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HOW DOES THE ENTREPRENEURIAL ORIENTATION OF SCIENTISTS AFFECT THEIR SCIENTIFIC PERFORMANCE? EVIDENCE FROM THE QUADRANT MODEL

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How does the entrepreneurial orientation of scientists affect their scientific performance? Evidence from the Quadrant Model

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ABSTRACT

Using Stokes's (1997) "quadrant model of scientific research," this paper deals with how the entrepreneurial orientation of scientists affects their scientific performance by considering its impact on scientific production (number of publications), scientific prestige (number of forward citations), and breadth of research activities (interdisciplinarity). The results of a quantitative analysis applied to a sample of 1,957 scientific papers published by 66 scientists active in advanced materials research in Japan found that (i) entrepreneurial scientists publish more papers than traditional scientists do, (ii) the papers published by Bohr scientists (traditional scientists with a stronger intention to fundamentality) demonstrate better citation performance than those published by Pasteur scientists (entrepreneurial scientists with a stronger intention to fundamentality) do, on average; (iii) if the focus is confined to high-impact papers, their prestige (i.e., forward citation counts) is favored by the authorship of Pasteur scientists; and (iv) the portfolio interdisciplinarity of papers authored by Pasteur scientists is higher (more diverse) than that of Bohr scientists.

1. Introduction

Universities have become increasingly entrepreneurial over the last few decades as science and technology policies have been oriented to strengthen the link between academia and industry (Etzkowitz, 1983, 1998; Slaughter and Leslie, 1997). These policies have put in place initiatives aimed to increase universities' patenting activity and to facilitate university spin-off companies. Many contributions to the literature have attempted to explain how academic entrepreneurship has influenced firms' innovation activity (Cohen et al., 2002; Mowery et al., 2002; Murray, 2002; Powell et al., 1996; Zucker and Darby, 1996; Zucker et al., 2002) through a variety of university-industry (U-I) interactions. Several studies have also examined the possible contribution of U-I relations to scientific productivity, mainly by investigating how scientists' patenting activities influence their publication performances in terms of both quantity and quality (Agrawal and Henderson, 2002; Breschi et al., 2008; Carayol and Matt, 2004, 2006; Fabrizio and Di Minin, 2008; Meyer, 2006a, 2006b). However, the impact of U-I interactions on the scientific performance of universities is still unclear; thus, further understanding is needed on the heterogeneity in scientists' entrepreneurial orientation and their idiosyncratic impact on scientific performance.

We aim to investigate this topic empirically by asking how academic entrepreneurship affects the publication performance of scientists in the advanced materials field in Japan. To compare the entrepreneurial orientation of scientists, we classified scientists by using Stokes' (1997) quadrant model. In the quadrant model, four types of scientists are identified: Edison, Bohr, Pasteur, and Other. Edison scientists conduct mainly pure applied research, oriented toward discovering knowledge to be applied to the real world and having little interest in deepening the understanding of basic science. Bohr scientists are keener to develop pure basic research, oriented to the pursuit of knowledge for its own sake, having little interest in the potential uses of their research findings for the real world. Pasteur scientists are devoted to application-oriented basic research, never losing sight of their hope to advance scientific understanding while contributing to real-world utility. By applying this classification, which is rather peripheral with respect to the current literature, we investigate differences in publication performance among differently modeled scientists. Adopting Lam's (2010) typology, Edison scientists are mainly entrepreneurial, whereas Bohr scientists are "ivory tower" traditional, and Pasteur scientists turn out to be the "hybrids."

In this paper, we intend to expound the effects of the entrepreneurial orientation of scientists on their scientific performance by considering three key performance indicators: scientific production (number of publications), scientific prestige (number of forward citations), and breadth of research activities (interdisciplinarity).

First, we chose to focus our analysis in Japan where emerging entrepreneurial institutions, which are modeled on the US system, make it easier for universities and their faculty to engage more directly in commercial activity (Walsh et al., 2008). Reforms have led a great number of scientists to be involved in entrepreneurial activities since the mid-1990s (Nagaoka et al., 2009). Second, we selected advanced materials as a field of research because interaction between science and technology is particularly relevant. This interaction is leading, on the one hand, to generation of new scientific knowledge, and, on the other hand, to identification of industrial applications for scientific discoveries (Maine and Garnsey, 2006; Niosi, 1993; Schmoch, 1997). We also chose to focus on the TiO_2 photocatalyst, a subfield of advanced materials, because emerging academic entrepreneurship in this field has opened up a wide range of industrial applications to bring about sizable markets all over the world (Baba et al., 2010).

The following analysis is based mainly on bibliographic data (1976-2010) taken from the database Scopus (Elsevier, 2010), and on patent data taken from the Japanese Patent Office (JPO) database. Additionally, we conducted intensive interviews in the mid-2000s with scientists operating in the field, based on semi-structured questionnaires. The results of quantitative analysis applied to a sample of 1,957 scientific papers published by 66 scientists found that (i) entrepreneurial scientists (Pasteur and Edison) publish more papers than traditional scientists (Bohr and Other) do; (ii) the papers published by Bohr scientists demonstrate better citation performance than those published by Pasteur scientists do on average; (iii) if the focus is confined to the high-impact papers, their prestige (forward citation counts) is favored by the authorship of Pasteur scientists; and (iv) the degree of interdisciplinary papers authored by Pasteur scientists is higher (more diverse) than that of Bohr scientists.

The paper is organized as follows. Section 2 reviews the previous research on the issue, providing an analytical framework to investigate the heterogeneity of scientists, and presents our testable hypotheses. Section 3 describes the data and methodology. Section 4 presents the results of our quantitative analyses. Finally, Section 5 provides a discussion and some concluding remarks.

2. The Heterogeneity of Scientists in the Context of University-Industry Linkages: Theoretical Background and Testable Hypotheses

2.1. Impact of University-Industry Linkages on Scientific Research

There has been a research tradition examining the nature of the interaction between science and technology. In contrast to the common view that emphasizes causality as running from science to technology, a series of seminal papers explains that scientific knowledge has often grown out of searching for a solution for a particular technical problem in a narrow societal context (Dosi, 1982; Dosi, 1988; Murmann, 2003; Nelson, 1962; Rosenberg, 1982). From this viewpoint, which holds that causality may also run from technology to science, it can be inferred that there are some cases when U-I linkages could positively contribute to progress in scientific research

(Agrawal and Henderson, 2002; Breschi et al., 2008; Carayol and Matt, 2004, 2006; Fabrizio and Di Minin, 2008; Meyer, 2006a, 2006b). A number of recently published studies have examined the contribution of U-I linkages to academic research, mainly by investigating the relation between scientists' patenting activities and their publication performance, measured in terms of both quantity and quality. Scientists who engage in patenting are, broadly speaking, the most productive in scientific research (Breschi et al., 2008; Carayol and Matt, 2004; Carayol and Matt, 2006; Fabrizio and Di Minin, 2008), or their research is of higher quality (Agrawal and Henderson, 2002; Meyer, 2006a; Meyer, 2006b). Similarly, from a patent-publication pair perspective, the event of patent application is more likely to produce an increase in the number of publications in the year of the invention, or in the following 1 to 2 years (Azoulay et al., 2006; Breschi et al., 2008; Calderini and Franzoni, 2004; Fabrizio and Di Minin, 2008). Besides, research funding from industry to universities through contract research expands the scale and raises the quality of scientific research (Breschi et al., 2005), and it is suggested that linkages with industry have the potential to contribute to the training of researchers at universities (Blumenthal et al., 1986).

In some cases, university patenting and licensing activities are perceived and have proven to be detrimental, producing a decline in the quality of publications and inducing a substitution effect between patents and publications, as in the case of the biotech field (Murray and Stern, 2005). As Powell et al. (2007: 140) claimed, "paying excessive attention to blockbuster patents and potential licenses, and not enough to planting seed corn, can produce a failure to 'restock the R&D pantry.'" Certainly, patenting skews scientists' research agendas toward commercial priorities (Blumenthal et al., 1996; Krimsky, 2003), but the interaction with industry, broadly speaking, is a positive influence on their experimental work (Siegel et al., 2003), without negatively altering publishing rates (Agrawal and Henderson, 2002). Based on a comparison between patenting and non-patenting scientists, Fabrizio and Di Minin (2008) found a statistically positive effect of academics' patent stocks on their publication counts, and Stephan et al. (2007) demonstrated, through a survey on the cross-sectional relationship between patenting and publishing, that patenting and publishing relate positively.

Additionally, the direction of research is known to be affected by U-I linkages. According to Blumenthal et al. (1996), U-I linkages are significantly more likely to result in the choice of commercial-oriented research topics. Although Thursby et al. (2007) showed that the most likely outcome of university licensing is that both basic and applied research effort increase, the applied effort increases more than the basic effort. Scientists' orientation towards industry may be seen from their preference of choosing applied journals for their publication output, which could affect observed publication quality because "applied research" is less likely to be cited by "basic research" (Narin et al., 1976). Even though their research output still remains within basic research, their discoveries may categorized as of a not-yet-established (i.e., "interdisciplinary") nature, affected by the non-scientific (i.e., commercial) nature of their inquiry. The fact that interdisciplinary research (IDR) tends to be published in journals with a lower citation impact (Rinia et al., 2002; Rinia et al., 2001) may undermine their citation performance regardless of the nature of the discoveries. Thus, we believe that the measure of the scientific performance of scientists as the number of papers and citations could be upgraded by supplementing the counts with their research breadth—that is, interdisciplinarity.

2.2. Nature of Scientists' Heterogeneity: Stokes's Quadrant Model

From the viewpoint of the theory of technical change, it is not worth discriminating between basic and applied research because drawing "the line on the basis of the motives of the person performing the research – whether there is a concern with acquiring useful information (applied) as opposed to a purely disinterested search for new knowledge (basic)," is irrelevant because some of the most fundamental scientific breakthroughs have come from people who thought they were doing applied research (Rosenberg, 1982: 149). From the viewpoint of the sociology of science, it is known that the heterogeneity of scientists' motivation is more complex than the dichotomy of professional rewards in the scientific community and private financial gain (Merton, 1973), which includes such motives as intellectual challenge as well as contributing to society (Sauerman et al., 2010). The number of patents is traditionally taken as a measure of scientists' orientation to pursuing commercial activities, but financial returns are not the key reason why scientists active in such fields as bio-medical sciences get involved in patenting. Depending on the nature of their particular motivation or orientation, scientists are known to use different types of logic and reasoning in solving scientific problems (Dewey, 1938; Peirce, 1932; Rao, 1997; Sebeok and Umiker-Sebeok, 1980). In order to shed light on the heterogeneity of scientists and their variable entrepreneurial orientations, we use Stokes's (1997) quadrant model, whose main characteristics will be summarized in the following sections.

2.2.1. EDISON SCIENTISTS

In solving scientific problems, among the many types of logical reasoning, the importance of abduction is widely recognized. Abduction was originally advocated by C. S. Peirce (1932), a nineteenth-century pragmatist. It is the cognitive process of articulating a hypothesis that provides a consistent explanation of the various observed data and phenomena (Sebeok and Umiker-Sebeok, 1980). In solving problems, skilled inventors (corresponding to the Edison type) are known to use abduction—that is, the creation of new knowledge by intuition, without data (Rao, 1997)[1]—which is based largely on a synthetic knowledge base (Baba and Nobeoka, 1998;

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[1] The distinction between induction and abduction is somewhat subtle (Rao, 1997). In induction, scientists are guided by experimental data and its analysis to provide an insight. But the ultimate step in the creation of new knowledge does depend on previous experience and a flight of imagination.

Takeda et al., 2001). Thomas Edison represents the ideal type of scientist to be included in this quadrant: although he is notorious for his weakness in mathematics, he had a "talent for asking questions that could be translated into hypotheses, which in turn established the strategy and tactics of experimentation" (Hughes 1983: 26).[2]

2.2.2. BOHR SCIENTISTS

The Bohr scientist acts as a traditional academic. Bohr scientists set the goal of producing codified theories and models that explain and predict natural reality and embark on a course of research that involves stipulating preconditions by simplifying and reducing the number of observable variables. The essential skills of conventional academics are known "to simplify the essential to allow modeling and prediction" (Pavitt, 1998: 795). Those scientists usually use logical methods of deduction (verification of proposed theories) and induction (creation of new knowledge based on observational data) to solve scientific problems.

Regarding the nature and direction of the research activities, we know that the incentive for conventional academics (Bohr scientists) to perform well is to obtain appraisal from their peers and to improve their standing in the scientific community (Merton, 1973). They are therefore more willing to present their research results in a form that can be properly evaluated and preferably cited by their peers. They must be traditional enough to establish strategic similarities that connect their work to that of others in the field, yet original enough to establish strategic differences that impart novelty to their work (Hackett, 2005; Hackett et al., 2004). Under the

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[2] When Edison began his research on the incandescent light bulb, the technology already existed for lighting up a filament inside a glass bulb by conducting an electric current into it. However, the filaments that existed at the time would burn out in two hours, making it difficult to market them as replacements for gas lamps. Scientists at the time took it for granted that filaments would burn out (oxidize) quickly at temperatures high enough to give off light, so they did not work on ways to extend the life of incandescent bulbs. Edison, on the other hand, did not have the scientific understanding that it was physically difficult to create the phenomenon of illumination while simultaneously prolonging that phenomenon. As a result, he carried out a process of trial and error, using 7,000 different types of materials before he succeeded, by chance, in extending the life of his incandescent bulbs to 300 hours.

circumstances, those scientists are assumed to opt for research whose agendas and experimental protocols do not differ considerably from those used in earlier research in the field, and to use conventional deductive/inductive reasoning to carry out their analyses.

2.2.3. PASTEUR SCIENTISTS

As inferred from the fact that Pasteur's interest in the phenomenon of fermentation derived from his relationship with the French distilling industry, his research was also led by "preconceived (scientific) ideas" that enabled him to become the founder of bacteriology (Geison 1995: 95); thus, a Pasteur scientist is a hybrid academic. He shows an ambidextrous attitude toward basic and applied science, and an interest not only in promoting his reputation within the scientific community, but also in benefiting society through the commercialization of science.

His ambidexterity appears to fuel his scientific production, and it is supported by a twofold viewpoint. Following the definition of Pasteur scientists, we claim that scientists under this category would resemble both Bohr and Edison scientists. Pasteur scientists have two faces, which allow them to use either deductive/inductive or abductive reasoning, depending on the type of problem they are solving: when wearing their Bohr face, they use deductive/inductive reasoning for deepening the understanding of science; when wearing their Edison face, they use abductive reasoning for developing use-inspired technologies. Partially borrowing from Edison scientists, Pasteur scientists set the goal of arriving at an understanding of how a phenomenon behaves under a given set of conditions and embark on a course of research that explores the technological possibilities for satisfying user needs in a society. Employing these two faces, "many able scientists, of whom Pasteur is a fine example, have found no conflict in focusing on particular fundamental problems because of their practical utility" (Metcalfe, 2010).

Recently, because of increased incentives to make a socio-industrial contribution through U-I linkages, science policy researchers have insisted that the prevailing academic entrepreneurship may undermine the university's core mission of promoting "public science" (Dasgupta and David, 1994; Nelson, 2004) and the norms in the scientific community (Etzkowitz, 1998; Glenna et al., 2007; Nelson, 2004; Owen-Smith, 2003). As a consequence, it has been increasingly likely that academics will be encouraged to select research projects on the basis of commercial rather than scientific merit (Dasgupta and David, 1994; Heller and Eisenberg, 1998; Thursby and Thursby, 2003), to avoid sharing information about their current research and to delay publication for business reasons (Blumenthal et al., 1997; Blumenthal et al., 2006), and to deny requests for transferring research materials to peers (Walsh et al., 2007). Accordingly, it can be inferred that entrepreneurial academics (Pasteur scientists), paying attention to their socio-industrial profiles, would have other types of motivation for advancing their research than publishing papers for their peers in the scientific community.

2.3 Hypotheses

Research motivation/orientation differs among the four types of scientists in Stokes's quadrant model, affecting the nature and direction of their scientific performance. The observations presented above have led to hypotheses oriented toward producing a finer grained categorization of the publication performance of present-day scientists.

First, since entrepreneurial-oriented scientists are living up to their socio-industrial commitments, they may be less interested than conventional academics in facing the essential tension between tradition and originality. Edison and Pasteur scientists are liberated—even if only partially so—from the incentive to present their research findings in a format that their peers are most likely to evaluate. When they acquire novel scientific knowledge, those scientists who stress the importance of disseminating knowledge for society are willing to publish papers in a wide variety of journals without concern for the degree of influence the journals have upon the scientific community.

Hypothesis 1: Entrepreneurial-oriented scientists (Edison and Pasteur scientists) publish more papers than traditional scientists (Bohr and Other scientists) do.

Second, since U-I linkages tend to shift scientists' research from basic to applied (Blumenthal et al., 2003), and applied research journals tend to have a lower impact factor than journals that publish papers on basic research (Narin et al., 1976), when comparing the publishing portfolios of Bohr scientists, it is inferred that research from entrepreneurial-oriented scientists will be characterized by lower numbers of highly cited papers and higher numbers of infrequently cited papers.

Hypothesis 2a: On average, traditional scientists publish more prestigious (highly cited) papers than entrepreneurial-oriented scientists do.

Third, when pre-existing research agendas and experimental protocols make it difficult to achieve the R&D objectives they have established in accordance with their socio-industrial commitments, Pasteur scientists tend to develop hypotheses and advance their research through unorthodox research agendas and experimental protocols. When this happens, whereas they acknowledge the possibility of their hypotheses being fallible, Pasteur scientists are given an opportunity to ensure both an industrial solution and progress in the existing scientific frontier. Consequently, although the percentage of successful intuitions is rather slim, the research that Pasteur scientists conduct sometimes leads to the publication of high-impact papers.

Hypothesis 2b: Regarding highly prestigious papers, their prestige is favored by the authorship of Pasteur scientists.

Fourth, reflecting their research motivations, when pre-existing research agendas and experimental protocols make it difficult to achieve R&D objectives, Pasteur scientists try to understand how the phenomenon behaves under a given set of experiments and embark on a course of research that explores the use-inspired technology. Those scientists are assumed to use abduction by articulating a hypothesis that provides a consistent explanation of the various observed data and phenomena. Since the research processes are complex, involving numerous components, materials, performance constraints, and interactions (Pavitt, 1998: 795), Pasteur scientists do not necessarily carry out their research based on a single scientific discipline. Whereas Bohr scientists (opting for research whose agenda and experimental protocols do not differ considerably from those used in earlier research in the field) tend to use conventional deductive/inductive reasoning to get academic results, Pasteur scientists would continue the search process, occasionally with a new protocol based on multiple theories crossing over several scientific disciplines for the purpose of getting industrial results. Therefore, the third hypothesis is as follows:

> *Hypothesis 3: The research breadth of entrepreneurial-oriented scientists is larger than that of traditional scientists.*

3. Methodology

3.1. Methodological Notes

Among the various types of advanced materials, eco-friendly TiO_2 materials and their applications (e.g., TiO_2 coating films for self-cleaning applications, TiO_2 nano-fiber membrane and its applications for water treatment) are considered to be industrially promising because their properties are activated only by sunlight. When TiO_2 absorbs ultraviolet light, the TiO_2

photocatalyst demonstrates a very strong oxidation power that decomposes most organic compounds adsorbed on substrate. Such catalytic reactions induced by light are called photocatalysis (Fujishima et al., 2000). These findings have opened up a wide range of industrial applications and have yielded a series of product developments. The Photocatalyst Industry Association of Japan (PIAJ) estimated the size of the worldwide commercial photocatalyst market as 1 billion US dollars in 2009.[3]

Evaluating the research activities of individual scientists is far from easy because in the scientific fields, where experimentation plays a crucial role in problem solving, scientific inquiry is carried out collectively, led by the head of the laboratory, who happens to be either a professor or the principal investigator of a funded project. In this paper, we aim at focusing on the activities of these principal investigators (PIs), who have full responsibility for research at laboratories by initially setting research agendas and experimental protocols. Although previous research has used the individual researcher or professor (Breschi et. al, (2008), and many other articles) as a unit of analysis, this choice inevitably includes the performance of co-authors collaborating with the PIs. Those co-authors (graduate students, post-docs, and so on) are often members of a laboratory headed by a PI. For the purpose of sorting out those subordinate co-authors and identifying the PIs in the field, we collected the publishing record of all the individual authors and compared their publication patterns. If a certain author's research portfolio (i.e., a set of publications) was broadly similar to those from other authors, we selected the scientist with the top research portfolio (i.e., largest number of publications) and assumed that he or she was a PI. By using the method of filtering junior co-authors, we obtained a sample of PIs—that is, the

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[3] The first product design utilizing oxidation power makes it possible to develop anti-bacterial ceramic tiles and so forth; the second design, utilizing super-hydrophilicity, develops self-cleaning building materials and anti-fogging window glasses, leading to the creation of new markets.

laboratory heads in universities or public research organizations (PROs)—which we considered our unit of analysis.[4]

3.2. Data and Sampling Procedure

3.2.1. Publication data

To evaluate the performance of scientists involved in photocatalyst research, we searched scientific papers related to the keyword “photocatalyst,” using the bibliographic database Scopus (Elsevier, 2010).[5] As a result, we obtained 15,219 articles published worldwide from 1960 to 2010. Since our present observation is focused on papers with authors who are affiliated with Japanese universities or PROs, our sample comprises 3,832 articles that contain at least one author who is geographically located within Japan. For those articles, first, we canonicalized the name of an individual author. If two authors shared the same notation of name, we employed affiliation data to reveal whether they were actually the same person or not. To eliminate canonicalization failure, various other data sources, including the national researcher database

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[4] By way of using the research portfolio of those researchers, we tried to sort out what we called leading scientists. The filtering process is as follows: 1) authors of papers are sorted according to the number of articles. Comparison of publication patterns is done from the author with the largest to the one with the smallest number of articles; 2) first scientist (the author with the largest number of articles) is treated as a leading scientist; 3) the portfolio vector of scientists is defined as $v_c \equiv (p_{1,c}, p_{2,c}, \ldots, p_{n,c})$ where $p_{i,c} = 1$ if scientist *c* is included as an author of article *i*, otherwise 0.4) To evaluate the similarity of a portfolio, we calculate Salton's cosine similarity measure of a candidate's portfolio vector v_c, and each leading scientist’s portfolio vector v_I was defined as $\frac{v_c \cdot v_I}{|v_c| \cdot |v_I|}$. If the similarity measure is larger than 0.5, we assumed that the candidate's portfolio is too similar to that of the leading scientist; hence the candidate was eliminated as a junior author. This threshold value (0.5) is arbitrary, but the result does not change much (less than 5%) if we change the threshold to 0.3 – 0.7.

[5] Here the search expression TITLE-ABS-KEY(photocatal*) is used to extract articles whose title or abstract or keywords match with “photocatal*.” Since the asterisk represents a wildcard, this expression matches with *photocatalyst, photocatalysis, photocatalytic*, and so on.

(JST, 2010), the JSPS funding database (NII, 2005-2010), and personal and organizational web pages were used. As a result, we identified 3,537 individual scientists across 127 academic organizations. In the next step, we excluded a body of junior co-authors by using publication-similarity based filtering.[6] In the end, we identified 66 PIs, 52 of them belonging to universities and 14 belonging to public research organizations.

3.2.2. Patent data

To evaluate the number of scientist entrepreneurial activities, we collected all the patents applied for by the 66 sample scientists to the Japan Patent Office (JPO) in the field of photocatalysis in the period 1970-2008. We counted the number of patents applied for by each PI as an inventor.[7]

3.2.3. Identification of entrepreneurial and traditional scientists

We allocated the 66 PIs to each category in Stokes's (1997) quadrant model according to two measures: the number of patent applications (PAT), which is used as a measure of orientation toward delivering utility to society (in the vertical axis), and the average citations (ACITE—the number of his or her citation counts divided by the number of his or her publications), which is a measure of orientation toward deepening scientific research (in the horizontal axis). By choosing a reference line as the median of each variable,[8] we classified the 66 PIs into four categories. Table 1 illustrates the attributes of each scientist category in terms of (i) average number of

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[6] In a comparison of the research portfolios, 3032 candidates' portfolios were found to be fully included by certain independent researchers. The remaining 505 candidates were further examined, and 439 candidates were dropped due to similarity criterion.

[7] Since the result of this search method includes type I errors (i.e., including patents from different inventors sharing the same name), spurious patents were removed after an examination of the address of each patent inventor.

[8] From skewness and the Shapiro-Wilk test, distribitions of PAT and ACITE could not properly be treated as normal distribution (5% level); thus we used the median instead of the mean to average their distribution.

scientific papers published per-researcher, (ii) average sum of citations counts per-researcher, and (iii) number of researchers belonging to the category.

Insert Table 1 about here

3.3. Variables

In order to investigate scientists' heterogeneity in terms of publication performance, we conducted an analysis based on three dependent variables: scientific productivity, prestige, and research breadth (multi/inter-disciplinarity).

1. Scientific productivity (PUB)

We measured the scientific productivity of scientists by means of the number of articles published in the target research field.

2. Scientific prestige (CITE)

As a dependent variable, the number of forward citations (CITE) is used as a proxy variable to evaluate scientific prestige. To measure this, we calculated the sum of forward citation numbers for all articles published.

3. Research breadth/multi/inter-disciplinarity

How to assess the coverage of scientific discipline or the inter-disciplinarity of scientific outputs remains controversial, and there is no consensus on the appropriate frameworks and methodologies (Bordons et al., 2005; Huutoniemi et al., 2010). Recently, a series of bibliometrics researchers (Leydesdorff and Rafols, 2009; Rafols et al., 2010; Wagner et al., 2011) created a methodology to calculate the inter-disciplinarity of scientific outputs, which is called the Rao-Stirling diversity.

In Stirling (2007), a general diversity heuristic is proposed, where diversity indices ($\Delta_{\alpha,\beta}$) can be explored for different valuations of the properties of diversity—variety, balance and disparity—by changing the parameters α and β :

$$\Delta_{\alpha,\beta} = \sum_{i,j} \left(1 - s_{i,j}\right)^{\alpha} \left(p_i p_i\right)^{\beta} ,$$

where $s_{i,j}$ means similarity between categories *i* and *j*, and p_i means a proportion of category *i*, respectively. Here, we call the Rao-Stirling diversity index the variant where $\alpha = 1$ and $\beta = 1$, initially introduced by Rao (1982). In calculating Rao-Stirling diversity, we used the journal level scientific genre categorization from the "Web of Science" (Thomson Scientific). In the Web of Science, each academic journal is classified into one or more scientific categories (SC). In order to calculate Rao-Stirling diversity, information concerning inter-category similarity (s_{ij}) is needed. We used the co-citation based inter-category (SC) similarity matrix proposed by Rafols and his colleagues (Leydesdorff and Rafols, 2009), and diversity is calculated on the portfolio of each scientist type.

4. Empirical Results

4.1. Testing hypothesis 1: scientific productivity

To compare the scientific productivity of entrepreneurial scientists and traditional scientists, the statistical difference was determined by a two-sided Mann-Whitney's U-test. A difference with $p < 0.001$ was considered significant. The result, not surprisingly, shows there is a statistically significant difference between the underlying distributions of the publication count of entrepreneurial scientists and the publication count of traditional scientists ($z = -3.659$, $p = 0.0003$).

4.2. Testing hypothesis 2: prestige

In order to identify the patterns of forward citation for each type of scientist, we focused on the 1,957 articles authored by the 66 PIs in photocatalyst research in Japan. First, we classified the articles into four classes according to the number of forward citations they received: large citation counts (top 25% of articles in citation counts ranking), medium-large citation counts (top 25% to 50% of articles), medium-small citation counts (top 50% to 75% of articles), and small citation counts (bottom 25% of articles). Second, we re-classified the articles in each class into four categories: those articles that include at least one Pasteur scientist as an author, and the same for the Bohr and Edison scientists, and others. Although 210 articles have more than two types of PI as authors, the overlap is possibly small (less than 11%). The result derived from the classification is shown in Figure 1. As for the large citation counts class, we found that the share of Bohr scientists is 39%, that of Pasteur scientists is 29%, and that of Edison scientists is 22%. In the class of small citation counts, we found that the share of Bohr scientists is 12%, that of Pasteur scientists is 20%, and that of Edison scientists is 22%.

Insert Figure 1 about here

If we read Figure 1 through the lens of traditional research evaluation criteria, the pattern of Bohr scientists seems more favorable than those of Pasteur and Edison scientists. A large number of papers published by Bohr scientists are frequently cited, and a small number of papers fail to be properly cited. In stark contrast, relatively fewer papers published by Pasteur scientists are frequently cited, and a large number of papers published by Pasteur scientists fail to be properly cited. Since citation rank is not normally distributed, we used the two-sample Wilcoxon rank-sum test to determine whether there were significant differences of relative citation distribution between Pasteur scientists and Bohr scientists. As a result, by using the Mann-Whitney U-test, we found a statistically significant difference ($p = 0.0001$) in citation rank distribution between the two scientist types. Thus, we can suggest that the pattern of Bohr scientists is more favorable than that of Pasteur scientists (and even Edison scientists) from the viewpoint of traditional research evaluation.

To test hypothesis 2, we estimated a set of models using negative binominal regression to evaluate the determinants of citation impact at the individual article level. Table 2 describes the variables used in this analysis. In order to evaluate the contribution of distinct scientist types, a dummy variable for each scientist type identified by the attributions of authors is introduced as independent variable. The variable PASTEUR takes a value of 1 when at least one Pasteur scientist participates as an author of the target article. The variables BOHR, EDISON, and OTHERS are also defined similarly. Since the scientific impact of research is highly correlated with the amount of labor used to deliver the observation described in the article, we introduced the number of authors (NAUTH) as a proxy for labor input to control the effect on the dependent variable. Journal impact metrics (SCImago Journal Rank; SJR) is also introduced as a control variable as a proxy for the prestige of the journal, since articles published in more influential journals are likely to have more impact than articles published in less influential journals. The duration from the publication year to 2010 (AGE) is included as a control variable because the number of received citations is highly dependent on the duration of exposure to the academic community.

As discussed earlier, the photocatalyst field is already industrialized, and its economic impact is quite large; hence, a growing number of industrial scientists were found as authors of scientific articles. Accordingly, a considerable number of articles are co-authored with industrial scientists, although the effect of the participation of industrial scientists may vary across scientist types. Because Pasteur scientists are more interested in social benefits through industrial application and have more experience in creating industrially useful knowledge, they are more likely to use the contributions of industrial scientists effectively. Thus, the dummy variable U-I is introduced as a control variable, which denotes the existence of the industrial scientist as co-author of a target article.

Table 3 shows the descriptive statistics; Table 3 shows the correlation matrix. The result of the estimation is shown in Table 4.

Insert Tables 3,4,5 about here

In Table 5, model (1) shows the estimated result in all samples while model (2) shows the estimated result of the top 25% of citation ranking articles only. In both results, SJR and AGE remain highly ($p < 0.001$) significant. The significance of SJR suggests that the citation impact of a paper is highly dependent on the journal in which it appears. The significance of AGE suggests that citation increases according to time. In model (1), the effect of Bohr scientist authorship is significantly higher ($p < 0.001$) than that of Pasteur scientist authorship. Thus, hypothesis 2 is supported. The order of magnitude of the effect of scientist authorship is Bohr (highest), Pasteur, Other, and Edison (lowest); these results again suggest that traditional scientists are favored over entrepreneurial scientists according to the individual articles' citation level.

To view the situation from a different standpoint, further investigations were performed that were limited to the top 25% of citation ranking articles. In model (2), the effect of Bohr scientist authorship does not have a significant effect to leverage the prestige of article. To the contrary, the effect of Pasteur scientist authorship has a significant effect in leveraging prestige. Thus, hypothesis 2b is supported.

4.3. Testing hypothesis 3: Research breadth/Interdisciplinarity

From the observations obtained in the previous two hypotheses, the two sets of productive scientists, Pasteur and Bohr, possibly have quite different research strategies while concentrating on the same research target. To explore this idea, we evaluated the diversity of their research portfolios (scientific category level Rao-Stirling diversity). The distributions of the research portfolio diversity of Pasteur scientists and those of Bohr scientists are shown in Figure 2.

Insert Figure 2 about here

The mean of diversity for Pasteur scientists (0.48) is higher than that for Bohr scientists (0.41). Using a two-tailed t-test, a significant difference ($p < 0.008$) of mean diversity is found between these two scientist types. Thus, hypothesis 3 is supported.

5. Discussion and Concluding Remarks

When we compare the research performance of entrepreneurial scientists with that of conventional academics, the results of a quantitative analysis applied to a sample of 1,957 scientific papers published by 66 scientists active in advanced materials research in Japan confirm that (i) entrepreneurial scientists (Pasteur and Edison scientists) publish more papers than traditional scientists (Bohr and Other scientists) do; (ii) the papers published by Bohr scientists demonstrate better citation performance than those published by Pasteur scientists, do on average; (iii) the prestige of high-impact papers is favored by the authorship of Pasteur scientists; and (iv) the degree of the multi/inter-disciplinarity of the papers authored by Pasteur scientists is higher (more diverse) than that of Bohr scientists.

The general trend of scientific performance—that is, although the quantity of research output is larger for entrepreneurial scientists, the overall citation performance of Pasteur scientists is not as good as that of Bohr scientists—suggests that the prevailing academic entrepreneurship exerts rather an unclear influence on scientific activities. However, our findings on the authorship of high-impact papers and the breadth of research suggest that entrepreneurial scientists make a relatively large contribution to furthering the scientific frontier by not relying on conventional research traditions. Bohr scientists may resemble Isaac Newton, who famously remarked, "If I have seen a little further, it is by standing on the shoulders of giants." Comparatively speaking, when Pasteur scientists see a little further, they may rely less on the shoulders of "giants," meaning, in this case, the impact factor of the scientific journals in which their papers are published. In addition, our finding that the coverage of scientific disciplines in the papers of Pasteur scientists is more diverse than that of Bohr scientists suggests that the impact of influential papers authored by the former is derived from the number of citations coming from heterogeneous scientific articles and crossing over several scientific disciplines.

Certainly, our findings are due to the specificity of the research subject: in the field of advanced materials, the two-way interaction between science and technology provides scientists with the opportunity to extend their scientific research into unexplored areas, and it is the type of entrepreneurial scientists that benefits mostly from such opportunities. Recently, the role of Pasteur scientists, especially those in the field of advanced materials, has become highly esteemed in that they can afford to cultivate the unexplored research areas of the traditional Bohr scientists (Kitazawa, 2008, 2010). Overall, Adam Smith's combinatorial benefits of knowledge refinement and fragmentation resulting from the division of labor between university and industry are realized by the offspring of such boundary spanners as Pasteur scientists in some scientific fields (Baba et al., 2009; Metcalfe, 2010; Murray, 2002).

Recently in Japan, as in Europe, the state has cut backing for universities, and public support for R&D is predominantly allocated towards "outcome-based basic research" intended to meet the specific needs of society (e.g., solving the problems of global environmental issues, cancer treatment, and an aging society). When governments are allocating shrinking public funds, an ongoing science and technology policy that gives priority to research intended to solve societal problems seems relevant for its own sake. Additionally, this paper posits a theoretical explanation that enables us to deepen our understanding of the nature of "outcome-based basic research." In our view, the essence of the policy resides in the research policy typically pursued by Pasteur scientists: while they often publish papers in scientific journals with low impact, which are less likely to be cited in the short term, they sometimes publish papers with the potential to contribute to the progress of science because, over the long term, the contents of their papers will receive positive evaluations in multiple scientific disciplines.

However, we admit the qualification attached to our policy discussion: the same scientists are willing to adopt different research policies depending on their place in the scientific community or their position in the lifecycle of a scientist (Stephan and Levin, 1992). For junior researchers (i.e., doctoral and postdoctoral students, and assistant professors), the rational strategy is usually to begin by adopting the Bohr mode to produce research results quickly and steadily in order to secure a position in the scientific community. This understanding provides the caution that labeling a given scientist as a Bohr scientist or a Pasteur scientist is not an adequate use of the "quadrant model of scientific research" because a junior researcher may prefer the Bohr mode in order to survive in the tightly competitive scientific community, only to switch modes once his or her position has become more secure. Facing the global trend towards "outcome-based basic research" policy, this paper provides a preliminary discussion that promises to open further lines of investigation on appropriate policy settings that will enable scientists to better qualify as proactive actors for both scientific progress and contribution to society.

Finally, we acknowledge some methodological limits on our study. Because our research was highly focused on a specific industry and nationally bounded, the general applicability of the analysis is limited. First of all, it is likely that the government-driven academic culture currently prevailing in Japan and the idiosyncrasies of individual scientists are related to the observed performance divide between the Bohr and Pasteur scientists. It would be necessary to collect corresponding data from a couple of other countries to make sure that the results are consistent across different countries. Similarly, the hypotheses derived from the observation of one specific field are not necessarily true for all scientific fields. Again, it would be better if a couple of sub-fields from different areas were included in the study to make sure that the results are robust and consistent. Thus, it is important to note that this argument is not about the divide between Bohr and Pasteur scientists in scientific contributions generally, but specifically under these conditions: 1) scientists working in the field of advanced materials, 2) scientists whose scientific production originated and developed mainly in Japan, and 3) scientists who are willing to reach define their success by their contributions to society. Further research is needed to develop our conjectures, to see how the conditions that produce the scientific divide differ in other countries, and, thus, to investigate more deeply how each type of scientist contributes to furthering the scientific frontier in the long run.

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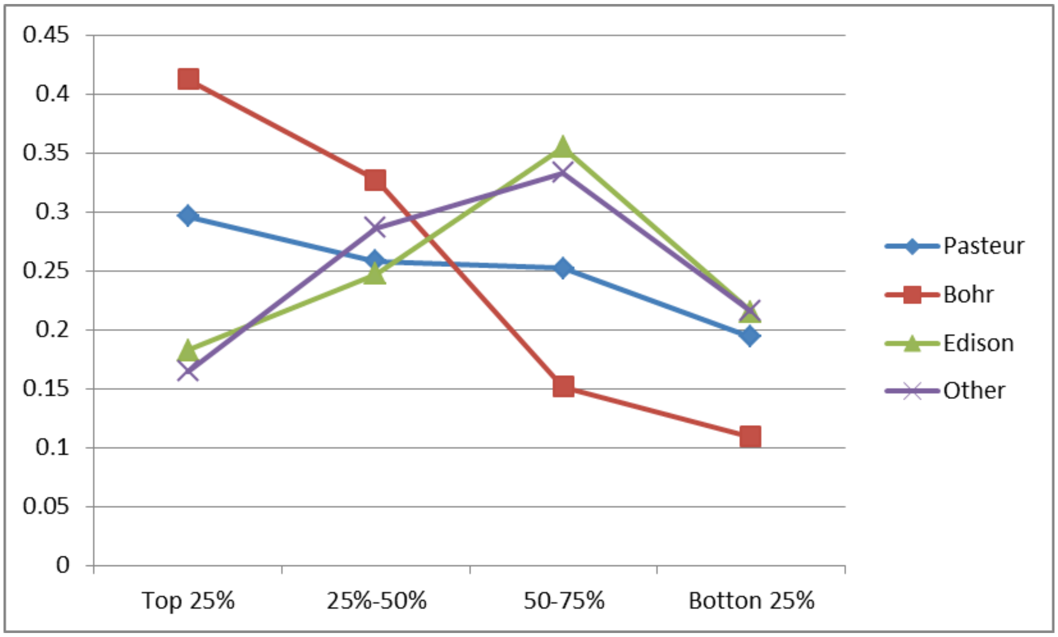

Figure 1 Comparison of publication impact breakdown

Source: Authors' elaborations

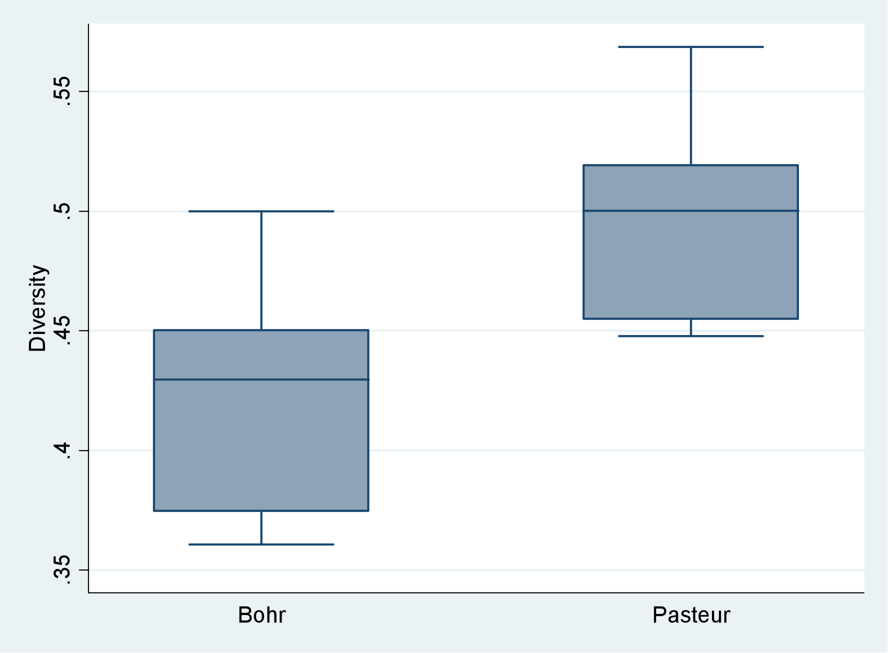

Figure 2 Comparison of Rao-Stirling diversity by scientist types

Source: Authors' elaborations

Table 1 Classification of scientists in the “Quadrant model of scientific research”

		Number of patents (PAT)		
		Less <=6	More ≥6	Total
Average of citations (ACITF)	More >22.2	Bohr scientists 21.2 papers 745.2 citations 13 researchers	Pasteur scientists 61.5 papers 2150.5 citations 21 researchers	46.1 papers 1613.2 citations 34 researchers
	Less <=22.2	Others 22.0 papers 329.0 citations 22 researchers	Edison scientists 27.3 papers 436.3 citations 10 researchers	23.6 papers 362.5 citations 32 researchers
Total		21.7 papers 483.6 citations 35 researchers	50.5 papers 1597.5 citations 31 researchers	35.2 papers 1006.8 citations 66 researchers

Source: Authors’ elaborations

Table 2 Variables description (Article level)

Type	Name	Description	Source
Dependent variable	CITE	Number of cumulative forward citations	Scopus
Independent variables	PASTEUR	Dummy variable (1/0) denoting if the paper is authored by a Pasteur scientist	Scopus/IPDL
	EDISON	Dummy variable (1/0) denoting if the paper is authored by an Edison scientist	Scopus/IPDL
	BOHR	Dummy variable (1/0) denoting if the paper is authored by a Bohr scientist	Scopus/IPDL
	OTHERS	Dummy variable (1/0) denoting if the paper is authored by Others	Scopus/IPDL
Control variables	NAUTH	Number of authors of the paper	Scopus
	SJR	SCImago Journal & Country Rank (2009)	SCImago
	AGE	Age of the article (i.e. years passed after publication)	Scopus
	UI	Dummy variable (1/0) denoting if the paper is co-authored by a corporate researcher	Scopus

Source: Authors’ elaborations

Table 3 Descriptive statistics (Article level)

Variable	Obs	Mean	Std. Dev.	Min	Max
CITE	1957	26.67	59.23	0	1878
PASTEUR	1957	0.43	0.49	0	1
EDISON	1957	0.08	0.28	0	1
BOHR	1957	0.05	0.21	0	1
OTHERS	1957	0.13	0.34	0	1
NAUTH	1957	3.05	1.69	1	12
SJR	1957	0.22	0.36	0	8.016
AGE	1957	7.72	6.14	0	34
UI	1957	0.08	0.26	0	1

Source: Authors' elaborations

Table 4 Correlation matrix (Article level)

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1)	CITE	1							
(2)	PASTEUR	0.0803^{***}	1						
(3)	EDISON	0.0426^{+}	-0.1808^{***}	1					
(4)	BOHR	-0.0341	-0.0551^{*}	-0.0486^{*}	1				
(5)	OTHERS	-0.0635^{**}	-0.2789^{***}	-0.1117^{***}	-0.0405^{+}	1			
(6)	NAUTH	-0.0014	0.1118^{***}	-0.0305	0.0104	0.0237	1		
(7)	SJR	0.2559^{***}	0.0238	-0.0259	0.0174	0.0125	0.033	1	
(8)	AGE	0.1652^{***}	-0.0299	0.1343^{***}	-0.0179	-0.0813^{***}	-0.025	-0.0211	1

Significance level: *** for 0.1%, ** for 1%, * for 5%, $^{+}$ for 10%

Source: Authors' elaborations

Table 5 Determinants of citation impacts (Negative binominal regression; article level)

	(1) All sample	(2) Top 25%
Dependent variable: cite		
Independent variables:		
PASTEUR	0.231***	0.225***
	(4.72)	(4.95)
BOHR	0.367***	-0.0267
	(3.59)	(-0.32)
EDISON	-0.511***	-0.227
	(-4.09)	(-1.61)
OTHERS	-0.191*	-0.188^{+}
	(-2.21)	(-1.88)
NAUTH	2.129***	0.217***
	(11.01)	(4.89)
SJR	0.0117	-0.0773***
	(0.68)	(-4.96)
AGE	0.107***	0.00649
	(15.45)	(1.17)
UI	0.0498	0.00713
	(0.47)	(0.08)
Intercept	1.634***	4.331***
	(16.98)	(48.62)
N	1957	495
Log likelihood	-7958.5	-2519.7
chi2	495.4	97.16

Note: *t* statistics in parentheses

$+ p < 0.10$, $* p < 0.05$, $** p < 0.01$, $*** p < 0.001$

Source: Authors' elaborations