by doing so, it proposed an original classification of the research organization partners. The main contribution resides in the estimation of the role played by collaborations with differently experienced scientists. In contrast with previous studies, whose empirical setting was the life science industry, in the advanced materials industry the most effective collaborations are not with "Star scientists", but with "Pasteur scientists". The latter concept was empirically tested first by the authors of this article, to deepen the present understanding of industrial heterogeneity in innovation processes and to offer new insights for the formulation of corporate innovation strategies. The results of the estimation of a negative binomial regression model applied to a sample of 455 firms active in the photocatalysis in Japan confirm the idea that engaging in research collaborations, measured as co-invention, with "Pasteur scientists" increases firms' R&D productivity, measured as number of registered patents. In contrast, we found that firms' collaborations with "Star scientists" exert little impact on their innovative output.

1. Introduction

The role of university–industry (U–I) collaborations in shaping the innovative performances of universities and firms has been a key issue in the recent debate on determinants of innovation (Bonaccorsi and Piccaluga, 1994; Agrawal and Henderson, 2002; Cohen et al., 2002a; Feldman et al., 2002; Murmann, 2003). Most empirical research in the field has attempted to explain innovation patterns observed in the life science sector (Murray, 2002; Owen-Smith et al., 2002; Zucker et al., 2002; Owen-Smith and Powell, 2004; Gittelman, 2007), but few studies aimed to shed light on other science-based industries such as nanotechnology (Meyer, 2006, 2007), micro-electronics, and electronics (Balconi and Laboranti, 2006; Furukawa and Goto, 2006a), overlooking the risk that analysis focused primarily on the biotech and pharmaceuticals sectors might not convey generally applicable understanding to a larger pool of innovation processes in other sectors.

The innovation process differs across industries depending upon their knowledge base (Asheim and Coenen, 2005; Asheim and Gertler, 2005; Moodysson et al., 2008) and the role that publicly funded research plays in innovation differs among industrial sectors (Pavitt, 1984). Among the sectors categorized by the terms of "science-based", the contribution of basic science is known to be very high in pharmaceuticals and chemicals (Marsili, 2000). Biotechnology or related fields in the pharmaceutical sector are the only few industries where new ideas developed originally within university labs are quickly captured by industry (Cohen et al., 2002a). Certainly, the commercialization of science can be regarded as a form of one-way knowledge transfer from university scientists to corporate researchers in those industries.

In contrast, although the impact of public research on innovation is pervasive, firms must have knowledge of user needs in order to carry on R&D activities in the advanced materials sector (Maine and Garnsey, 2006). Since the nature of U–I collaborations in advanced materials is bilateral, the 'two-way' interaction model between university and industry appears to be the most appropriate theoretical perspective to look at innovation dynamics in this field (Meyer-Krahmer and Schmoch, 1998; Mehta, 2002). As the process of demand articulation in advanced materials is exploratory, rather than purely analytical, it becomes critically important to establish effective institutional or organizational settings for promoting

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[*] Corresponding author. Tel.: +81 3 5452 5375; fax: +81 3 5452 5375.
E-mail addresses: baba@zzz.rcast.u-tokyo.ac.jp (Y. Baba), shichi@iii.u-tokyo.ac.jp (N. Shichijo), silvia.sedita@unipd.it (S.R. Sedita).
[1] Tel.: +81 50 3367 6953; fax: +81 50 3367 6954.
[2] Tel.: +39 049 827 4236; fax: +39 049 827 4211.

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appropriate coupling of scientific knowledge and user demands in an innovation system.

This paper aims to examine how scientific research and product development are integrated through U–I collaborations, which lead to knowledge transfer and interactive learning between university scientists and corporate researchers in the important, but understudied, field of advanced materials. As pointed out by the seminal work of Nonaka, the importance of knowledge assets for firms' innovative performance is widely acknowledged (Nonaka, 1994). In the theory of dynamic knowledge creation, organizational knowledge is created within firms through a continuous dialogue between tacit and explicit knowledge. Explicit knowledge is codified knowledge transmittable in formal, systematic language, whereas tacit knowledge is personalized knowledge that is hard to formalize or communicate and is deeply rooted in action, commitment, and involvement in context (Polanyi, 1962). In this paper, aligning with Hermans and Castiaux (2007), we extend the unit of analysis to inter-organizational knowledge interaction, which involves universities and public research organizations as firms' partners.

The paper contributes to the literature on both U–I collaborations and organizational knowledge creation by examining how academia and industry interact with each other in the Japanese titanium dioxide (TiO_2) photocatalysts sector. What are the collaborations that are more likely to be conducive of successful knowledge interactions between the two parties? What types of collaborations, by means of co-invention with corporate researchers, are more influential in transforming scientific knowledge into technological achievements, and thus, for increasing firm's R&D productivity? Particularly, we use the concept of "Pasteur scientists", introduced first by Stokes (1997), to identify the key players in the technology transfer mechanism between universities and firms belonging to the TiO_2 photocatalysts sector. We designate as "Pasteur scientists" those university scientists who have been involved in many patent applications, in addition to authoring many high-quality scientific papers. Therefore they are experts who are positively inclined both towards invention activities as well as building a strong reputation in the scientific community.

Armed with our sample covering 455 firms involved in photocatalytic research and development in Japan, we statistically evaluated how collaborations with "Pasteur scientists" influence firms' R&D productivity. Bibliometric analysis of scientific papers and patents, as well as interviews, were conducted to examine the way in which "Pasteur scientists" interact with corporate researchers, in terms of co-invention activities, in order to facilitate knowledge interaction for innovation in the advanced materials industry.

The paper is organized as follows. Section 2 illustrates the theoretical foundations of the paper, providing an original analytical framework to investigate the patterns of U–I collaborations. Section 3 highlights the specificities of the advanced materials industry. Section 4 presents our testable hypotheses. Section 5 describes the empirical setting, the methodology applied, and the results of a quantitative analysis on the photocatalyst sector, which tests our hypotheses. Finally, Section 6 provides a discussion and some concluding remarks.

2. Theoretical background and analytical framework

According to Asheim and Coenen (2005) and Moodysson et al. (2008), the innovation process of firms and industries is strongly dependent on their specific knowledge base, either "analytical" or "synthetic". The analytical knowledge base is typical of industrial settings where scientific knowledge is fundamental for innovation. University-to-industry is the dominant direction of knowledge flows, as in the case of the biotechnology sector. The synthetic knowledge base pertains to industrial settings where innovations are rooted in the capacity to apply new combinations of existing knowledge. Industry-to-university knowledge flows are the prevalent modality, since more concrete know-how and skills are required in the knowledge production and circulation process, which often asks for an interactive learning mechanism between clients and suppliers, as in the case of plant engineering and shipbuilding.

We argue that a combination of synthetic and analytical knowledge bases is typical of industrial settings where the need for radical innovation is high, and it is related to the capacity to establish two-way U–I relationships, which imply an extensive tacit and codified knowledge transfer between academic and industrial community, as in the cases of medical devices (Rosenberg et al., 1995) and advanced materials (Niosi, 1993; Maine and Garnsey, 2006).

For the purpose of clarifying the function of "two-way" interaction between university and industry, research tradition makes use of the patenting and publishing performance of individual scientists and researchers (Narin and Breitzman, 1995; Schmoch, 1997; Murray, 2002; Furukawa and Goto, 2006a,b). The pioneering work of Zucker and Darby demonstrated the significance of an individual researcher as a unit of analysis and elected the "Star scientists", defined as those who had published 40 or more genetic sequence discoveries in *GenBank*,[3] as the best corporate partners in biotechnology (Zucker and Darby, 1995, 1996, 2001; Zucker et al., 1998a, 2002). Furukawa and Goto (2006a,b) identified the "core scientists", defined as corporate scientists who collected an exceptionally large number of research papers and paper citations, as the most relevant firm innovation drivers in pharmaceuticals and electronics.

We elaborated from the seminal contribution of Stokes (1997), who argued that scientists should be conceptualized as falling into quadrants, where the utility and the fundamental understanding of their research lie in the axes (the Pasteur's Quadrant). In our perspective the axes are science and technology, as the two main orientations of the scientists' research. We classified them accordingly.

The first quadrant contains scientists who conduct pure applied research (such as Thomas Edison), oriented to the creation of artifacts and systems through technological design, invention, production to meet people's needs. We called them "Edison scientists". The second quadrant contains scientists who never lose sight of the desire to advance scientific understanding, but whose research has potential real-world utility (such as Louis Pasteur). We named them "Pasteur scientists". These scientists are key actors in the process of co-evolution of science and technology. The third quadrant contains scientists who conduct pure basic research, oriented to the pursuit of knowledge and understanding for its own sake through scientific discovery, having little interest in the potential uses of the research findings for the real world (such as Niels Bohr). Nevertheless they do not exclude the possibility that their discoveries might find a potential market. The "Star scientists" illustrated by Zucker and Darby (1995, 1996, 2001), Zucker et al. (1998a, 2002) fall on this category. Even if they report some patents (only a minority of them—22% in Zucker et al., 1998b), their patenting activity is mainly the result of a relationship with firms driven by commercialization objectives, in a one-way knowledge transfer perspective from science to industry.

In order to tackle the important issue of U–I collaborations for innovation, we built an analytical framework, which attempts to classify different industrial settings according to their prevalent knowledge base, and the specificities of their innovation process (Table 1).

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[3] The classification of the relationship between stars and firms is conducted by examining the affiliation of the author associated with every article through 1989 reporting a gene-sequencing discovery written by a star.

Table 1
Main features of industry-specific knowledge bases for innovation.

Main features	Knowledge bases of the industry		
	Synthetic (A)	Analytical (B)	Synthetic + analytical (C)
Nature of innovation	Application or novel combination of existing knowledge	Creation of new knowledge	A + B
Prevalent type of knowledge	Technical knowledge	Scientific knowledge	A + B
Open search strategies for innovation	Strongly based on client–supplier interactions	Rooted in U–I collaborations	A + B
Innovation type	Mainly incremental	Mainly radical	A + B
Knowledge ontology	Dominance of tacit knowledge due to more concrete know-how, craft and practical skills	Dominance of codified knowledge due to documentation in patents and publications	A + B
Principal direction of the U–I knowledge transfer	One-way: industry to university	One-way: university to industry	Two-way U–I knowledge transfer
Most influential research organization partners	Edison scientists	Star scientists	Pasteur scientists
Typical industrial settings	Engineering-based, i.e. plant engineering, shipbuilding	Science-based, i.e. biotechnology, pharmaceuticals	Hybrid, i.e. advanced materials, medical devices

3. Industry specificities

The advanced materials sector is peculiar because the urge for innovation is very high, but the risks related to market uncertainty play an important role in shaping the industry dynamics. Radical innovations often come from R&D collaborations between scientific institutions and corporate researchers working in R&D laboratories of large firms. If basic research is a prerequisite of universities and public research organizations, applied research involves a two-way interaction between the latter and corporate researchers through several trial-and-error procedures. Although the impact of university research is pervasive in advanced materials, scattered scientific contributions alert us that tacit knowledge embodied in corporate researchers appears crucial for the identification of potential users' needs in advanced materials (Niosi, 1993; Maine and Garnsey, 2006).

Most of the knowledge transmitted from universities to firms in this industry has nothing to do with the diffusion of results derived from basic science. Taking an initiative in commercialization, much of what firms draw upon from public science is background knowledge, enabling them to find analogies for new problems and to support a viable search for possible solutions (Pavitt, 1998; Salter et al., 2002). As the flow of tacit knowledge increases from corporate researchers to university scientists, the size of universities' background knowledge increases to reach the point where university researchers can afford to generalize their knowledge to generally applicable know-how for commercialization. Emergent know-how is available to firms as long as the disclosure does not infringe on trade secrets of related firms. Clearly, the advanced materials sector features both an analytical and a synthetic knowledge base, and, therefore, the innovation process differs from other science-based industries.

Advanced materials embody novel functions, which were not possible to achieve with traditional materials, and extend the range of applications to diverse fields with varying degrees of technical uncertainty and market potential (New Materials Research Group, 1998). Among the various types of advanced materials, the TiO_2 photocatalyst, developed in Japan from 1989, is particularly promising, as it makes use of only sunlight for the emergence of its unique properties. When TiO_2 absorbs UV light, very strong oxidation power is produced, decomposing most organic compounds adsorbed on its surface. Such a photo-induced reaction is called TiO_2 photocatalysis (Fujishima et al., 2000a). Since TiO_2-coated materials can achieve clean conditions only with sunlight and rainwater, without using any chemicals, they do not require large facilities, maintenance, or experience for their utilization, and can actively contribute to environmental preservation. Accordingly, recent findings on the novel functions of decomposition of organic compounds and superhydrophilicity opened up the range of applications of the materials; among those which have been commercialized by now are: self-cleaning building materials, anti-bacterial ceramic tiles, and anti-fogging window glass (Fujishima et al., 1997, 2000b). Subsequently, applications for Japanese patents on photocatalysis started to increase in the early 1990s and jumped rapidly in the middle of the 1990s, surpassing greatly those of the United States and Europe. The development of these applications led to the creation of new markets that did not exist ten years ago, with the market size of commercial products utilizing photocatalysis estimated to be 300 million US dollars (Bureau of Industrial Technology and the Environment, 2002).

In this field, in Japan, university scientists are working to find commercial applications for their research, and they are eager to develop partnerships with corporate researchers. Among others, Professors Akira Fujishima and Kazuhito Hashimoto of the University of Tokyo, who discovered fundamental phenomena concerning the TiO_2 photocatalyst, have played a major role in industrial collaboration. To give an example, concerning patent applications for the field of photocatalysis within Japan, Fujishima and Hashimoto were ranked first and second in terms of the cumulative numbers of individual applications up to 2002: 119 applications for Fujishima, and 117 for Hashimoto. The number of applications for the next most highly ranked university scientist was 34, which shows that the industrial collaboration achievements of both professors have been superior. Also, Fujishima and Hashimoto have been energetically publishing both original and review papers on photocatalysis with epochal discoveries since the end of the 1960s. Among Japanese scientists, they were ranked second in terms of the cumulative numbers of publication with 191 papers, but were ranked first in terms of the cumulative number of paper citation with 3228. Consequently, these professors were awarded the Prime Minister's Prize for distinction in the field of U–I collaborations for 2004 for their work on "finding industrial applications for photocatalytic technology". Accordingly, they have earned recognition for creating the photocatalytic industry in Japan. An in-depth study of the innovation process which involved these two professors and the firms they collaborated with stands at the basis of the argumentations put forward in the present paper. The findings shown in Baba and Yarime (forthcoming) provided insights on the functioning of the U–I interactions mechanism, supporting the existence and importance played by "Pasteur scientists" in advanced materials.

We will report briefly the antecedents to the commercialization of TiO_2 photocatalyst coated products by TOTO Ltd., the leading Japanese sanitary fixtures maker that embarked on a close research relationship with Fujishima and Hashimoto. The story (see Table 2) significantly pinpoints the role of U–I collaborations in the TiO_2 photocatalysts sector.

Table 2
The discovery of TiO_2-coated materials properties by Fujishima and Hashimoto and consequent innovations resulting from the collaboration with TOTO Ltd.

Time	Step 1 Discovery–Science	Step 2 U–I collaboration	Step 3 Innovation–Technology	Step 4 Commercialization of products by TOTO Ltd.
1989	Discovery that TiO_2-coated materials exposed to weak UV light have the power to decompose various organic contaminants			
1990–1993		Hashimoto and Fujishima started to conduct joint research with TOTO Ltd. on tiles and other building materials coated with TiO_2 film photocatalyst	The U–I knowledge exchange led to the discovery that TiO_2 photocatalyst coated two-dimensional surfaces have cleaning and anti-bacterial functions. Joint patent applications follow	
1994				Anti-bacterial tiles
1995	Discovery that UV irradiation makes the surface of TiO_2-coated materials become highly hydrophilic			
1995		Hashimoto and Fujishima work with TOTO Ltd. corporate researchers on potential applications, including anti-fogging mirrors	Several other joint applications based on the new discovery	
1996				Self-cleaning tiles
1998				Coating for automobiles; films for door mirrors
Overall–10 years			27 Joint patent applications and 4 joint publications	4 products

Source: Our elaboration from Hashimoto et al. (2005).

After the discovery of new properties of TiO_2 photocatalysts, Hashimoto's original idea was to use the disaggregating feature of photocatalysts to eliminate yellowing in sanitary products, but it was corporate researchers in TOTO Ltd., with their thorough knowledge of the product market, who insisted that merely eliminating yellowing would not be enough to give their products an edge, and that no marketability would be generated without an odor-eliminating effect (Kishi, 2003). Therefore, scientists and corporate researchers started to work together and their collaborations resulted in the commercialization by TOTO Ltd. of the first anti-bacterial tiles in 1994. In 1995, further development in science led to the discovery of the photo-induced hydrophilicity of TiO_2-coated materials, and collaboration with TOTO Ltd. was determinant to the individuation of the potential marketable applications, ending with the commercialization of a variety of products such as self-cleaning tiles and anti-fogging films for door mirrors in the late 1990s.

4. Testable hypotheses

Generally, in the field of science-based innovation, the commonly held view assumes that academic scientists provide firms with knowledge related to basic science through U–I collaborations. However, in the field of advanced materials, academic researchers working with firms consider issues such as how to link the new functions made possible through the use of a given material and the development of products, or how to provide end-users with new services. In order to achieve this process, academic researchers consult with firms, aiming to resolve complex problems that involve numerous components, materials, performance constraints, and interactions. As discussed above, the specificities of the advanced materials industry lead us to describe the industry as composed of a combination of analytical and synthetic knowledge bases, and in this field, the consulting activity of scientists works as a driver for science-based knowledge to flow in specific technological environments, where marketable applications are developed as a result of U–I interaction.

Consulting is a two-way interaction mode between scientists and corporate researchers, whose nature has to be found in the reciprocal expectation of gaining some advantages. Industry partners normally receive from universities a deeper understanding of the nature of scientific phenomena. In the photocatalyst sector, even though some firms employ many people with deep prior knowledge of business gathered through past market experience, they often lack personnel with the ability to solve the problem of how to use photocatalysts effectively in product development based on sophisticated scientific understanding. Academic partners normally engage in U–I collaborations to gain access to complimentary assets needed to advance their scientific activities. The partnership is often seen as a means to overcome the limits of universities' process technology for testing a scientific hypothesis, or to receive financial support. In the photocatalyst sector, without the support that came from close partnerships with firms, the material designs for thin photocatalytic films, which were based on the scientific capabilities of universities, probably never would have reached a stage of technological maturity.

Reflecting these circumstances, universities and firms formed collaborative partnerships in the case of photocatalysts, and as a result of knowledge interaction that takes place between universities, which provide material design models and scientific problem solving, and firms, which have deep knowledge of the needs that end users bring to their products, proofs of concept that satisfy end users are generated. "Pasteur scientists" have strong backgrounds in scientific and applied knowledge, and they are able to work as boundary spanners between the two aspects of technology, namely the body of understanding and the body of practice (Nelson, 2004). When firms engage in collaboration with them, it is expected that knowledge interaction between universities and firms will become more advanced, and corporate R&D productivity will improve. Therefore we put forward our first hypothesis:

Hypothesis 1. Collaborations with "Pasteur scientists" are important to the determination of R&D productivity of firms in advanced materials industry.

In the advanced materials field, unlike the field of life science, the core of universities' contribution to industry consists of problem solving achieved by providing firms with appropriate consulting, and the scientific contribution made by the community of "Star scientists" ultimately plays no more than an indirect role in corporate R&D activities. It can be predicted that the type of "Star scientists" seen among academic scientists will not play an active role in the firms' R&D productivity. Therefore we put forward our second hypothesis:

Hypothesis 2. Collaborations with "Star scientists" are not important to the determination of R&D productivity of firms in advanced materials industry.

As explained above, in order to generate successful use of advanced materials in product development, continuous knowledge interaction between universities and firms becomes indispensable. Those scientists who are not well integrated within the scientific community, mostly because they work for public research organizations, are at a disadvantage when they try to access advanced areas of science. Therefore "Edison scientists" who report a very low record of publishing activity, even if they are highly experienced in technological aspects due to their numerous patent applications, are not able to offer firms with guidance related to new material design, and to resolve one after another the problems that emerge during product development. Therefore we put forward our third hypothesis:

Hypothesis 3. Collaborations with "Edison scientists" are not important to the determination of R&D productivity of firms in advanced materials industry.

5. Empirics

5.1. Methodological notes

As for the setting of a unit of analysis, observing scientific performance at the level of laboratory or research group seems desirable since research tends to be performed at the group level in the present academic community (Azagra-Caro et al., 2006; Carayol and Matt, 2006). Following research tradition, we considered scientists/researchers specializing in photocatalysis at universities, public research organizations, and firms to belong to a single research group, and we took individual organizations as the unit of analysis. This decision is due to the fact that the field of photocatalytic research is a narrowly segmented area of advanced materials research, and close collaborations are generally observed among researchers within a single organization.

After conducting several interviews with researchers specializing in this field, we recurred to statistical multivariate analysis of secondary data, which allowed us to illustrate the publishing and patenting activities of firms and universities. In particular, the estimation of a negative binomial regression model provided interesting insight on the determinants of firms' R&D productivity, pinpointing the key role played by their collaborations with "Pasteur scientists".

5.2. Data and sampling procedure

5.2.1. Patent data

To evaluate the research productivity of firms, we used the number of patents applied to the designated technological area, "Photocatalyst". Although patent applications for photocatalysts are produced all over the world, we used Japan as a target country for further investigation since the patenting activity is most active in this area. Since patents from different patent conferment offices are not comparable to each other (Singh, 2007), we used patent information from the Japanese Patent Organization (JPO) as a single data source.

We specified the specific technological area using full-text search of patent documents by supplying the keyword ("Photocatalyst") to obtain 19,784 patent applications using the PATOLIS-J database applied from 1970 to 2006. About 12.8% (2532) of applications are eventually registered as patent (as of October 31, 2007), and 97.2% of those applications (19,223) are from Japan. The remaining applications by non-Japanese organizations and individuals are disregarded for further investigation.

This set includes 6749 inventors from 3207 organizations viz. 2994 firms, 109 public research organizations (PROs), and 104 universities. The affiliations of 956 inventors are unidentified. By incorporating acquisition and merger or change and variation of corporate names, we identified 2726 distinct firms.

For corporate inventors, affiliation was identified by address (basically, the corporate name and address are listed in the "place of inventor" field in the patent gazette). For university and PRO researchers, affiliation is not always indicated in patent journal descriptions. Therefore, we used external data sources [Directory Database of Research and Development Activities (ReaD), by the Japanese Science and Technology Corporation (JST), and Database of Grants-in-Aid for Scientific Research, by the National Institute of Informatics] to match a person's name, residential area, and patent class (IPC) to their affiliated organization name.

From this data, we counted the number of patent applications by organizations as an organization-level patenting activity indicator. In order to analyze firms whose core activity was photocatalyst, we set a threshold of 5 patents for inclusion in the sample, which was finally composed by 455 firms. Additionally, only for firms, we identified the number of patent applications co-invented with researchers affiliated with PROs and universities. In this sample, 10.3% are classified as U–I co-inventorship.

5.2.2. Publication data

Besides patents, research paper publications are one of the methods of external expression of knowledge accumulations in organizations. We used the bibliographic database of academic articles prepared by Thomson Scientific Inc. (called SCI-EXPANDED) to evaluate the amount of scientific knowledge accumulation in firms. To restrict our analysis to specific technological area under investigation, we used the full-text search functionality of the database to extract photocatalyst-related articles from the database. From this search procedure, we obtained 6992 articles published from 1970 to 2004 written by 9801 individual researchers from 2002 organizations. Within this sample, 26.8% of articles (1873) are written or written jointly by Japanese researchers (including researchers affiliated with firms, PROs, and universities). From this sample, we counted the number of papers and the number of citations (the sum of citations eventually received by all the papers the organization has ever published) as organization-level academic research performances.

5.3. Measures

In order to investigate the effect of collaborations with university researchers on innovative output of firms, we first classified the universities and PROs according to the quantity and quality of their patenting and publishing activities. The criteria adopted to identify the four groups reported in Table 3 is very simple. We discriminated the research organizations' (universities and PROs) activity using two variables: the number of patent applications (UPRO_PAT) and the average quality of the publications (UPRO_QPUB) of their

Table 3
The proposed classification of scientists.

Number of patents (UPRO_PAT)	Quality of publications (UPRO_QPUB)		Total
	Low (UPRO_QPUB ≤ 2.56[a])	High (UPRO_QPUB > 2.56)	
Low (UPRO_PAT ≤ 10[b])	Others, 175 (70.6%) 120 PROs (60.57%), 55 universities (31.43%)	Star scientists, 31 (12.5%) 5 PROs (16.13%), 26 universities (83.87%)	206 (83.1%)
High (UPRO_PAT > 10)	Edison scientists, 19 (7.7%) 14 PROs (73.68%), 5 universities (26.32%)	Pasteur scientists, 23 (9.3%) 4 PROs (17.39%), 19 universities (82.61%)	42 (16.9%)
Total	194 (78.2%)	54 (21.8%)	248 (100%)

[a] 2.56 is the mean value of the distribution of the variable UPRO_QPUB, which counts the value of the publications of the universities and PROs.

[b] 10 is the mean value of the distribution of the variable UPRO_PAT, which counts the number of patent applications reported by the universities and PROs.

Table 4
Variables description, period of analysis: 1970–2006.

Role	Phenomenon	Variable name	Description
Independent variables	Collaborations with “Star scientists”	STAR_COPAT	Number of joint patent applications between corporate researchers and university “Star scientists”.
	Collaborations with “Pasteur scientists”	PASTEUR_COPAT	Number of joint patent applications between corporate researchers and university “Pasteur scientists”.
	Collaborations with “Edison scientists”	EDISON_COPAT	Number of joint patent applications between corporate researchers and university “Edison scientists”.
Control variables	Absorptive capacity	F_PUB	Total number of publications authored by the firm’s members.
	Size	SIZE	Number of corporate inventors.
Dependent variable	R&D productivity	PROD	Number of patent applications.

members. UPRO_QPUB is built dividing the number of citations by the number of publications. We took as a reference line the average value of each variable.

We thus propose a classification of the research organizations, and therefore the scientists (see discussion in Section 5.1), into four groups: (1) Star scientists; (2) Edison scientists; (3) Pasteur scientists; and (4) others.

The first group identified outperforming university scientists as “Star scientists”; they reported a publications record above the average, but a patenting activity below the average. This group represents 12.5% of the overall sample, and 83.87% of its components are scientists affiliated with universities (only 16.13% to PROs).

The second group, called “Edison scientists”, is formed by scientists who showed a patenting activity above the average, but a publication record below the average. It represents 7.7% of the sample, and it is composed mainly of scientists affiliated with PROs (73.68%—against 26.32% affiliated with universities).

Finally, the third group, named “Pasteur scientists”, collects scientists that reported a publication record above the average, but also a patenting activity above the average. It represents 9.3% of the overall sample, and it is formed mainly of scientists affiliated with universities (82.61%). Only a minority of the scientists included in this group work for PROs (17.39%).

Furthermore, we performed a negative binomial regression analysis in order to identify the key determinants of innovative capacity of firms operating in the photocatalyst sector. The following sections propose a brief description of the variables entered in the model (see also Table 4) and the results of the estimation (see also Table 6).

5.3.1. *Dependent variable*

Our dependent variable is R&D productivity (PROD). Earlier studies have suggested that patents are a fairly good indicator of the inventive output of a firm’s research department and a measure of the output or success of R&D (Bound et al., 1982; Hausman et al., 1984; Zucker and Darby, 1995, 1996, 2001). Following this tradition, we measure the firms’ R&D productivity in terms of the number of registered patents taken by a firm. This variable takes positive discrete values.

5.3.2. *Independent variables*

5.3.2.1. U–I collaborations. Recent research on the issue of U–I collaborations identified a variety of channels for knowledge to flow between the two worlds. Cohen et al. (2002a) compared the role played by formal channels, viz. patent licenses provided by universities with the role of open channels, viz. publishing and consulting, concluding in favor of the latter. Other contributions pinpointed the role of co-patenting activities, and others the utility of labor mobility. When we use the term “collaboration” to illustrate the relationship between university and industry, we intend to analyze the intensity of co-invention activity. The latter is registered each time both corporate researchers and PRO or University researchers appear as inventors in a patent application in the field of study. This choice is driven by the need to have a fair measure for the U–I collaborations. The use of co-publishing would lead to a bias due to the fact that many U–I joint publications in the photocatalyst sector appear in Japanese journals, which are not included in the Thomson Scientific database.

5.3.2.2. Collaborations with “Star scientists”. We measured the strength of the firm’s collaborations with “Star scientists” as the number of collaborative patent applications (STAR_COPAT) where both corporate researchers and university “Star scientists” signed as inventors.

5.3.2.3. Collaborations with “Edison scientists”. We measure the strength of the firm’s collaborations with “Edison scientists” as the number of collaborative patent applications (EDISON_COPAT) where both corporate researchers and university “Edison scientists” signed as inventors.

5.3.2.4. Collaborations with “Pasteur scientists”. We then measure the strength of the firm’s collaborations with “Pasteur scientists” as the number of collaborative patent applications (PASTEUR_COPAT) where both corporate researchers and university “Pasteur scientists” signed as inventors.

5.3.3. *Control variables*

5.3.3.1. Absorptive capacity. Knowledge captured by corporate researchers depends on the quality and quantity of knowledge

Table 5
Descriptive statistics, period of analysis: 1970–2006.

Variable	*N*	Mean	Std. Dev.	Minimum	Maximum	1.	2.	3.	4.	5.
1. PROD	455	33.2	71.97	5	930					
2. STAR_COPAT	455	.17	.83	0	43	.402***				
3. PASTEUR_COPAT	455	1.60	6.45	0	116	.634***	.507***			
4. EDISON_COPAT	455	.59	1.85	0	20	.444***	.447***	.565***		
5. F_PUB	455	.70	3.29	0	43	.304***	.173***	.376***	.259***	
6. SIZE	455	20.08	35.81	1	285	.835***	.252***	.385***	.296***	.211***

*** $p < .001$.

flows as well as by their absorptive capacity (Cohen and Levinthal, 1990). We chose the total number of publications authored by the firm's members (F_PUB) at the time of the sample as proxy for the firm's absorptive capacity. This choice aligns with major studies on the field of U–I knowledge transfer, where the role of core scientists is widely acknowledged as an important driver for innovation (Furukawa and Goto, 2006a,b).

5.3.3.2. Size. We argue that one of the main sources of unobserved heterogeneity in our innovation model lies in the different firms' size, which may be related to more patents, more academic publications as well as more inventions. In particular, since we focus on R&D productivity, the availability of a larger pool of corporate researchers may exalt the innovative capacity of firms. Therefore we included in the model the variable SIZE, which is calculated as the cumulated number of corporate inventors registered in the overall firm patent applications.

5.4. Statistical analysis and results

Since the dependent variable (R&D productivity—PROD) is a count of scores (nonnegative integers), ranging from one to many, rather than continuous, a negative binomial model is applied as the means of estimation (Bound et al., 1982; Hausman et al., 1984; Zimmerman and Schwalbach, 1991; Licht and Zoz, 1998).[4] Descriptive statistics on our dependent, independent, and control variables are summarized in Table 5.

The negative binomial regression model predicting R&D productivity from type of U–I collaborations is statistically significant (Wald chi-squared = 930.38, df = 5, $p < .0001$—see Table 6).[5] The choice of the negative binomial for the estimation of our model is appropriate, since the outcome of the likelihood-ratio test for over-dispersion suggests that the probability of the data having been generated by a Poisson process is very low.[6] The estimation of robust standard errors attempts to adjust for heterogeneity and misspecification problems in the model, therefore robust estimators are obtained.

Table 6
Negative binomial regression (dependent variable: PROD – log).

	Model estimation	
	Coefficient	Robust S.E.
STAR_COPAT (log)	.019	.087
PASTEUR_COPAT (log)	.171***	.057
EDISON_COPAT (log)	.134*	.070
F_PUB (log)	.173**	.060
SIZE (log)	.678***	.034
Constant	1.202***	.088
No. of observations	455	
Log pseudo likelihood	−1694.268	
Wald chi-squared	930.38***	
LR chi-squared alpha = 0	3156.58***	

* $p < .05$.
** $p < .01$.
*** $p < .001$.

By the conventional .05 standard statistical significance, negative binomial analysis indicates that higher R&D productivity of firms operating in the photocatalyst sector is associated with greater number of collaborations with "Pasteur scientists" and "Edison scientists", larger absorptive capacity, and experience. Collaborations with "Star scientists" do not affect firms' innovative performance.

In order to interpret the regression coefficients for these variables, we took into account the logarithmic transformation of the variables. The model indicates that engaging in collaborations with "Pasteur scientists" has a positive and significant impact on the firm's innovative output (a doubling of the number of collaborations is associated with a 1.13% increase in the number of patents).[7] This result confirms Hypothesis 1, and stresses the importance for corporate managers of selecting university partners with specific characteristics, which fit properly the industry's need to consult with scientists of high scientific value and technological experience.

On the contrary, collaborations with "Star scientists" are not significant in improving the firms' innovative performance. This result strongly supports Hypothesis 2, and underlines the heterogeneity in the scientists' capabilities, which discriminates their ability to "speak the language of the firm" and to offer valid consulting for firms in the advanced materials sector. Being a "Star scientists" is not a sufficient condition to engage in a two-way knowledge interaction process with corporate researchers.

Collaborations with "Edison scientists" have a lower,[8] but still positive and significant impact on the firms' R&D productivity (a doubling of the number of collaborations is associated with a 1.10%

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[4] The Poisson regression model assumes that the variance of the counts is equal to the mean, which appears not to hold in our situation, where we witness an overdispersion phenomenon. The negative binomial succeeds in accommodating this problem. The negative binomial model is an extension of the standard Poisson model where the Poisson parameter for each firm has an additional random component, accounting for (unobserved) heterogeneity, not yet accounted for by the regressors that determine the individual mean function.

[5] The number of co-patents plays a dual role in our econometric specification, both as the measure of the collaborations as well as the measure of a component of the performance. This may create a potential bias for finding positive correlations between collaborations and performance. Being firm patents resulting from U–I collaborations a large minority (10.3%), the bias cannot undermine the validity of the model.

[6] The likelihood-ratio test for the over dispersion coefficient (alpha), where the null hypothesis is alpha = 0, reported an associated chi-squared value of 315,658.58 with 1 degree of freedom ($p < .0001$), which suggests to reject the null hypothesis. In other words, this result strongly suggests that the negative binomial model is better than the Poisson regression model.

[7] Given the coefficient of .171 for the number of collaborations with "Pasteur scientists", a doubling of the number of these collaborations would multiply the R&D productivity by $\exp(.171 \times \log(2))$, which is 1.13.

[8] The test for the equality of the coefficients related to "star scientists" and "Pasteur scientists" led to reject the null hypothesis (chi-squared = .23, df = 1), therefore the two coefficients are statistically different.

increase in the number of patents.[9] This result leads to reject Hypothesis 3. The attitude towards invention activities of the scientists is important, but still an insufficient condition to provide firms with the appropriate knowledge base to develop new products incorporating cutting edge science.

6. Discussion and conclusions

This paper aimed to identify the effect of U–I collaborations on the innovative performance of firms operating in the advanced materials field, and by doing so, it proposed a test inspired by the Stokes' classification of the research organization partners. The main contribution of the work resides in the estimation of the role played in this industry by collaborations with differently experienced scientists. In contrast with previous studies, whose empirical setting was the life science industry or one of its components, in the advanced materials industry the most effective collaborations are not with "Star scientists", but with "Pasteur scientists". The latter concept was tested empirically first by the authors of this paper, to deepen the present understanding of industrial heterogeneity in innovation processes and to offer new insights for the formulation of corporate innovation strategies.

The results of the estimation of a negative binomial regression model applied to a sample of 455 firms active in the photocatalysis in Japan confirm the idea that engaging in research collaborations, measured as co-inventions, with "Pasteur scientists" increases firms' R&D productivity, measured as number of registered patents. In contrast, we found that firms' collaborations with "Star scientists" exert little impact on their innovative output. Moreover, the model suggests to evaluate carefully some important firm-specific assets, such as absorptive capacity (Cohen and Levinthal, 1990) and firm size, which affect positively and significantly the firm's innovation performance.

Recent research showed that official channels play a limited role in the flow of knowledge between universities and industries by providing patent licenses, while the open channel of academic paper publication, consulting and scientific advising, which occur informally between academic and corporate researchers, play a critical role in knowledge transfer (Cohen et al., 2002b). Our findings strongly support the importance of consulting as mean for knowledge re-combination and tacit knowledge flows between firms and universities through the contribution of "Pasteur scientists", who work as boundary spanners in charge of combining their science-based background with the knowledge, mainly ingrained into practice and trial-and-error procedures, of corporate researchers.

The ability to communicate with firms and to be oriented towards the commercialization of scientific discoveries is a peculiar characteristic of "Pasteur scientists". Therefore, a direct managerial implication of the results of our investigation concerns the knowledge procurement strategy of the firm, which must be dependent by the industry knowledge base (Asheim and Coenen, 2005) and on the characteristics of the partnering scientists. In industries where an analytical knowledge base prevails, such as in the life sciences, the knowledge procurement strategy, at least initially, could be based upon contacts with "Star scientists" through Technology Licensing Offices (TLOs). In contrast, in industries characterized by a combination of synthetic and analytical knowledge bases, such as in the field of advanced materials, the knowledge procurement strategy must be based upon the building of appropriate channels for two-way knowledge interaction between "Pasteur scientists" and corporate researchers, the latter playing an active role in the transfer of prior firm-specific and market knowledge. The ability of "Pasteur scientists" leads to a kind of customization process of science-based knowledge, which takes place only through a strong bilateral U–I communication, facilitated by a proactive attitude of both the research partners. A common language and mutual understanding is in fact a prerequisite to the success of the joint research activity, which is sustained not only by formal agreements, but by informal commitment rooted in friendship and reciprocal trust, as the case of professors Fujishima and Hashimoto revealed.

In advanced materials, firms should look for experts oriented towards technology (reporting lots of patents) as well as science (reporting well cited papers)—the "Pasteur scientists". This is due to the fact that "Star scientists" may be the key actors in innovation carried out in biotech or sectors alike, but they lack the important quality of being able to play as boundary spanners between university and industry, which is very important in the advanced materials.

The success of U–I collaboration proved to be strictly connected to the absorptive capacity of the industrial partner (see also Schmoch, 1997). Our recommendation to managers in the advanced materials field is to cultivate their corporate researchers in order to be an active part in the U–I knowledge transfer process. Adequate search strategies are needed in order to find the appropriate "Pasteur scientist" whose knowledge and experience match the firm's requirements. Participation in industrial gatherings and scientific conferences might be good channels to establish direct contacts with candidates of "Pasteur scientists", but industrial proposals to universities for specific material designs might work as well.

We acknowledge some limitations in our work, which are mainly related to the national boundary of our research design and to the very narrow sector of analysis: photocatalysts. Nevertheless, we believe that our findings contribute to the present understanding of firms' innovation strategies pinpointing the role played by the industry specific knowledge base and the type of U–I collaborations. Further research is needed to evaluate the extent to which the results of our analysis can be extended to other industrial segments, geographical contests, and national systems of innovation.

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[9] Given the coefficient of .134 number of collaborations with "Edison scientists", a doubling of the number of these collaborations would multiply the R&D productivity by $\exp(.134 \times \log(2))$, which is 1.10.

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