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When publications lead to products: The open science conundrum in new product development

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ABSTRACT

This paper examines interdependencies between firms' activities in the realms of open science and commercial product development. We present a theoretical framework that outlines when a firm's involvement in academic communities enhances its innovative performance in terms of new products in development. We argue that the disclosure of more, valuable R&D work in quality scholarly publications and collaborations with academic partners positively affect firm innovation. We further hypothesize a differential effect of adopting open science strategies on the innovation type, being more pronounced for radical innovations than for incremental innovations. We empirically analyze a unique panel dataset containing information on the product innovation performance and R&D activities of 160 UK therapeutic biotechnology firms over the period 1998- 2009. Our results from count data models on the number of new products in development provide empirical support for our hypotheses.

1. Introduction

A growing number of firms in knowledge-intensive sectors participate in open science, a system of cumulative knowledge production that facilitates the disclosure of scientific discoveries through publications in academic journals (Dasgupta and David, 1994; Ding, 2011; Gittelman and Kogut, 2003; Mukherjee and Stern, 2009). In fact, prominent firms have developed into core hubs for scientific knowledge exchange in several fields. Whereas in 1975 none of the 25 most-cited articles in Science were (co-) authored by researchers affiliated with firms, in 2009 there were 6.[1] Comparative research on the extent to which products and processes build on academic science across different sectors highlights that this development has been particularly potent in the life sciences sector (Mansfield, 1995, 1998). A single biotechnology firm, Genentech published 5038 articles in scientific journals over the period 1976–2008, of which 249 in Science or Nature.[2]

Despite success stories of firms like Genentech, significant variation remains in the extent to which individual firms embrace open science strategies, with some firms adopting more open R&D models and others opting to adhere to more traditional, closed R&D models. Scholarship suggests that the imprint left by founders plays an important role in shaping corporate R&D strategies in general and firms' willingness to adopt open science practices in particular (Ding, 2011; Jong, 2006; Murray, 2004; Powell and Sandholtz, 2012). Although the importance of organizational imprinting for firms' varying strategies in interacting with academic communities is well understood, the dynamics governing the interdependencies between firms' activities across the realms of open science and commercial product development remain less clearly defined.

Existing studies highlight a range of benefits for firms that participate in open science, including the opportunity to learn from academic collaborators (Almeida et al., 2011; Cockburn and Henderson, 1998; Liebeskind et al., 1996; Zucker et al., 2002), to enhance firms' absorptive capabilities (Cohen and Levinthal, 1990; Fabrizio, 2009; Fleming and Sorenson, 2004), to attract and retain high-quality scientists (Stern, 2004), and to signal the possession of strong scientific competences to external parties (Luo et al., 2009; Polidoro and Theeke, 2012). However, other studies highlight potential drawbacks for firms' involvement in open systems of knowledge exchange because of the conflicts that exist between the institutional logics governing the realms of science and technology. For example, Gittelman and Kogut (2003) point out that the production of high-profile scientific papers actually harms the production of high-value patents.

Our research aims to explore boundary conditions that govern the benefits of firms' involvement in academic communities. Specifically, we examine the impact of publishing better scholarly research and collaborating with university scientists on firm

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[1] *Source*: Web of Science, Science Citation Index Expanded, accessed 8 June 2012.
[2] *Source*: Web of Science, Science Citation Index Expanded, accessed 8 June 2012.

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innovative performance. Building on insights from the sociology of organizations and knowledge literature we propose conditions under which the stratification logics of science and technology are mutually reinforcing: We argue that the academic value of firms' publishing activities and the ties firms develop with academic laboratories positively affect firms' ability to leverage resources embedded in external open scientific systems of knowledge exchange in internal R&D programs. However, we contend that this positive effect varies with the type of innovation and is more pronounced for radical than for incremental innovations.

To test our hypotheses we create a panel dataset containing detailed information on the publishing and R&D activities of 160 UK therapeutic biotechnology firms over the period 1998–2009. This dataset allows us to analyze how variations in firms' interactions with academic communities have an impact on firm R&D productivity, after controlling for R&D input related variables. The biotechnology sector has proven a fruitful context, in which to examine the effect of adopting open science strategies on firm innovation for several reasons. First, there is no sector, in which commercial and academic research networks are so closely intertwined as these are in biotechnology (Mansfield, 1995, 1998). Second, the commercialisation environment and appropriability regime in biotechnology are among the most supportive to open exchanges of ideas across organizational boundaries in general and the science–industry boundary in particular (e.g. Gans and Stern, 2003; Teece, 1986). Third, for the specific purposes of this study, the choice of the setting of therapeutic biotechnology enables a systematic classification and operationalization of the degree of novelty of product innovations.

Our results from estimating negative binomial models on the number of new therapeutic projects entering clinical trials provide support for our main hypotheses. Specifically, our findings reveal that firms that disclose more, valuable R&D work in quality scholarly publications exhibit higher levels of innovative output in terms of the new therapeutic projects these firms move into the development pipeline. Adding to previous work on the value of connectedness to university scientists, we find that while controlling for firms' publishing activity, pursuing research collaborations with scientists at academic institutions further enhances firms' innovative performance. In addition, we find that the beneficial effect of making more substantive contributions to open science is a limited effect; while increasing a firm's propensity to develop radically innovative products, it does not increase a firm's propensity to develop incrementally innovative products.

Our research advances the literature on firms' interactions within open systems of knowledge exchange in two principal ways. First, it contributes to on-going debates about the interrelationships that govern firms' activities across the spheres of science and technology. While some suggest that corporate science that is more highly valued in academic circles is associated with superior innovative performance (e.g. Almeida et al., 2011; Zucker et al., 2002), others argue that a stronger performance by a firm in one sphere is associated with a weaker performance in the other sphere (Gittelman and Kogut, 2003). We highlight that open science strategies have an overall positive effect on new products in development. Notably, this effect holds if the academic esteem of firms' scholarly contributions is taken into account, which some suggest to be a drag on the production of commercially valuable knowledge (Gittelman and Kogut, 2003). Consequently, we extend previous studies on positive effects of publishing and collaborating with university scientists on the importance of firm patents (Cockburn and Henderson, 1998), the timing and importance of firm inventions (Fabrizio, 2009), and the number of patent families (Almeida et al., 2011).

Second, our study makes a contribution by defining boundary conditions for the efficacy of efforts to enhance innovative performance through open science strategies and advances scholarship on the challenges firms face in capturing value in open innovation networks. Prior work for example highlights how firms face behavioral constraints in managing too many academic collaborations (Lavie and Drori, 2012; McFadyen and Cannella, 2004). Our study illuminates the contingent value of open science strategies for the type of innovation outcome (e.g. radical or incremental innovations) that firms focus on in R&D. By considering the type of innovation, this work extends past research on the link between the importance of inventions and the usage of scientific and distant knowledge (Fabrizio, 2009; Fleming and Sorenson, 2004; Rosenkopf and Nerkar, 2001).

The remainder of this paper is organized as follows. First, we present the conceptual motivation behind the study. We subsequently construct our theoretical framework and develop testable hypotheses. Next, we describe the study design and the data used to perform the empirical analyses. We subsequently present and discuss the results of our analyses. Finally, building on a discussion of the generalizability of our findings, we outline future research directions.

2. Theory and hypotheses

Creative processes underlying product innovation in many industries increasingly extend beyond the commercial realm. The central role academic communities now play in fuelling product innovation in sectors such as the biotechnology, nanotechnology, and clean technology sectors exemplifies this trend (Cockburn and Henderson, 1998; Fleming and Sorenson, 2004; Laursen and Salter, 2004; Liebeskind et al., 1996). To tap into creative processes in scientific communities firms rely on so-called absorptive capabilities that allow firms to assimilate and exploit external knowledge. The development of such capabilities is a principal rationale for investments in in-house R&D (Cohen and Levinthal, 1990; Fabrizio, 2009; Rosenberg, 1990).

Managers face a number of trade-offs in the organization of in-house R&D. The extent to which firms adopt organizational models associated with open science, and disclose and share R&D findings, is among the most important of these trade-offs. There used to be clear differences between organizational models governing academic and commercial research, in particular with regards to the willingness of researchers to disclose and share work in open forums such as scientific journals (e.g. Dasgupta and David, 1994). High levels of secrecy used to be the norm for corporate R&D organizations, which were seen as necessitated by the for-profit orientation of these organizations. However, assertions underlying traditional, closed corporate R&D models have become increasingly contested with the rise of successful new firms adopting open science strategies over recent decades (Ding, 2011; Fabrizio, 2009; Powell and Sandholtz, 2012). Such strategies entail the incorporation of academic practices in corporate R&D such as encouraging priority-based publishing of research findings, sharing of proprietary knowledge with community members, and showing deference to academic status hierarchies (Dasgupta and David, 1994; Gittelman and Kogut, 2003; Kaplan and Murray, 2010; Merton, 1968; Stephan, 1996).

The extent to which firms incorporate more open approaches in interactions with academic communities has been linked to the organizational imprint founders left on the R&D organizations of these firms. Firms with a higher level of involvement of senior academic scientists during the formative development phase generally embrace more academic, open approaches in the organization of R&D. Firms with a more corporate imprint, at which managers and researchers with an industry background play a more dominant role during the formative development phase tend to stick to more

traditional, closed organizational practices in R&D (Ding, 2011; Powell and Sandholtz, 2012). Although existing studies explain how firms follow distinctive paths in terms of the adoption of different R&D models, the interdependencies governing firms' activities across the realms of science and technology and the mechanisms through which these interdependencies affect firms' comparative advantages remain less well understood. Given the durability of varying approaches to the adoption of open science strategies among life sciences firms (Ding, 2011; Powell and Sandholtz, 2012), our primary interest is not in determining whether open or closed R&D models (or any particular mix of the two models) represent an organizational archetype that leads to universally superior innovation outcomes. Instead, we will seek to outline boundary conditions within which open science strategies that involve the disclosure of R&D in scientific publications perform better and to identify contingent factors that might tilt trade-offs firms face in organizing interactions with academic communities.

2.1. Firms' contributions to science and firm innovation

Publishing confers various benefits on firms in innovation processes. Existing work highlights how the scientific proficiency of corporate researchers who publish is key to the development of a firm's absorptive capabilities in science-intensive industries (Fabrizio, 2009; Cockburn and Henderson, 1998). For example, research on the early development of the biotechnology industry highlights that pharmaceutical R&D laboratories that tied compensation and promotion decisions to workers' publications were more successful in adapting to the era of biotechnology (Cockburn and Henderson, 1998; Henderson and Cockburn, 1994; Henderson, 1994). However, the boundary conditions under which improved absorptive capabilities are helpful in supporting product innovation remain less well understood.

A particularly vexing, unresolved issue is whether firms that ascend in the scientific stratification order by disclosing and sharing better science through publications derive advantages from this ascend. Some argue that investing in advancing a firm's academic standing may be a distraction and is not conducive to improving R&D performance as conflicting stratification logics across the realms of science and technology prevent firms to carry over and enjoy an advantage gained in one realm in another realm. Highlighting difficulties firms face in producing both publications and patents that are widely cited, Gittelman and Kogut (2003) for example argue that what determines a firm's ability to enjoy enhanced absorptive capabilities in science-based R&D is the proficiency of firm researchers in their scientific subjects, not the level of academic recognition these researchers receive for publications.

We posit that disseminating better research in scientific communities constitutes a source of comparative advantage in advancing corporate R&D goals. Scientific knowhow of commercial value is often tacitly held by members of academic communities, particularly those members who are higher up in the scientific stratification order. Therefore, so-called star scientists have played a critical role in the development of the biotechnology industry and confer a comparative advantage on the firms they associate themselves with (Liebeskind et al., 1996; Zucker et al., 1998).

Sociologists of knowledge highlight that scarce resources in science such as tacit knowhow held by star scientists and collaboration opportunities with top laboratories flow disproportionally to those who are already situated higher up in scientific stratification orders (e.g. Crane, 1965; Merton, 1968). Indeed, gaining a good standing in academic communities is often seen as critical to securing access to upstream intellectual resources in science-based R&D. Gans and Stern (2003) for example argue that litigious behavior by Johnson & Johnson during the 1980s undermined the company's reputation in academic circles and put it at a disadvantage in securing critical upstream R&D partners. Moreover, highly regarded corporate scientists are better positioned as boundary spanners to gain access to and build on upstream scientific knowledge (Hess and Rothaermel, 2011), and to create collaboration opportunities with academic scientists (Hicks, 1995; Wang and Shapira, 2012). An important means to enhance a firm's standing in academic communities is to publish more and better articles. For example, Darby et al. (1999) find that publications by star scientists affiliated with a firm, increase the financial valuation of this firm and Stuart et al. (2007) show a similar effect for firms' ability to secure upstream licensing agreements with universities. Accordingly, we expect that firms with open science strategies that produce better science enjoy a comparative advantage in using critical R&D resources in product development and our first hypothesis is the following:

Hypothesis 1. Publishing quality scholarly research has a positive effect on firms' product innovation performance.

2.2. Academic collaborations and innovative performance in science-based R&D

The decision with whom to partner in the development of open science strategies is an important one and the inclusion of academic partners in such strategies can be beneficial for a number of reasons. First, individuals are important conduits for knowledge flows across organizations in general (e.g. Almeida and Kogut, 1999; Casper, 2007; Saxenian, 1994; Sorenson et al., 2006), and across the science–industry barrier in particular (e.g. Casper and Murray, 2005; Liebeskind et al., 1996; Thursby and Thursby, 2000; Zucker et al., 1998). Apart from providing conduits for these flows, personal interactions in university collaborations also enhance trust and increase the willingness of academic partners to share knowhow (Bouty, 2000; Haeussler, 2011; Hicks, 1995). As a result, corporate researchers in university collaborations enjoy additional learning opportunities (Liebeskind et al., 1996; Zucker et al., 2002), and such collaborations provide firms an edge in securing access to novel, emerging science for use in proprietary R&D (Stuart et al., 2007). Accordingly, the setting of university collaborations increases the creativity of corporate researchers (Lavie and Drori, 2012; McFadyen and Cannella, 2004), and the speed of invention processes researchers are engaged in (Fabrizio, 2009). Moreover, university collaborations have a positive effect on the number and quality of firm patents (Almeida et al., 2011; Fabrizio, 2009; Cockburn and Henderson, 1998).

Second, university collaborations offer economies of scope and scale opportunities, allowing firms to make more efficient use of financial resources (e.g. Katz and Martin, 1997). In fact, firms with university linkages incur lower R&D expenses while achieving higher levels of innovative output (George et al., 2002). Finally, firms are able to tap into and benefit from the reputation and collaboration networks of university partners (Wang and Shapira, 2012). Building on these insights, we anticipate collaborations with university scientists to provide firms with a source of comparative advantage in product innovation that is different from the benefit associated with publishing quality research and we posit the following hypothesis:

Hypothesis 2. Collaborating with university scientists on scholarly publications has a positive effect on firms' product innovation performance.

2.3. Publishing quality scholarly research and innovation type

We argue that the impact of open science strategies is contingent on the type of innovations firms pursue, specifically whether the emphasis in a firm's R&D is on the development of radical or incremental innovations. The distinction between radical and

incremental innovations is a fundamental one; whereas a radical innovation represents a genuinely new product, an incremental innovation represents an enhancement or modification of an existing product. The capabilities and resources required to successfully develop radical and incremental innovations are different and often opposed (e.g. Cardinal, 2001; Katz and Tushman, 1981; Laursen and Salter, 2006; Lee and Allen, 1982). We expect that open science strategies exert a greater positive effect on a firm's ability to spawn radical innovations than on its ability to spawn incremental innovations.

First, open science strategies provide access to external knowhow that is more valuable in the development of radical innovations. The pursuit of radical innovations is associated with a greater emphasis on the combination of knowledge from internal R&D groups as well as from external communities (Ahuja and Lampert, 2001; Fleming and Sorenson, 2004; Jong, 2011; Katz and Tushman, 1981; Lee and Allen, 1982; Phene et al., 2006). In contrast, for the successful pursuit of incremental innovations firms are less dependent on external sources of knowledge. Instead, expertise and knowledge firms rely on in the development of successful incremental innovations is often specific to a firm or project (e.g. Aiken et al., 1980). Thus, participation in external exchanges of scientific knowledge will likely be of more value to the generation of innovations that are radically innovative rather than incrementally innovative.

Second, the scientific 'search mode' that researchers who engage in open science employ in research is more beneficial in the development of radical than of incremental innovations. Fleming and Sorenson (2004) make a distinction between local search and science as search modes firms employ in creative processes underlying product innovation. Local search is a search mode that is closely linked to the concept of exploitation (March and Simon, 1958; Cyert and March, 1963/1992; Hansen and Lovas, 2004; Nelson and Winter, 1982; Stuart and Podolny, 1996). It implies that inventors search incrementally, altering one component of a product at a time, either reconfiguring it relative to the other components or replacing it with a different component. Science, which is a search mode organized around attempts to generate and test theories on the other hand offers researchers a 'map' in more complex search processes, requiring researchers to bring together previously uncombined configurations of coupled, interdependent technical components (Fleming and Sorenson, 2004). The theoretical understanding of (the interactions between) the underlying properties of technological components that science provides its practitioners offers support in the discovery of radical innovations. Such support for example helps researchers to hypothesize about proper combinations of components to solve a technical problem or in identifying useless directions of search before undertaking any actual experiments.

Finally, the experimental method of science is thought to better attune researchers to the negative feedback loops following failure that are more commonly associated with the development of radical innovations (Fleming and Sorenson, 2004). Whereas the pursuit of incremental innovations can be managed as a relatively predictable process, the pursuit of radical innovations is associated with a greater emphasis on experimentation as well as higher levels of uncertainty and risk (e.g. March, 1991; Rosenkopf and Nerkar, 2001). Researchers who engage in open science therefore seem better equipped to succeed in the creative processes underlying the development of radical innovations. Taken together, these arguments lead to the following hypothesis:

Hypothesis 3. Publishing quality scholarly research has a greater positive effect on a firm's propensity to produce radical innovations than on a firm's propensity to produce incremental innovations.

3. Data and methodology

3.1. Research setting and sample

Our research setting is the UK therapeutic biotechnology industry. Commercial R&D in the biotechnology industry is closely intertwined with university research (Kenney, 1986; McMillan et al., 2000; Zucker et al., 1998) and the challenges managers face in organizing biotechnology R&D epitomize the challenges managers face in managing science-based proprietary R&D (e.g. Cockburn and Henderson, 1998; Liebeskind et al., 1996; Powell et al., 1996; Pisano, 2006; Rothaermel and Deeds, 2004). To construct our sample, we identify all 190 UK-based biotechnology firms, founded de novo after 1976 that originated at least one drug development project between 1999 and 2009 according to the Pharmaprojects database, which is a leading commercial database that tracks the development of new therapeutic products and is widely used for market research in the global pharmaceutical industry.

Further, we collect bibliographic information from Thomson Scientific's Science Citation Index Expanded and Journal Citation Report on all publications by researchers affiliated with these firms. 65% of the firms from our initial sample have at least one publication in indexed journals over the period 1999–2009 and 93% of these firms have at least one article co-authored with an academic institution. However, the intensity of publishing is not evenly distributed across firms; only 16% of firms published more than 10 papers in total for the whole time span under consideration.

We also use the Pharmaprojects database to collect data on each firm's R&D pipeline and the number of novel therapeutic projects each firm moves into (pre)-clinical trials in any given year. The focus on products in development as a proxy for innovative performance is appropriate given the importance of development-stage products in this industry as a driver of company value. For example, in its acquisition of Pharmasset that was announced at the end of 2011, Gilead Sciences in essence paid US$11 Billion for a hepatitis C drug that was in clinical trials phase 2 of the drug development path (Grocer, 2011). Accordingly, the development of product pipelines is seen as central in guiding managerial decision making regarding the deployment of (intellectual) resources and venture capital investors generally plan exits around product development milestones that long precede the launch of products.

Next, to gather data on the patent portfolios of firms, we rely on patent applications by these firms documented by the European Patent Office (EPO). Further, data on R&D investments are obtained from R&D Scoreboard, which provides information on the UK top R&D-active companies. Additionally, to collect data on alliances forged by firms in our sample, we use the RECAP database, which offers comprehensive information about alliance formation activities in the biopharma sector. Moreover, we use the FAME database to retrieve corporate information on the firm total assets, founding year, group structure, company divisions, subsidiaries, and name changes.

Our final sample is represented by 1033 firm-year observations of 160 UK therapeutic biotechnology firms for the period 1998–2009.

3.2. Measures

3.2.1. Dependent variable

The dependent variable in this study is product innovation performance and it is measured as the annual count of drugs in development that enter (pre)clinical trials for the first time. Tracking the progress of these compounds through further clinical trials is beyond the scope of this paper.

Our theoretical model predicts that inter-firm heterogeneity in capturing the benefits from open science depends on whether an

innovation the firm is developing is radically or incrementally innovative. Following a method used in past research on pharmaceutical R&D (Bierly and Chakrabarti, 1996; Cardinal, 2001; Herrmann and Peine, 2011), we classify projects that represent new chemical entities (NCEs) as radically innovative. NCEs in our sample are drugs that had not previously been approved for human use. Drugs that are not NCEs are classified as incrementally innovative. An example of an incrementally innovative drug would be a drug that was previously approved for human use to treat breast cancer, and now enters clinical trials to gain approval for use in the treatment of other types of cancer (e.g. gastric cancer). We rely for the classification of drugs as NCEs or non-NCEs on coding by the Pharmaprojects editorial team. We operationalize the variable radically innovative new products in development as the annual count of new compounds that are NCEs; we measure the variable incrementally innovative new products in development as the annual count of new compounds that are not NCEs.

We calculate our dependent variables for each year over the period 1999–2009. We use a one-year lag for the dependent variable after the measurement of our independent and control variables to allow time to pass between a firm's publishing activities and the creation of new therapeutic products for clinical development. The lead-up time (including the lag) we use to assess the effect of publications on innovative performance is consistent with estimates of R&D lead-up times for novel ideas to enter (pre)-clinical trials by both management scholars and industry practitioners (e.g. Pisano, 2006; The Pharmaceutical Research and Manufacturers of America, 2007). Moreover, the incorporation of the one-year lag allows us to mitigate potential issues relating to endogeneity and reverse causality in our setting (universities might for example be more interested in collaborating with firms that develop radical innovations, which in turn are more likely to be publishable).

3.2.2. Independent variables

With the variable impact factor weighted publications we capture the level of a firm's participation and recognition in open science communities. Publishing in prominent scholarly journals is an indicator of the quality of the research performed by firm scientists (e.g. Gittelman, 2007). Moreover, publication counts are widely used not only to proxy a firm's scientific expertise but also to provide evidence of a firm's scientific contributions to academic communities (e.g. Ding, 2011). We measure the variable impact factor weighted publications as a publication count weighted by the impact factor of the journal for the year 2009. Consistent with past work (e.g. McFadyen and Cannella, 2004), this approach measures the quantity of publications by a firm's scientists while accounting for the quality of these publications. Moreover, it is reasonable to believe that the creation of new therapeutic innovations is a function of a firm's stock of knowledge; therefore, to smooth annual fluctuations, we use a three-year window to measure our main independent and control variables.

To check for the robustness of our results, we create an alternative measure of the firm's adoption of open science strategies, basic research publications, that excludes clinical trials studies. While publication counts are widely used as a proxy for the basic research performed by firms, a trade-off R&D managers face in formulating open science strategies is whether to only share findings from more applied, downstream development activities or to also disclose a firm's more basic, upstream R&D activities. Studies on open, user-driven innovation strategies emphasize the importance of the involvement of users in downstream product development as a strategy to encourage the uptake of innovations (e.g. Chesbrough, 2003; Von Hippel, 2005). An example of this strategy in the biotechnology industry is the publication of results from human subject studies that are part of the drug development process, after these drugs entered clinical trials. Such publications, ideally co-authored with clinicians who are considered thought leaders in their field, are seen as critical in supporting the incorporation and diffusion of therapeutic innovations in clinical practice. However, clinical trials publications do not generally disclose information about the underlying biological mechanisms of drugs and therefore do not necessarily reflect a willingness of firms to disclose proprietary information and adhere to norms of open science. Also in terms of their audience clinical trials publications are not as much targeted at scientists as they are at medical practitioners, whom biotechnology firms wish to encourage to prescribe their products. Finally, clinical trials studies by definition deal with products that are already in the pipeline or on the market and it was prudent to create an additional measure that excludes these studies from our sample. To identify basic research publications and exclude clinical trials publications, we searched in the titles and abstracts of all the publications in our sample for keywords that denote clinical trials (i.e. 'patients', 'persons', 'subjects', and 'clinical trials'). Accordingly we coded publications as either basic research publications or clinical trials publications. Basic research publications constitute 85.6% of publications in our sample.

To measure collaborations with universities, we construct a dummy variable that takes the value of 1 if the firm has at least one publication co-authored with university scientists within the last three years; it takes the value of 0, otherwise. We use the authors' mailing addresses as listed by Science Citation Index Expanded for each publication to identify universities, colleges, and research institutes involved in research collaborations with the focal firm. In our sample, approximately 72% of all the firm publications and 73% of the firm basic research publications are co-authored with universities.

3.2.3. Control variables

We include various controls in the estimations. First, to proxy firm age we use the difference between the current year and the company's founding year. Second, firm size is measured as a logarithm of total assets. In addition, the number of products in development stands for a firm's experience in developing new drugs; this variable is calculated for a three year window. Next, R&D investment is measured as R&D investment in Million GBP. Next, we control for a firm's prior patenting activity, and count the number of patent applications at the EPO for a moving window of three years. The number of patents has been used in the literature as a proxy for a firm's ability to generate new ideas and technological knowledge internally (Bierly and Chakrabarti, 1996). Finally, to account for alternative channels for accessing external knowledge and competences, we control for whether or not a firm has entered into an alliance over the last three years.

3.2.4. Statistical method

We analyze a panel database, comprised of yearly observations for 160 UK therapeutic biotechnology firms over the period 1998–2009. Since we employ a panel data format, we control for time effects. In other words, we control for factors that vary over time but affect the entire biotech sector by using a dummy variable for each year in the examined period. By using firm fixed effects, we further control for unobserved heterogeneity at the firm level, in other words, for factors such as internal organization, management style, etc. This estimation procedure results in more conservative models as the covariates vary within the firm.

The nature of the dependent variable, namely that of a count variable taking only non-negative integer values, underlies the use of negative binomial regression models for hypotheses testing (Cameron and Trivedi, 1998). An advantage of the negative binomial approach as compared to the Poisson specification approach is that it accounts for overdispersion; in our case this might be a

Table 1
Description of variables, data and sources.

Variable	Description	Data source
New products in development (year $t+1$)	Number of new drugs in development that enter for the first time the firm's product development pipeline in (pre-)clinical trials	Pharmaprojects database
Radically innovative products in development (year $t+1$)	Number of new drugs in development that are new chemical entities	Pharmaprojects database
Incrementally innovative products in development (year $t+1$)	Number of new drugs in development that are not new chemical entities	Pharmaprojects database
Collaborations with universities (year t, $t-1$, $t-2$)	A dummy variable that takes the value of 1 if the firm has at least one publication co-authored with university scientists within the last three years and the value of 0 otherwise	Thomson Scientific's Science Citation Index Expanded
Impact factor weighted publications (year t, $t-1$, $t-2$)	Number of publications weighted by the impact factor of the journal for the year 2009	Thomson Scientific's Science Citation Index Expanded; 2009 Thomson Reuters Journal Citation Report – Science Edition
Alliances (year t, $t-1$, $t-2$)	A dummy variable that takes the value of 1 if the firm has entered into an alliance with an external partner over the last three years and the value of 0 otherwise	RECAP database
Patents (year t, $t-1$, $t-2$)	Number of patent applications at the EPO for a moving window of three years	European Patent Office (EPO)
R&D investment	R&D investment in Million GBP	R&D Scoreboard
Firm size	A logarithm of total assets	FAME database
Firm age	Difference between the current year and the company's founding year	FAME database
Number of products in development (year t, $t-1$, $t-2$)	Number of products in development over a window of three years	Pharmaprojects database
Basic research publications (year t, $t-1$, $t-2$)	Number of publications excluding the publications on clinical trials studies	Thomson Scientific's Science Citation Index Expanded

concern, given that the variance of the dependent variable exceeds its mean. Thus, to account for both overdispersion and firm-specific fixed effects, we employ fixed effects negative binomial regressions to perform the estimations (Hausman et al., 1984).

4. Empirical results

Table 1 includes a description of the variables, data and sources. Table 2 reports descriptive statistics, including the means, standard deviations, minimum and maximum values, and a correlation matrix among the main variables used in the analysis. On average, a firm in our sample introduces 0.66 new compounds in development each year. The pair-wise correlations among the independent and control variables are relatively low, suggesting that multicollinearity is unlikely to be problematic in the analysis.

Table 3 presents the results of the fixed effects negative binomial regression models for new products in development. Our results are based on an analysis of 1033 firm-year observations for 160 therapeutic biotechnology firms. The findings confirm our main hypotheses.

Model 1 is the baseline model before including the effect of the main independent variables. We observe a positive and statistically significant effect of alliance activity, number of patents, firm size and firm age on a firm's overall innovative performance. These results are not surprising given that in science-based industries firms rely on both patenting and alliances in new product development processes. Hypothesis 1 predicts that impact factor weighted publications have a positive impact on the number of new products in development. In Model 2 we include the number of articles published by the firm over the previous three years, weighted by the impact factor of the journal. The beta coefficient of this variable is positive and statistically significant at level $p < 0.05$, which provides empirical support for Hypothesis 1.

To test Hypothesis 2, we include a dummy variable, measuring whether or not the focal firm has engaged in collaborative research with university scientists for the last three years. In support of Hypothesis 2, the beta coefficient of collaborations with university scientists is positive and significant at level $p < 0.05$, even after controlling for the firm's publishing activity. The results are displayed in Models 3 and 4.

Hypothesis 3 predicts that a more substantive publication track record is more beneficial for radical innovations than it is for incremental innovations. To test this effect, we follow the methodology used in past empirical studies (e.g. Bierly et al., 2009; Chatterji and Fabrizio, 2013; Jansen et al., 2006), and re-estimate the specification in Model 4 separately for each type of innovation outcome. Accordingly, Models 6 and 8 examine the effect of adopting open science strategies on the type of innovation. The dependent variable in Model 6 is the count of the radically innovative products in development; the beta coefficient of impact factor weighted publications is positive and statistically significant at level $p < 0.05$, supporting the prediction that publishing quality research has a positive effect on firm radical innovations. The estimated coefficients in Models 4 and 6 suggest that, keeping all other variables constant, an increase in impact factor weighted publications with one standard deviation increases the number of new products in development by approximately 16% and the number of radically innovative products in development by approximately 31%. We further re-estimate the same model specification (as in Model 4) for incrementally innovative products, and the results are presented in Model 8; the beta coefficient of impact factor weighted publications is negative and not statistically significant. This finding shows a different pattern for firms' propensity to develop incremental innovations as compared to radical innovations; engaging in open science fosters the development of radical innovations (Model 6), but has no effect on the development of incremental innovations (Model 8). Following the methodology and reasoning by Bierly et al. (2009), the positive and significant effect of publishing quality research on firm radical innovations and its non-significant effect on firm incremental innovations provide support for Hypothesis 3.

Because of the use of firm fixed effects and the focus on within firm variation over time rather than on across-firm variation, firms that have never introduced any radical innovation are dropped from the estimation of Model 6, which is the specification for radical innovations. This approach results in more conservative models (e.g. Benner and Tushman, 2002; Chatterji and Fabrizio,

Table 2
Descriptive statistics and correlations.

Variable	Mean	S.D.	Min	Max	1	2	3	4	5	6	7	8	9	10	11	12
1. New products in development (year $t+1$)	0.66	1.32	0.00	9.00	1.00											
2. Radically innovative products in development (year $t+1$)	0.34	0.95	0.00	8.00	0.77	1.00										
3. Incrementally innovative products in development (year $t+1$)	0.32	0.84	0.00	6.00	0.69	0.08	1.00									
4. Collaborations with universities (year $t, t-1, t-2$)	0.37	0.48	0.00	1.00	0.06	0.05	0.03	1.00								
5. Impact factor weighted publications (year $t, t-1, t-2$)	10.83	30.28	0.00	278.98	0.06	0.10	−0.02	0.45	1.00							
6. Alliances (year $t, t-1, t-2$)	0.37	0.48	0.00	1.00	0.12	0.12	0.05	0.35	0.30	1.00						
7. Patents (year $t, t-1, t-2$)	4.77	9.17	0.00	89.00	0.11	0.11	0.05	0.35	0.56	0.33	1.00					
8. R&D investment	1.53	4.12	0.00	32.30	0.08	0.07	0.05	0.37	0.53	0.39	0.51	1.00				
9. Firm size	10.36	2.75	0.69	16.45	0.03	0.03	0.02	−0.04	−0.04	−0.06	−0.06	−0.03	1.00			
10. Firm age	6.65	5.18	0.00	28.00	−0.07	−0.10	0.001	0.35	0.31	0.22	0.33	0.31	−0.04	1.00		
11. Number of products in development (year $t, t-1, t-2$)	2.95	4.33	0.00	34.00	0.10	0.10	0.04	0.36	0.51	0.42	0.63	0.59	−0.03	0.32	1.00	
12. Basic research publications (year $t, t-1, t-2$)	1.96	5.17	0.00	51.00	0.07	0.10	−0.01	0.47	0.89	0.30	0.59	0.52	−0.04	0.34	0.55	1.00

2013). Nevertheless, because this analysis is based on a subsample of firms that have introduced at least one radical innovation, there exists a potential concern that those firms benefit more from adopting open science regardless of the type of innovations these firms develop. To rule out this alternative explanation and a sample bias, we follow Chatterji and Fabrizio (2013) and re-estimate Model 8 using the sample of firms from Model 6. Using the sample of firms that have generated at least one radical innovation, we find that the results are comparable to those of Model 8.

To check for robustness of the results, we estimate additional sets of models. First, we use an alternative measure and consider only basic research publications for a moving window of three years (that is, eliminating from the dataset clinical trials publications). The results are presented in Table 3. Model 5 highlights that the effect of basic research publications on new products in development is positive and statistically significant at level $p < 0.1$, Model 7 highlights that the effect of basic research publications on new, radically innovative products in development is positive and statistically significant at level $p < 0.01$, and Model 9 highlights that the effect of basic research publications on new, incrementally innovative products in development is negative and not statistically significant.

Next, we measure publishing by the number of publications by the firm over the previous three years, and perform the specifications in Models 4, 6, and 8. For an alternative test of Hypothesis 2, we split firm publications into two subsets: publications co-authored with university scientists and publications not co-authored with university scientists, and run the regression specified in Model 2. Results across all these specifications are similar to those reported in Table 3.

Furthermore, we address a potential concern that some of the new drugs in development that are not classified as NCEs in Pharmaprojects (and are therefore considered incrementally innovative) may be radically innovative in their application in treating other diseases. Specifically, we coded drugs not classified as NCEs, for which a therapeutic use had already been established in a different therapeutic class than the therapeutic class for which these compounds were developed, as less incrementally innovative. We further re-estimated the regression specified in Model 8 for this subset of drugs not classified as NCEs, and the results remain unchanged.

Finally, the issues of potential endogeneity and reverse causality are always a concern. Beyond using firm fixed effects and a time lag in our models, we control for firms' prior innovation output, and include as a control variable in our regression models, firm innovative output at time t; the results remain qualitatively unchanged.

5. Discussion and implications

Firms adopting open science strategies are increasingly prominent in the current R&D landscape and this study offers novel insights into how such strategies support firms in product innovation. We highlight that firms that produce better science enjoy benefits in new product development. Moreover, we outline boundary conditions for these benefits. Specifically, benefits of open sciences strategies are stronger for the development of radical product innovations and not significant for the development of incremental innovations. In addition, the benefits of open science strategies are stronger if these strategies involve collaborations with academic partners.

This study advances the literature on interdependencies between firms' activities across the realms of open science and commercial product development in several ways. The current literature highlights that by publishing, corporate researchers develop and maintain a 'proficiency in science' that is key for a

Table 3
Results of panel data negative binomial regressions with firm fixed effects for new products in development.

	New products in development					Radically innovative products in development		Incrementally innovative products in development	
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9
Basic research publications (year t, $t-1$, $t-2$)					0.039*		0.077***		−0.003
					(0.022)		(0.029)		(0.047)
Impact factor weighted publications (year t, $t-1$, $t-2$)		0.006**		0.005*		0.009**		−0.002	
		(0.003)		(0.003)		(0.004)		(0.007)	
Collaborations with universities (year t, $t-1$, $t-2$)			0.411**	0.377**	0.371**	0.433*	0.397	0.188	0.179
			(0.176)	(0.178)	(0.178)	(0.250)	(0.250)	(0.241)	(0.246)
Alliances (year t, $t-1$, $t-2$)	0.303*	0.313*	0.276	0.291*	0.288*	0.629***	0.614**	0.070	0.070
	(0.173)	(0.173)	(0.173)	(0.174)	(0.174)	(0.239)	(0.239)	(0.235)	(0.235)
Patents (year t, $t-1$, $t-2$)	0.028***	0.024***	0.027***	0.023***	0.021**	0.030***	0.024**	0.038**	0.038**
	(0.007)	(0.008)	(0.007)	(0.008)	(0.008)	(0.009)	(0.009)	(0.016)	(0.017)
R&D investment	0.017	0.010	0.013	0.007	0.011	0.038	0.053*	−0.012	−0.012
	(0.017)	(0.018)	(0.017)	(0.018)	(0.018)	(0.033)	(0.031)	(0.023)	(0.023)
Firm size	0.109**	0.109**	0.104**	0.104**	0.107**	0.179***	0.178***	0.015	0.014
	(0.043)	(0.043)	(0.043)	(0.043)	(0.043)	(0.064)	(0.064)	(0.054)	(0.055)
Firm age	0.085**	0.081**	0.065	0.065*	0.063	−0.017	−0.034	0.129**	0.130**
	(0.040)	(0.039)	(0.040)	(0.039)	(0.039)	(0.061)	(0.061)	(0.059)	(0.060)
Number of products in development	−0.096***	−0.112***	−0.098***	−0.112***	−0.113***	−0.185***	−0.197***	−0.079**	−0.080**
	(0.028)	(0.029)	(0.028)	(0.029)	(0.029)	(0.039)	(0.041)	(0.037)	(0.037)
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	−1.743**	−2.356***	−1.672***	−2.337***	−1.661**	−3.002***	−2.991***	−1.702**	−1.700**
	(0.770)	(0.584)	(0.778)	(0.587)	(0.779)	(0.943)	(0.940)	(0.740)	(0.741)
Number of observations	1033	1033	1033	1033	1033	646	646	755	755
Number of firms	160	160	160	160	160	101	101	116	116
Log likelihood	−733.35	−731.34	−730.61	−729.09	−729.10	−369.79	−369.02	−426.56	−426.59
Chi squared	54.52	58.18	59.48	61.80	62.55	63.19	67.68	29.09	29.07

Standard errors are in parentheses.
* $p<0.10$.
** $p<0.05$.
*** $p<0.01$.

firm's capability to assimilate and exploit external scientific knowledge in R&D (Cockburn and Henderson, 1998; Cohen and Levinthal, 1990; Deeds et al., 2000; Fabrizio, 2009). We extend this work by examining firms' innovative performance in light of the quality and quantity of scholarly contributions by firm researchers. Specifically, we add to debates on whether, given the distinctive stratification logics of open science and product development, a firm's propensity to conduct better science enhances or hampers a firm's innovative performance (Cockburn and Henderson, 1998; Gittelman and Kogut, 2003). We find confirmation for the former.

Furthermore, we contribute to work on the positive effects of collaborations with university scientists for firm innovation. For example, Almeida et al. (2011) highlight a differential effect of distinctive collaboration types (e.g. scientific collaborations with universities and firms, and strategic alliances) on firm innovation, and Fabrizio (2009) underscores the importance of a firm's scientific orientation in R&D and the degree of connectedness to university scientists for the timing of and the recognition for firm inventions. We extend this work by accounting for the quality of a firm's scientific publications and the type of a firm's innovation output.

In addition, our theoretical and empirical examinations of the differential effect of 'open science' strategies on distinctive types of innovations constitute an important contribution. By considering distinctive types of innovations, our paper extends past research that focuses on the link between the use of scientific knowledge and the importance of inventions (e.g. Fabrizio, 2009; Fleming and Sorenson, 2004). This finding has important implications for managers and how they set up rules of interaction with open science communities. Moreover, our use of product development data as a measure of R&D performance is a methodological innovation in the literature on R&D that spans the realms of science and technology, which has traditionally focused on patent data. As we showcased in this article, product development data offer great potential for further examinations of antecedents of different types of innovation outcomes.

Our study has several limitations that offer avenues for future research. First, issues relating to the potential of endogeneity and reverse causality are always a concern for studies like ours. We employed commonly used statistical methods to address such concerns. For example, we used firm fixed effects and incorporated a time lag in our models. Furthermore, we controlled for firms' prior innovation output, and included as a control variable in our regression models, firm innovation output at time t. None of the analyses we conducted to statistically check whether endogeneity was an issue, qualitatively altered our findings. However, although the analyses we carried out provide us with statistically robust support for the relationships we identified, caution about inferring causality should be observed and further research will be required to develop richer insights into the mechanisms underlying the examined relationships.

Second, there are opportunities to extend our work in the specific context of the biotechnology industry. Our research question pertained to the impact of open science strategies on biotechnology firms' R&D performance in terms of firms' enhanced capabilities to develop new products. It did not pertain to possible costs associated with the disclosure of R&D findings that open science strategies entail. In particular, we did not consider possible costs relating to a weaker intellectual property (IP) position and firms' reduced ability to reap the commercial rewards of the enhanced innovative capabilities. Thus, while our paper does highlight benefits of open science strategies, it does not focus on the costs associated with these strategies. Building on methodological approaches used to analyze paper-patent pairs (e.g. Murray and Stern, 2007), future research will be able to clarify the trade-offs managers face in protecting IP while reaping rewards of open science strategies.

Moreover, this study highlights that the benefits firms reap from adopting open science norms in R&D activities are contingent on specific factors such as the type of innovation outcome a firm pursues. This insight opens up an avenue for a more comprehensive exploration of other levers managers have at their disposal in attuning strategic interactions with open science communities to specific R&D goals. Innovation antecedents at individual, firm and network levels of analysis have been highlighted to be complements or substitutes to one another (e.g. Murray and O'Mahony, 2007; Rothaermel and Hess, 2007). Thus, there is an opportunity for future research to examine the moderating role alternative mechanisms for sourcing external knowledge from open science communities play in supporting R&D goals such as forging licensing agreements, recruiting (students of) star scientists in research roles, or participating in pre-competitive research consortia.

Third, there are opportunities (and pitfalls) in exploring how findings from this study can be generalized beyond the context of the biotechnology sector. One limitation to the generalizability of our research is that there is only a limited number of sectors, in which academic communities play such an important role in R&D (e.g. Laursen and Salter, 2004). However, there is a growing number of sectors, in which like in biotechnology, expert groups outside the commercial realm play an important role. These for example include the computer software sector, where managers face dilemmas in deciding whether to share commercially developed software code in forums of open source communities that are similar to the dilemmas managers of biotechnology firms face in deciding whether to share R&D work in quality journals (Dahlander, 2006; Dahlander and Magnusson, 2005; Henkel, 2006, 2009; Lee and Cole, 2003; Von Hippel and von Krogh, 2003). We believe our results hold insights into the considerations that help managers resolve these dilemmas.

In further examining the applicability of our findings in other industrial sectors, it will be critical to focus on the distinctive commercialization environments of these other sectors. R&D strategies should be contingent on the specific commercialization environment of a sector (Gans and Stern, 2003). A critical part of this environment is the IP regime. The commercialization environment governing innovation in biotechnology is seen as archetypical for environments where IP protection is strong and so-called markets for ideas prosper as a result (Gans and Stern, 2003). There are other sectors such as the consumer electronics and software sectors where IP protection has traditionally been seen as weaker and the costs of 'open' innovation strategies like the ones discussed in this paper as higher. Future research will need to have a closer look at these differences across sectors and their impact on trade-offs R&D managers face in engaging external expert groups from outside the commercial realm in product innovation.

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