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Knowledge spillovers or R&D collaboration? Understanding the role of external knowledge for firm innovation

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Extant research has established that firms engage in R&D collaboration and access knowledge spillovers to enhance their innovativeness. We aim to take this conversation in a new direction by seeking to answer the question, 'How does engagement in R&D collaboration with suppliers, customers, and competitors, both domestically and internationally, as well as access to knowledge spillovers from universities and other open sources, influence a firm's innovation?' This is the primary goal of our study. The study develops a knowledge-based view on knowledge collaboration and spillovers, explaining how a firm's decision to collaborate, as opposed to accessing knowledge spillovers, shapes its innovation outputs and propensity to innovate. The theoretical utility of this framework lies in elucidating how the distinct types of knowledge (basic or applied) transferred to a firm when accessing external knowledge create different mechanisms that influence innovation output. By analyzing data on knowledge spillovers and R&D collaboration from the innovation survey of firms in the United Kingdom over the period 2002–2014, we demonstrate that in most instances of knowledge combinations, the cost effect of knowledge sourcing exceeds the complementary effect of knowledge, leading to a firm's choice between R&D collaboration and spillovers. The study contributes to the innovation and R&D management literatures by explaining why this pattern emerges and demonstrating that these relationships are contingent upon the degree of collaboration and the level of knowledge spillovers.

1. Introduction

Firm innovation and R&D management have long been focal points of both research and policy agendas (Chiesa and Piccaluga, 2000; Di Minin et al., 2021), prompting several policy responses across the United States and Europe. The emphasis has been placed on aspects such as R&D collaboration, knowledge spillovers, and innovation performance (Leyden and Link, 2015; Bernal et al., 2022).

While many scholars view R&D collaboration as a general source of innovation from various perspectives (Kenney and Patton, 2005; Belderbos et al., 2015), we define R&D collaboration as the exchange of applied knowledge between two or more directly engaged partners. This exchange can encompass individual interactions, joint practices, and capability development (Caloghirou et al., 2004; Agarwal et al., 2010; Nissen et al., 2014; Bernal et al., 2022), often forming a formal relationship between a firm and its suppliers, customers, and competitors (Ritala, 2012; Bouncken et al., 2020). We define knowledge spillovers as externally developed knowledge by other organizations, which, being not entirely excludable, can be freely accessed by third parties as a positive externality (Griliches, 1979; Jaffe et al., 1993; Audretsch and Feldman, 1996; Cassiman and Veugelers, 2006; Agarwal et al., 2010).

Despite the significant attention given to the roles of R&D collaboration and knowledge spillovers in innovation output, there remains a lack of understanding regarding what determines the positive impact of R&D collaboration (Chesbrough, 2003) and knowledge spillovers (Audretsch and Feldman, 1996; Acs et al., 2009) on innovation output. Additionally, recent research on knowledge transfer and innovation calls for greater clarity about the firm characteristics that enable the cross-fertilization of collaborative research projects to accelerate the innovation process (González-Piñero et al., 2021) and to leverage the limitations of knowledge transfers (Audretsch and Belitski, 2020).

Past research on open innovation and knowledge sourcing (Laursen and Salter, 2006, 2014; Kobarg et al., 2019; Audretsch and Belitski, 2020) has not effectively expounded on the mechanisms of knowledge sourcing and types of knowledge (basic vis-à-vis applied knowledge) (Leyden and Menter, 2018, 2022). Nor has it explored the complementary and substitutive effects of knowledge spillovers and collaboration for innovative firms under different conditions. Despite valuable theoretical contributions, what remains unclear is how a firm's engagement in R&D collaborations with different external partners and firms' reliance on knowledge spillovers to achieve its knowledge creation targets influences innovation performance. To address the above limitation, we combine transaction cost approach by Williamson (1979) related to the cost of knowledge creation and knowledge-based view (Wernerfelt, 1984; Dyer and Nobeoka, 2000; Barney et al., 2001; Grant and Baden-Fuller, 2004) to develop a theoretical perspective and explain how the interplay between different sources of knowledge inputs shapes innovation performance.

Thus, the objective of this study is to theoretically discuss and empirically examine how does engagement in R&D collaboration with suppliers, customers, and competitors domestically and internationally as well as access to knowledge spillovers from university and other open sources influence the firm's innovation and propensity to innovate. This study will fill a significant theoretical gap in R&D management and innovation research by investigating the extent to which a firm is constrained to choose between knowledge spillovers and R&D collaboration, and what combinations of knowledge could be more or less beneficial for innovation activity (Belderbos et al., 2010, 2015; Phelps, 2010; Bernal et al., 2022; Audretsch et al., 2023).

This study explores the choices between R&D collaboration and/or access to knowledge spillovers and how these choices can subsequently change innovation output. The contributions of this study is in R&D management and open innovation literature as follows.

First, we theorize and empirically test the interplay between R&D collaboration with external partners (such as customers, competitors, and suppliers) (Mariani and Belitski, 2023; Audretsch and Belitski, 2024) and knowledge spillover from universities, conferences, industrial standards, patents, academic publications to understand how each type of engagement related to basic and applied knowledge shapes innovation outputs and the overall propensity to innovate.

Second, we explain the mechanisms driving the complementary and substitutive effects between R&D collaboration and incoming knowledge spillovers for firm innovation. The key premises of the knowledge-based view (Dyer and Nobeoka, 2000; Grant and Baden-Fuller, 2004) is that firms are motivated to engage in R&D collaboration because they need to leverage external knowledge, expertise, and capabilities that cannot be found internally (Chesbrough et al., 2006). Hence, by choosing R&D collaboration and spillovers, a firm chooses how different types of knowledge (basic and applied) will enable complementarities in collaborations or will lead to an increased transaction costs (Williamson, 1979). Thus, both positive and negative effects of joint access to knowledge spillovers and engagement in R&D collaboration are sought.

Our results provide empirical evidence of the positive effect of incoming knowledge spillovers on firm innovation and propensity to innovate. Moreover, we demonstrate that both domestic and international R&D collaborations bolster firm innovation and the propensity to innovate. In a more dynamic view on R&D collaboration and knowledge spillovers, we argue that these strategies may be adapted by firms over time depending on the value obtained from their current combination of knowledge sources and types of collaboration partners (Asgari et al., 2017; De Leeuw et al., 2019).

This research contrasts previous works by Bernal et al. (2022) and Koch and Simmler (2020) in its approach to understanding the effects of various types of R&D collaboration and knowledge spillovers on innovation. We normalize incoming knowledge spillover, university spillover, and R&D collaboration on innovation domestically and internationally and compare the magnitude of the effects on innovation performance and propensity to innovate.

It extends robust literature on R&D collaboration and alliances by Koch and Simmler (2020) and Bloom et al. (2013), who have focused on the role of knowledge spillovers and a firm's decisions to engage in collaboration versus other sources of knowledge, much of this research often omits an analysis of the nature and heterogeneity in knowledge spillovers. They primarily consider the transfer of basic knowledge and regard it as an integral part of the knowledge collaboration process (Katz, 1986; d'Aspremont and Jacquemin, 1988; Li and Bosworth, 2020). This perspective, however, differs from that of Koch and Simmler (2020) and Audretsch et al. (2021). In this study, we offer both a theoretical discussion and empirical testing of these contrasting views.

The remainder of this article is as follows. The next section reviews the literature on knowledge spillovers and R&D collaboration and the interplay between them to motivate and develop our research hypothesis. Section 3 explains the data and empirical methodology, while the results of the estimation are discussed in Section 4. Section 5 provides multiple robustness checks. Section 6 discusses and Section 7 concludes.

2. Theoretical framework and hypotheses

2.1. *Knowledge spillovers and innovation*

Knowledge spillovers are generated when a firm accesses knowledge and information from a third party such as university or open source – technical reports, patent databases, conference attendance, scientific publications, and open Internet information. Research at universities often facilitates the spillover of basic knowledge (Audretsch, 2014) and its transfer to the industry where it can be applied and commercialized. Koch and Simmler's recent work (2020) discusses potential local public knowledge spillover channels, such as knowledge transfer from local public institutions (e.g., patents, universities) to firms. In this context, knowledge spillovers are built on basic knowledge that can be accessed and used directly from the source, such as patents, copyrights, trademarks, textbooks, and case studies. This basic knowledge can enhance the performance of companies, a topic explored extensively in open innovation literature (Chesbrough, 2003; Cassiman et al., 2008). These properties make basic knowledge decentralized and accessible beyond geographical boundaries. Koch and Simmler's concept of knowledge spillover (2020) posits that third parties advance basic scientific knowledge and create technological knowledge, which then spills over to firms in close geographic proximity (Belenzon and Schankerman, 2013; Guenther et al., 2023). The authors also mention a second channel of collaboration between firms and public institutions that allows firms not only to access knowledge via spillovers but also to collaborate in creating new knowledge.

Information from open sources such as academic publications, conferences, technical know-how, and patents is considered a useful source of information on the technical characteristics of industry inventions (Caloghirou et al., 2004). Therefore, spillovers of specific knowledge produced by third public and private organizations, but not commercialized, could serve as a source of new knowledge and be commercialized in a market by creating a new product or establishing a new business (Acs et al., 2009; Audretsch and Belitski, 2013).

While the benefits of knowledge spillovers are often locally bound (Boschma, 2005), the development of digital tools has changed the implicit assumption that basic knowledge is geographically bounded (Acs et al., 1992; Bloom et al., 2013; Audretsch and Belitski, 2021). Developments in technologies such as fiber optics, which can manage more data traffic and more customers, including 4G and 5G networks, as well as broader access to broadband, reduce the cost of data maintenance and transmission. This allows basic knowledge to be transmitted beyond a firm's physical location, even through face-to-face communication platforms like Zoom and Teams in real time. Thus, we hypothesize:

> H1. Firms that access knowledge spillovers will increase their innovation output.

2.2. R&D collaboration and firm innovation

Knowledge spillovers can catalyze innovation activities, but firms that are unable to access such spillovers or that need more applied knowledge may turn to R&D collaborations (Caloghirou et al., 2004; Belderbos et al., 2010, 2015; Helfat and Martin, 2015).

There are several compelling reasons for firms to pursue R&D collaboration. First, R&D collaboration, 'crossing knowledge and technologies, provides a way to enhance the competitive position of partners when looking for a collaborative advantage' (González-Piñero et al., 2021, p. 36), increasing absorptive capacity through learning effects garnered through R&D with suppliers, customers, and competitors (Schamberger et al., 2013; Ritala, 2012; Bernal et al., 2022). Second, strategic know-how and competencies are developed and shared within R&D collaborations and networks (Lundvall and Johnson, 1994). Innovation research positively correlates R&D collaboration between organizations with improved innovation outcomes (Belderbos et al., 2015; Kobarg et al., 2019; Audretsch et al., 2023). Third, R&D collaboration can focus on meeting specific industry needs and societal demands, where applied knowledge is generated through personal contacts between knowledge creators in various spaces (Audretsch and Belitski, 2022). R&D collaboration often involves co-creation and the sharing of experiences among managers and technical staff, facilitated by formal and informal interactions at work and through the mobility of human capital between partners (Kogut, 1988).

Finally, previous research shows that R&D collaborations allow firms to bring in new expertise and applied knowledge and match them to their needs (Ciborra, 1991). In this way, firms can exchange and enrich applied knowledge, which can be product-, industry-, and market specific, through close links between different firms and managers. In today's era of rapid digitization, firms use various platforms and digital tools to connect with multiple, functionally diverse partners and engage in R&D collaboration (Beers and Zand, 2014).

Besides the learning and co-creation benefits, R&D collaboration can reduce a firm's cognitive and product development costs by facilitating the discovery of new products and providing access to applied knowledge that can be quickly integrated into the value creation process (Lanzolla and Suarez, 2012). It can also help distribute the organizational costs of innovation between partners (Veugelers, 1998), thereby reducing product development and innovation production cycles (Hagedoorn, 1993).

Given the increasing complexity of knowledge and market demands, firms are engaging competitors, suppliers, and customers in R&D collaboration (Laursen and Salter, 2006; Frenz and Ietto-Gillies, 2009; Beers and Zand, 2014; Kobarg et al., 2019). This facilitates faster commercialization and development of new products. While applied knowledge is traditionally thought to be localized and more easily exchanged within close proximity (Acs et al., 1992). Accordingly, we hypothesize:

> H2. Firms that engage in formal R&D collaboration domestically and internationally will increase their innovation output.

2.3. Complementarity between basic and applied knowledge for innovation

At the heart of knowledge spillovers lies basic knowledge, which for a firm could translate into a reliance on foundational knowledge and core university disciplines (Audretsch, 2014). While basic knowledge plays a crucial role, the industrial application of this knowledge necessitates its combination with applied knowledge. This is typically obtained via linkages between firms, managers, competitors, suppliers, and customers with the objective of addressing specific technological, social, and economic challenges. Applied knowledge primarily focuses on providing solutions and applications for major issues confronting society and industry. Basic knowledge needs to be transformed into marketable products, hence a R&D collaboration strategy that encourages cross-fertilization of basic and applied knowledge could significantly boost innovation outcomes and lead to direct market commercialization in the form of new products and services (see Leyden and Menter, 2018, 2022 for discussion).

We propose that the fusion of basic and applied knowledge introduces a diverse range of competencies, capabilities, and skills to partnerships. Amid heightened competition for knowledge and digitalization, firms aim to access basic knowledge from the academic sector and complement their applied knowledge, derived from internal R&D efforts and external collaborations, to innovate. Collaboration with competitors and suppliers can conserve resources for innovation and ensure that the critical mass of basic knowledge attained via spillovers and internal R&D is augmented with applied knowledge. Current research indicates that there is pressure on firms to enter markets (Ritala, 2012; Bouncken et al., 2020; Belitski and Mariani, 2023) and that basic research in corporate laboratories and universities, which aims to create new scientific knowledge, should be integrated with applied research activities (Caloghirou et al., 2004).

A positive outcome of combining R&D collaboration and spillovers is the knowledge complementarity effect. It is reasonable to posit that the role of R&D collaboration is twofold for a firm's incentive to invest in such collaboration and spillovers. First, R&D collaboration allows the flow of applied knowledge across different partners, while also facilitating the understanding and assimilation of external knowledge in the form of knowledge spillovers. Second, applied knowledge simplifies intra-firm learning, creating a stronger absorptive capacity (Cohen and Levinthal, 1989), and aids in transforming basic knowledge from spillovers into marketable solutions. This process is partially explained by open innovation scholars (Hagedoorn, 1993; Beers and Zand, 2014) and can be condensed into three themes, associated with the reductions in cognitive, transactional, and organizational costs that encourage firms to engage in both R&D collaboration (Cassiman and Valentini, 2016). Firms will accelerate organizational learning and develop impactful and valuable breakthrough inventions that enhance their performance in collaboration (Belitski et al., 2023). By supplementing R&D collaboration with spillovers, firms may further filter out less promising combinations of knowledge partners and identifying the most promising partner types (Fleming and Sorenson, 2004).

Despite the importance of equipping a firm with both basic and applied knowledge for innovation, firms might not be able to access both types of knowledge equally and to the extent they wish to do due to major resource constraints and risks (Williamson, 1979; Kobarg et al., 2019). Bernal et al. (2022) found that the propensity to initiate or continue collaboration with business partners (customers, suppliers, competitors) correlates with whether firms already benefit from access to knowledge resources, such as knowledge spillovers. Increasing basic and applied knowledge transfer from various external sources raises operational and transaction costs, resulting in diminishing marginal returns from combining knowledge spillovers and R&D collaboration (Audretsch and Belitski, 2022, 2023; Saura et al., 2023). We refer to this negative effect from combining R&D collaboration and spillovers as the cost effect.

Primary costs are adjustment and operational costs, which may depend on the costs and extent of existing collaborations, as every subsequent collaboration will entail less additional costs. While adjustment costs will diminish as firms continue to adapt to the existing and subsequent technological and scientific collaborations, using their absorptive capacity (Cohen and Levinthal, 1989), the 'learning-by-collaborating' process is not limitless and will eventually contribute to operational costs. Adjustment costs will operate similarly for both R&D collaboration and knowledge spillovers. Although the costs of absorbing every unit of new information and knowledge are likely to be smaller than those of absorbing existing knowledge, these costs are nonetheless cumulative.

Therefore, the positive complementary effect of combining knowledge spillovers and R&D collaboration is constrained by the resource scarcity effect, and a firm's readiness to invest in both knowledge transfer channels when faced with such a choice. We hypothesize:

> H3. The relationship between R&D collaboration and knowledge spillovers for firm's innovation is (a) positive if the knowledge complementarity effect outweighs the cost effect and (b) negative if the cost effect exceeds the knowledge complementarity effect.

The conceptual model we test is illustrated in Figure 1.

3. Data and method

3.1. Sample

To test our hypotheses, we employed six pooled cross-sectional datasets from the Business Structure Database, also known as the Business Register, and the UK Innovation Survey (UKIS) spanning from 2002 to 2014. Despite these two datasets originating from separate sources, they can be effectively

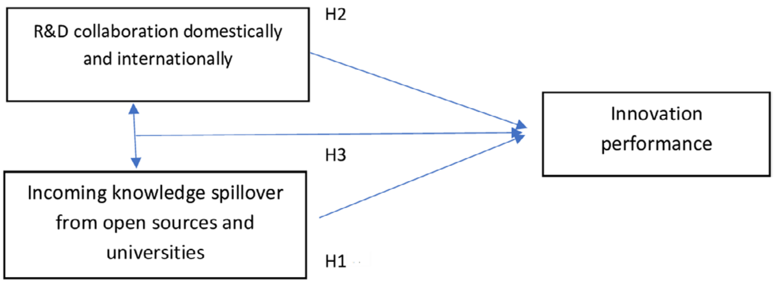

Figure 1. The conceptual model. *Source*: Authors. [Colour figure can be viewed at wileyonlinelibrary.com]

paired. First, we compiled and matched six consecutive waves of the UK Innovation Surveys (UKIS 4 2002–2004, UKIS 5 2004–2006, UKIS 6 2006–2008, UKIS 7 2008–2010, UKIS 8 2010–2012, and UKIS 9 2012–2014), each conducted biennially by the Office of National Statistics (ONS) in the United Kingdom (UK). The surveys were organized on behalf of the Department of Business Innovation and Skills (BIS). Second, we utilized data from the Business Structure Database (BSD) for the years 2002, 2004, 2006, 2008, 2010, and 2012, and matched these to the corresponding CIS survey waves, using BSD data from the initial year of the UKIS period. The Business Structure Database includes information on firm legal status, ownership (foreign or national firm), alliance information (whether the firm belongs to a larger enterprise network), export activity, turnover, employment, industry at a five-digit level, and firm location by postcode.

Given the available data on our two operationalizations of innovation, we created two samples to test our research hypotheses. The first sample, called 'innovative sales', contains a total of 21,702 observations and focuses on the factors that impact sales of new products, using the share of new product sales as the dependent variable. Our second sample, called 'innovation output', includes 26,908 observations with the binary dependent variable being product innovation. The distribution of firms across industries, regions, and survey years shows a 95% overlap between the two samples. In our first sample, consisting of 21,702 observations, we perform two robustness checks by excluding firms in the Greater London area (19,043 observations) and firms with subsidiaries (18,434 observations). We also estimate a sample with predicted values of knowledge spillover and collaboration to address endogeneity bias. Tables 1 and 2 display the industrial and geographical split across the original sample of 89,518 observations as well as the 'innovative sales' and 'product innovator' samples.

3.2. Variables

Detailed descriptions of dependent, explanatory, and control variables are provided in Table 3, while their summary statistics are in Table 4.

We use two dependent variables for innovation output. The first variable, 'innovation', is operationalized as a firm's turnover share from goods and services that were new to the market and to the firm over the past 3 years. This variable signifies whether a firm can invent new products and commercialize them (Arora et al., 2016; Giovannetti and Piga, 2017; Kobarg et al., 2019). An innovation sales value of zero does not necessarily imply a lack of innovation; instead, it may suggest that the innovation has not been commercialized. This measure has often been used to gauge knowledge commercialization and innovation (Roper et al., 2008; Frenz and Ietto-Gillies, 2009; Santamaria et al., 2009; Leiponen and Helfat, 2010; Kobarg et al., 2019; Audretsch et al., 2023). Unlike a binary variable, this sales related variable displays the commercial value of innovation (Negassi, 2004). Our second dependent variable, 'product innovator', is defined as one if a firm has reported a new product or service creation over the past 3 years, zero otherwise. This measure has been used as an indicator of innovation and a firm's ability to invent new products and services (Laursen and Salter, 2006, 2014; Giovannetti and Piga, 2017; Roper et al., 2017; Audretsch and Belitski, 2021, 2022). Both dependent variables are sourced from the UKIS and are available from 2004 to 2014.

Our independent variables relate to knowledge spillovers and R&D collaboration. First, we operationalize incoming knowledge spillover, following Cassiman and Veugelers (2002), Veugelers (1998), Griffith et al. (2006), Audretsch et al. (2021), and Bernal et al. (2022), as a sum of scores between zero and three, which pertain to the importance of various information sources for innovation activities. The final score for incoming knowledge spillover

Table 1. Three samples sector divisions (by SIC 2007)

Sector divisions	Baseline	%	Innovative sales	%	Product innovator sample	%
1. Mining and quarrying	486	0.65	175	0.81	186	0.69
2. Manufacturing basic	4,025	5.41	1,277	5.88	1,569	5.83
3. High-tech manufacturing	11,682	15.70	4,218	19.44	4,946	18.38
4. Utility	780	1.05	170	0.78	205	0.76
5. Construction	7,370	9.90	2,229	10.27	2,640	9.81
6. Wholesale, retail trade	12,530	16.84	3,481	16.04	4,324	16.07
7. Transport, storage	4,792	6.44	1,195	5.51	1,501	5.58
8. Hotels and restaurants	5,400	7.26	1,174	5.41	1,418	5.27
9. ICT	4,441	5.97	1,434	6.61	1,787	6.64
10. Financial intermediation	2,651	3.56	850	3.92	1,337	4.97
11. Real estate and other business activities	10,728	14.41	2,682	12.36	3,471	12.90
12. Public admin, defense	8,305	11.16	2,196	10.12	2,742	10.19
13. Education	213	0.29	152	0.70	191	0.71
16. Other community, social activity	1,024	1.38	469	2.16	592	2.20
Total observations	74,427	100.00	21,702	100.00	26,908	100.00

Due to missing values on firm's sector, the total amount of observations (once controlled for sectors) in the baseline sample is 74,427 observations.
Source: Department for Business, Innovation and Skills, Office for National Statistics, Northern Ireland. Department of Enterprise, Trade and Investment. (2018). *UK Innovation Survey, 1994–2016: Secure Access*. [Data collection]. *6th Edition*. UK Data Service. SN: 6699, http://doi.org/10.5255/UKDA-SN-6699-6 (hereinafter UKIS – UK Innovation survey). Office for National Statistics. (2017). *Business Structure Database, 1997–2017: Secure Access*. [Data collection]. *9th Edition*. UK Data Service. SN: 6697, http://doi.org/10.5255/UKDA-SN-6697-9 (hereinafter BSD – Business Structure Database).

Table 2. Three samples regional distribution (by 10 UK regions, Scotland, and Northern Ireland) and distribution over survey waves

	Baseline	%	Innovative sales	%	Product innovator sample	%
Regions						
North East	4,731	5.28	1,171	5.40	1,582	5.88
North West	8,506	9.50	1,997	9.20	2,443	9.08
Yorkshire and Humber	7,142	7.98	1,758	8.10	2,217	8.24
East Midlands	6,708	7.49	1,749	8.06	2,134	7.93
West Midlands	7,562	8.45	1,890	8.71	2,301	8.55
Eastern England	7,776	8.69	1,946	8.97	2,446	9.09
London	11,369	12.70	2,064	9.51	2,615	9.72
South East	10,353	11.57	2,367	10.91	2,928	10.88
South West	7,229	8.08	1,813	8.35	2,266	8.42
Wales	5,203	5.81	1,432	6.60	1,806	6.71
Scotland	7,487	8.36	1,700	7.83	2,163	8.04
Northern Ireland	5,452	6.09	1,815	8.36	2,008	7.47
Total	89,518	100.00	21,702	100.00	26,908	100.00
Years						
UKIS4 (2005)	16,445	18.37	12,557	57.86	11,334	42.12
UKIS5 (2007)	14,872	16.61	2,425	11.17	5,656	21.02
UKIS6 (2009)	14,281	15.95	1,454	6.70	4,273	15.88
UKIS7 (2011)	14,342	16.02	2,773	12.78	2,575	9.57
UKIS8 (2013)	14,487	16.18	1,174	5.41	1,362	5.06
UKIS9 (2015)	15,091	16.86	1,319	6.08	1,706	6.34
Total observations	89,518	100.00	21,702	100.00	26,908	100.00

BSD, Business Structure Database; UKIS, UK Innovation survey.

Table 3. Description of variables

Variable (source)	Definition
Innovation (UKIS)	Share of firm's turnover from goods and services that were new to the market and new to the firm over the last 3 years
Product innovator (UKIS)	Binary variable = 1 if firm reports a firm has created product or service innovation which was new to the market and a firm, zero otherwise
Incoming knowledge spillovers (UKIS)	Sum of scores (0–3) of how important to innovation activities was information from: conferences, trade fairs, or exhibitions professional and industry associations; technical, industry, or service standards; scientific journals and trade/technical publication. The final score was normalized between zero and one. The individual variables are described next
University knowledge spillovers	Sum of scores (–3) of how important to innovation activities was information from universities normalized between zero and one
R&D collaboration domestic (UKIS)	Sum of binary variables if a firm reported R&D collaboration on innovation with suppliers, customers, and industry (competitors) regionally and nationally (within the UK) that varies from zero to a maximum of six, for collaboration with a maximum of three types of partners regionally and internationally. The final score was normalized between zero and one
R&D collaboration international (UKIS)	Sum of binary variables if a firm reported R&D collaboration on innovation with suppliers, customers, and industry (competitors) in Europe and the rest of the world that varies from zero to a maximum of six, for collaboration with a maximum of three types of partners regionally and internationally. The final score was normalized between zero and one
Control variables	
Age (BSD)	Age of a firm (years since the establishment)
Employment (BSD)	Number of full time employees, in logarithms
Training (UKIS)	Binary variable equal one if a firm invested in training for innovation of employees, zero otherwise
Organizational innovation internal (UKIS)	Binary variable equals one if during the 3 years a firm has introduced new business practices for organizing procedures (i.e., supply chain management, business re-engineering, knowledge management, lean production, and quality management), zero otherwise
Organizational innovation external (UKIS)	Binary variable equals one if during the 3 years a firm has introduced new methods of organizing external relationships with other firms or public institutions (i.e., first use of alliances, partnerships, outsourcing, or sub-contracting), zero otherwise
Process innovation (UKIS)	Binary variable = 1 if firm has introduced process innovation, zero otherwise
R&D expenditure (UKIS)	The amount of expenditure for internal Research and Development (000s) in logarithm
Patents (UKIS)	Binary variable = 1 if firm has used patents as legal protection of its innovation outcomes, zero otherwise
Scientist (UKIS)	The proportion of employees that hold a degree or higher qualification in science and engineering at BA/BSc, MA/PhD, PGCE levels
Exporter (UKIS)	Binary variable = 1 if a firm sells its products in foreign markets, 0 otherwise
Foreign (BSD)	Binary variable = 1 if a firm has headquarters abroad, 0 otherwise
Survival (BSD)	Binary variable = 1 if a firm survived as an independent unit or as a part of a group until year 2017, 0 otherwise
Reporting unit (UKIS)	Number of local units (subsidiaries within the enterprise group, both in the country and abroad)
Variables used to create incoming knowledge spillover	
Associations (UKIS)	Knowledge spillovers component: how important to innovation activities was information from: professional and industry associations (0 – not applicable to 3 – high)
Standards (UKIS)	Knowledge spillovers component: how important to innovation activities was information from: technical, industry, or service standards (0 – not applicable to 3 – high)
Conferences (UKIS)	Knowledge spillovers component: how important to innovation activities was information from: conferences, trade fairs, or exhibitions (0 – not applicable to 3 – high)
Publications (UKIS)	Knowledge spillovers component: how important to innovation activities was information from: scientific journals and trade/technical publications (0 – not applicable to 3 – high)

Table 3. (Continued)

Variable (source)	Definition
Variables used to create R&D collaboration domestically and internationally	
Suppliers collaboration domestic (UKIS)	Binary variable = 1 if firm reports R&D collaboration with suppliers within a region or a country, zero otherwise
Customers collaboration domestic (UKIS)	Binary variable = 1 if firm reports R&D collaboration with customers within a region or a country, zero otherwise
Industry collaboration domestic (UKIS)	Binary variable = 1 if firm reports R&D collaboration with competitors within a region or a country, zero otherwise
Suppliers collaboration international (UKIS)	Binary variable = 1 if firm reports R&D collaboration with suppliers in Europe and the rest of the world, zero otherwise
Customers collaboration international (UKIS)	Binary variable = 1 if firm reports R&D collaboration with customers in Europe and the rest of the world, zero otherwise
Industry collaboration international (UKIS)	Binary variable = 1 if firm reports R&D collaboration with competitors in Europe and the rest of the world, zero otherwise
Variables used as instruments at the first stage regression	
Incoming knowledge spillover industry (UKIS)	Mean of incoming knowledge spillover variable aggregated by all firms in three-digit SIC2007 industry for each year
University knowledge spillover industry (UKIS)	Mean of university knowledge spillover variable aggregated by all firms in three-digit SIC2007 industry for each year
R&D collaboration domestic industry (UKIS)	Mean of a sum of scores of R&D collaboration with suppliers, customers, and competitors domestically aggregated by all firms in three digit SIC2007 industry for each year
R&D collaboration international industry (UKIS)	Mean of a sum of scores of R&D collaboration with suppliers, customers, and competitors internationally aggregated by all firms in three-digit SIC2007 industry for each year
Number of plants	Number of plats (manufacturing and service units) of a firm

BSD, Business Structure Database; UKIS, UK Innovation survey.

was normalized between zero and one. Second, we operationalize university knowledge spillover by summing scores between zero and three, indicating the importance of information received from local, national, and international universities for innovation activities. This variable was also normalized between zero and one.

Third, to measure domestic R&D collaboration, we used a sum of binary variables equal to one if a firm has reported R&D collaboration on innovation with suppliers, customers, and competitors within the UK, and zero otherwise (Ciborra, 1991; Nissen et al., 2014; Kobarg et al., 2019). Finally, to measure international R&D collaboration, we used a sum of binary variables equal to one if a firm has reported R&D collaboration on innovation with suppliers, customers, and competitors outside the United Kingdom, and zero otherwise (Faems et al., 2005; Audretsch et al., 2021). This procedure enables a continuous distribution of values between zero (minimum level of spillover or collaboration) and one (maximum level), and normalization allows for the comparison of marginal effects, which is vital for policy advice and managerial policy implications.

Our control variables include R&D expenditure in logarithms (Hall et al., 2013; Hall and Sena, 2017), the proportion of employees with a BA/BSc degree or higher in science and engineering (Cohen and Levinthal, 1989; Veugelers, 1998), training for innovation (Belitski et al., 2020), and the effectiveness of patents as a method for maintaining or increasing innovation (Arora et al., 2016). We control for firm age (number of years since establishment) squared, and the logarithm of firm size to measure the potential non-linear effect of a firm's age and size on innovation (Santamaria et al., 2009; Roper et al., 2017).

We also control for organizational innovation related to internal process changes and external collaboration practices (Helfat and Martin, 2015). Furthermore, we account for the number of reporting units such as subsidiaries within the enterprise group, which can proxy for the enterprise group size and potential absorptive capacity of a firm (Cohen and Levinthal, 1989). We also control for whether a firm is a foreign-owned subsidiary with headquarters abroad, and whether a firm engages in export activity, as these factors may influence firm performance and innovation (Laursen and Salter, 2014; Audretsch and Belitski, 2020). Finally, we control for survival bias for a firm that has survived until 2017 since its establishment.

Table 4. Summary statistics for variables used in this study across four samples

Sample	Baseline sample (collected by the ONS) = 89,518 obs.			Innovative sales = 21,702 observations		Innovative sales = 19,043 observations (excluding London)		Product innovator [0,1] sample = 26,908 observations	
Variables		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Innovative sales	33,969	4.68	13.66	4.24	12.74	4.23	12.63	3.88	12.25
Product innovator	89,518	0.24	0.43	0.40	0.49	0.38	0.47	0.35	0.48
Incoming knowledge spillover	89,518	0.19	0.27	0.32	0.27	0.31	0.26	0.28	0.27
University knowledge spillover	89,518	0.19	0.27	0.15	0.25	0.14	0.25	0.13	0.25
R&D collaboration domestic	73,435	0.13	0.34	0.08	0.18	0.08	0.18	0.07	0.17
R&D collaboration international	89,518	0.09	0.29	0.05	0.13	0.04	0.12	0.03	0.12
Age	64,192	18.32	10.80	17.48	9.81	17.79	9.69	17.84	10.09
Employment	89,505	4.09	1.52	4.06	1.50	4.02	1.45	4.02	1.48
Training	89,505	0.37	0.48	0.47	0.50	0.46	0.49	0.43	0.49
Organizational innovation internal	89,518	0.24	0.43	0.25	0.43	0.24	0.43	0.23	0.42
Organizational innovation external	67,951	0.19	0.39	0.27	0.44	0.27	0.43	0.25	0.43
Process innovation	68,162	0.17	0.36	0.27	0.40	0.26	0.44	0.23	0.41
R&D expenditure	67,753	1.47	2.27	1.32	2.17	1.35	2.14	1.27	2.09
Patents	67,753	0.11	0.31	0.23	0.43	0.22	0.41	0.19	0.39
Scientist	66,559	6.79	16.26	7.18	16.81	7.10	16.65	6.94	16.56
Exporter	89,518	0.30	0.46	0.38	0.48	0.38	0.48	0.37	0.49
Foreign	64,211	0.33	0.47	0.47	0.50	0.45	0.48	0.42	0.49
Survival	89,518	0.49	0.49	0.56	0.50	0.56	0.49	0.58	0.49
Reporting unit	64,192	1.33	2.49	1.44	2.55	1.46	2.75	1.42	2.65
Variables used to create incoming knowledge spillover									
Associations	89,518	0.61	0.93	0.92	0.96	0.91	0.96	0.89	0.97
Standards	89,518	0.65	0.98	0.96	1.03	0.96	1.02	0.95	1.03
Conferences	89,518	0.58	0.91	0.89	0.97	0.89	0.97	0.86	0.97
Publications	89,518	0.50	0.82	0.80	0.90	0.80	0.89	0.77	0.90
Variables used to create R&D collaboration domestically and internationally									
Suppliers collaboration domestic	89,518	0.05	0.23	0.07	0.25	0.07	0.25	0.06	0.24
Customers collaboration domestic	89,518	0.07	0.26	0.08	0.28	0.08	0.27	0.08	0.26
Industry collaboration domestic	89,518	0.04	0.17	0.04	0.19	0.04	0.18	0.03	0.18
Suppliers collaboration international	89,518	0.04	0.19	0.05	0.22	0.05	0.21	0.03	0.19
Customers collaboration international	89,518	0.05	0.19	0.05	0.21	0.05	0.20	0.04	0.21
Industry collaboration international	89,518	0.02	0.12	0.03	0.15	0.02	0.12	0.02	0.12
Instruments used in first stage of IV Tobit estimation									
Incoming knowledge spillover industry	89,518	0.19	0.09	0.21	0.08	0.21	0.09	0.20	0.09

Table 4. (Continued)

Sample	Baseline sample (collected by the ONS) = 89,518 obs.			Innovative sales = 21,702 observations		Innovative sales = 19,043 observations (excluding London)		Product innovator [0,1] sample = 26,908 observations	
Variables		Mean	SD	Mean	SD	Mean	SD	Mean	SD
University knowledge spillover industry	89,518	0.22	0.16	0.19	0.14	0.19	0.14	0.18	0.17
R&D collaboration domestic industry	89,517	0.07	0.04	0.04	0.06	0.06	0.03	0.05	0.03
R&D collaboration international industry	89,518	0.03	0.03	0.08	0.02	0.02	0.03	0.03	0.02
Number of plants	89,518	0.93	0.95	0.95	0.92	0.93	0.90	0.92	0.91

BSD, Business Structure Database; UKIS, UK Innovation survey.

3.3. Method

We estimate the innovation production function using a random-effects Tobit model with a dependent variable y_i (innovation sales) and an endogenous variables φ_i (R&D collaborations and knowledge spillovers):

$$y_i = \beta_0 + \beta_i x_i + \omega_i \varphi_i + u_i \quad (1)$$

We can also call it structural equation to emphasize that we are interested in β_i and that the equation to be measured as causal. Variables x_i and φ_i are explanatory variables of firm's innovation, including R&D collaboration domestically and internationally and two types of knowledge spillovers – industry and university (Jaffe, 1989) and u_i is an error term. x_i is exogenous and not correlated with u_i, while φ_i is likely to be correlated with u_i (Wooldridge, 2009, p. 517).

4. Results

4.1. Main hypothesis results

We initiated by estimating the innovation production function via a random-effects Tobit model (specifications 1–6, Table 5) using the initial 'innovation sales' sample of 21,702 observations. Tobit estimation resolves issues with left-censored observations (firms with zero product innovation) by establishing censoring limits for all observations. Due to the panel element in the sample, we requested a likelihood-ratio test comparing the panel Tobit model with the alternative pooled Tobit model. To account for unobserved heterogeneity, we incorporated city region, industry, and time fixed effects control into the estimation, which spanned two-digit SIC industries (90), city regions (128), and survey waves (6). These fixed effects were suppressed to save space.

H1 is supported as the incoming knowledge spillovers bolster innovation output. The marginal effect of a one standard deviation change in the sourcing of basic knowledge via industry spillovers boosts innovation sales by 7.77 to 13.63 percentage points (β=7.77–13.63, p<0.01) (specifications 1–3, Table 5). Likewise, a one standard deviation change in sourcing basic knowledge from universities via spillovers augments innovation sales by 3.70 to 5.42 percentage points (β=3.70–5.42, p<0.01) (specifications 1–3, Table 5).

H2 is supported as both international and domestic R&D collaborations amplify innovation output. In economic terms, a one standard deviation increase in the sourcing of applied knowledge via domestic R&D collaboration enhances innovation sales by 16.20 to 16.37 percentage points (β=16.20–16.37, p<0.01) (specifications 3–4, Table 5). A one standard deviation increase in the sourcing of applied knowledge via international R&D collaboration escalates innovation sales by 4.05 percentage points (β=4.05, p<0.01) (specification 4, Table 5).

H3b is supported, suggesting that the relationship between R&D collaboration and knowledge spillovers for a firm's innovation is negative, and a trade-off between both types of knowledge is observable (Bernal et al., 2022). Our study indicates that the cost effect of knowledge sourcing outweighs the knowledge complementarity effect from combining applied and basic knowledge. A joint increase in incoming knowledge spillover and domestic R&D collaboration reduces innovation sales by 17.3 percentage points (β=11.02–28.32, p<0.01) (specification 6, Table 5) – the cost effect of knowledge. A joint effect of integrating basic knowledge spillover and applied knowledge from international R&D collaboration reduces innovation sales by 4.01 percentage points (β=11.02–15.03,

Table 5. Results of Tobit estimation for innovation for pooled sample (all firms). Dependent variable: Sales of new to market products % in total sales

Variables	(1) Tobit	(2) Tobit	(3) Tobit	(4) Tobit	(5) Tobit	(6) Tobit
Incoming knowledge spillover (H1)	13.63*** (1.20)	9.55*** (1.30)	7.77*** (1.30)	7.75*** (1.30)	12.84*** (1.50)	11.02*** (1.50)
University knowledge spillover (H1)		5.42*** (1.20)	3.70*** (1.20)	3.60*** (1.20)	4.15*** (1.20)	7.92*** (1.20)
R&D collaboration domestic (H2)			16.37*** (1.60)	16.20*** (1.60)	34.14*** (3.51)	34.19*** (3.50)
R&D collaboration international (H2)				4.05*** (1.20)	17.47*** (5.10)	19.25*** (5.10)
Incoming basic knowledge spillover × R&D collaboration domestic (H3)					−36.29*** (6.40)	−28.32*** (7.10)
University basic knowledge spillover × R&D collaboration domestic (H3)					−20.35*** (8.40)	−11.76*** (9.30)
Incoming basic knowledge spillover × R&D collaboration international (H3)						−15.03*** (5.60)
University basic knowledge spillover × R&D collaboration international (H3)						−13.49** (6.00)
Age	−0.54*** (0.13)	−0.62*** (0.13)	−0.57*** (0.13)	−0.57*** (0.14)	−0.55*** (0.14)	−0.54*** (0.13)
Age squared	0.01*** (0.00)	0.01*** (0.00)	0.01*** (0.00)	0.01*** (0.00)	0.01*** (0.00)	0.01*** (0.00)
Employment	−3.18*** (0.25)	−3.06*** (0.25)	−3.10*** (0.25)	−3.12*** (0.24)	−3.11*** (0.25)	−3.11*** (0.25)
Training	7.74*** (0.66)	6.70*** (0.66)	6.45*** (0.64)	6.40*** (0.64)	6.09*** (0.64)	6.04*** (0.64)
Organizational innovation internal	4.36*** (0.70)	4.36*** (0.70)	4.34*** (0.70)	4.03*** (0.60)	3.89*** (0.60)	3.04*** (0.55)
Organizational innovation external	3.87*** (0.71)	3.43*** (0.71)	3.12*** (0.71)	3.06*** (0.68)	3.04*** (0.66)	3.04*** (0.66)
Process innovation	11.21*** (0.65)	10.78*** (0.65)	9.62*** (0.65)	9.63*** (0.64)	9.44*** (0.64)	9.39*** (0.64)
R&D expenditure	4.07*** (0.15)	3.92*** (0.15)	3.68*** (0.15)	3.64*** (0.15)	3.64*** (0.15)	3.65*** (0.14)
Patents	6.88*** (0.69)	6.42*** (0.69)	7.09*** (0.69)	6.88*** (0.69)	6.90*** (0.65)	6.85*** (0.65)
Scientist	0.12*** (0.01)	0.11*** (0.01)	0.11*** (0.01)	0.10*** (0.01)	0.11*** (0.01)	0.11*** (0.01)
Exporter	8.33*** (0.66)	7.96*** (0.65)	7.64*** (0.65)	7.36*** (0.65)	7.34*** (0.65)	7.28*** (0.66)
Foreign	−3.01*** (0.71)	−3.42*** (0.70)	−3.41*** (0.70)	−3.22*** (0.70)	−3.19*** (0.70)	−3.18*** (0.70)
Survival	0.29 (0.47)	0.21 (0.49)	0.09 (0.47)	0.50 (0.48)	0.50 (0.48)	0.47 (0.46)
Reporting units	0.04 (0.08)	0.03 (0.07)	0.01 (0.07)	0.04 (0.06)	0.03 (0.06)	0.04 (0.06)
Industry, year, and city region fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

(Continues)

Table 5. (Continued)

Variables	(1) Tobit	(2) Tobit	(3) Tobit	(4) Tobit	(5) Tobit	(6) Tobit
Constant	−34.01** (1.40)	−30.88** (1.40)	−30.96** (1.40)	−31.19** (1.40)	−31.28** (1.50)	−31.25** (1.40)
N	21,702	21,702	21,702	21,702	21,702	21,702
Left censored	15,260	15,260	15,260	15,260	15,260	15,260
Log-likelihood	−28,352.91	−27,733.47	−27,639.11	−27,432.05	−27,603.28	−27,599.38
LR test of sigma $u=0$:	0.081	0.087	0.094	0.112	0.119	0.122

Reference category for legal status is company (limited liability company), industry (mining), region (North East of England) instead of industry dummies in this estimation employment (in logs is used). Robust standard errors are in parenthesis. The coefficients of the Tobit and Probit regressions are the marginal effect of the independent variable on the probability of knowledge spillover, R&D collaboration, ceteris paribus. For dummy variables, it is the effect of a discrete change from 0 to 1.
BSD, Business Structure Database; UKIS, UK Innovation survey.
**$p<0.01$; ***$p<0.001$.

$p<0.01$) (specification 6, Table 5), supporting H3b. Intriguingly, firms that supplement basic knowledge with international applied knowledge from customers, suppliers, and competitors are able to minimize the size of the negative effect in reducing innovation, potentially due to a greater positive complementarity of knowledge effect. This finding extends the work of Holloway and Parmigiani (2016) and Bernal et al. (2022) on how access to incoming knowledge spillovers from a specific type of partner may determine firms' likeliness to collaborate with a specific type of partner.

H3b is also supported when combining university knowledge spillover and R&D collaboration with domestic partners. An increase in one standard deviation of university knowledge spillover and domestic R&D collaboration reduces innovation sales by 3.84 percentage points (β=7.92–11.76, $p<0.01$) (specification 6, Table 5) – the cost effect of knowledge. Similarly, an increase in one standard deviation of university knowledge spillover and international R&D collaboration reduces innovation sales by 5.57 percentage points (β=7.92–13.49, $p<0.01$) (specification 6, Table 5). Although the reduction in innovation input is smaller if R&D collaboration is combined with basic knowledge from universities rather than basic knowledge from patents, conferences, and industrial associations, suggesting the significance of a specific type of partner (Holloway and Parmigiani, 2016). It might be the case that universities bear greater responsibility and cost of innovation development and R&D costs, we find that the cost effect of knowledge combination still prevails over positive knowledge complementarity effect for innovation. The interaction and cumulative coefficients result negative; however, the degree of innovation reduction varies between the type of knowledge spillover and between domestic and international R&D collaboration.

4.2. Endogeneity bias

In order to analyze the relationship between R&D collaboration, spillovers, and innovation performance, we need to eliminate or at least control for endogeneity bias, so we know that the main findings holds. The procedure is known as the two-step instrumental variable (IV) estimation. (Wooldridge, 2009).

4.2.1. First stage estimation

In the first stage, we instrument φ_i – knowledge spillovers and R&D collaboration, using two exclusion restrictions (exogenous variables) assuming that ϱ_1 (industry level of knowledge spillovers) or R&D collaboration (by three-digit SIC), excluding firm's own collaboration that does not appear in (1) and are uncorrelated with the error u_i. In the reduced form of equation φ_i is estimated as:

$$\varphi_i = \pi_0 + \beta_i x_i + \pi_1 \varrho_1 + v_i \tag{2}$$

where $E(v_i) = 0, cov(\varrho_1, v_i) = 0, c$. For this IV not to be perfectly correlated with ϱ_1, we need $\pi_1 \neq 0$. The identification requires that $\pi_1 \neq 0$ (Wooldridge, 2009, p. 523).

We used four multivariate mixed effects models to predict the extent of knowledge spillover from industry and university as well as R&D collaboration (vertical and horizontal) domestically and internationally ($\widehat{\varphi}_i$). In addition to ϱ_1 which is our exclusion restriction, other explanatory exogenous variables x_i are included such as measure of firm age (log of age), firm size (log of employment and log of turnover), number of plants (units), firm ownership, as well as a set of time and legal status fixed effects. Regional dummies were not used, because our dependent variable φ_i in model (2) is domestic R&D collaboration, which is a linear combination of city region fixed effects. The results of the first stage IV estimation are reported in Table A1 in the Appendix, including the post-estimation test which supported the significance of chosen instruments.

4.2.2. Second stage estimation

Once the predicted values of knowledge spillovers and R&D collaboration were obtained, we moved to the second stage of estimation of Equation (1) using predicted values in the first stage of potentially endogenous variables $\hat{\varphi}_i$. Table 6 (specifications 3–4) reports the second-stage IV Tobit estimation results with $\hat{\varphi}_i$ and x_i as explanatory variables. Having estimated (1), we save u_i to provide the evidence of the second condition for IV to hold: ϱ_1 is uncorrelated with u_i corr $(\varrho_i, u_i) = 0$, any linear combination is also uncorrelated with u_i (Wooldridge, 2009). We estimate Equation (3), where the dependent variable is u_i from Equation (1) regressed on the chosen instrument (ϱ_1):

$$u_i = \beta_0 + \beta_i z_i + \rho_1 \varrho_1 + \epsilon_i \tag{3}$$

where u_i is error from Equation (1). Variables z_i are control variables such as regional, year, and industry three-digit SIC fixed effects, firm ownership status variable, and ϵ_i is an error term. Coefficients ρ_1 were not statistically significant and we conclude that corr $(\varrho_i, u_i) = 0$, thus ρ_1 is valid instrument for each type of knowledge spillover and R&D collaboration (φ_i). Our results overwhelmingly confirm H1 on both types of knowledge spillovers facilitate innovation outputs. The t test on the difference in two coefficients does not reject the null on no differences in the mean of the coefficients. This means that incoming knowledge spillover and knowledge spillover from university both facilitate innovation and the size of the effect is not different (specifications 3–4, Table 6). Our H2 is partly supported as we find that R&D collaboration domestically has a positive effect on innovation output, while the effect of R&D collaboration with international partners is insignificant. Our H3b is supported demonstrating the joint negative effect of knowledge spillovers and R&D collaboration internationally and domestically on innovation output. The negative signs of the interaction coefficients and the cumulative coefficient mean that an increase in cost of R&D collaboration and access to knowledge spillovers supporting Bernal et al. (2022) and will push managers to choose between the two.

5. Further robustness checks

5.1. Excluding enterprise group firms and firms in Greater London

We utilize Table 6 (specifications 1–2 and 5–6) for further robustness checks. Initially, we question if our hypotheses hold upon excluding 2,659 observations of firms located in the Greater London area. These firms are most likely to have direct access to international knowledge and innovation. This adjustment reduces our sample of innovators to 19,043 observations.

Our principal finding confirms Hypothesis 1 (H1), where two types of knowledge spillovers have significant statistical influence on innovation output. Hypothesis 2 (H2) receives partial support, with firms engaged in domestic R&D collaboration innovating more than those involved in international R&D collaboration, expanding upon Un et al.'s (2010) findings on R&D collaboration heterogeneity. Hypothesis 3b (H3b), stating that the relationship between R&D collaboration and knowledge spillovers for firm's innovation turns negative if the cost effect (Williamson, 1979) surpasses the knowledge complementarity effect (Hagedoorn, 1993; Belitski, 2019), is supported for incoming knowledge spillover and both types of R&D collaboration. This also applies to university knowledge spillover and R&D collaboration with international partners. This discovery theoretically furthers Bernal et al. (2022) argument, demonstrating specific combinations of knowledge spillover and collaboration that are most or least affected. For instance, coupling university knowledge spillover and domestic R&D collaboration diminishes the cost of knowledge sourcing, with the positive complementarity effect offsetting costs related to engagement in collaboration and spillovers. Our final question probes whether all enterprise units achieve equal benefits from knowledge spillovers and R&D collaboration. This is not a simple yes or no answer. To mitigate potential bias, we excluded all firms with more than one local unit/subsidiary from our sample of 21,702 observations, resulting in a final sample size of 18,434. Our findings uphold H1, as both types of knowledge spillovers enhance innovation outputs. H2 is partly supported as international R&D collaboration does not seem to correlate with innovation outcomes for standalone firms or those outside London. We conclude

Table 6. Results of random-effect Tobit estimation for innovation sales (all firms). Dependent variables: Innovation = % of new to market products (0–100)

Specification	(1)	(2)	(3)	(4)	(5)	(6)
Estimation	Tobit	Tobit	IV Tobit	IV Tobit	Tobit	Tobit
Sample	Innovative sales for firms outside Greater London		Innovative sales resolving endogeneity bias		Innovative sales for firms without subsidiaries	
Incoming knowledge spillover (H1)	6.68*** (1.32)	10.12*** (1.51)	8.16*** (3.61)	12.73 (6.98)	6.64*** (1.46)	10.71*** (1.67)
University knowledge spillover (H1)	3.41*** (1.18)	7.60*** (1.44)	2.11*** (0.87)	4.86** (2.17)	4.50*** (1.32)	7.68*** (1.61)
R&D collaboration domestic (H2)	17.31*** (1.59)	33.54*** (3.45)	17.45*** (11.25)	54.36*** (10.00)	20.62*** (1.80)	38.23*** (3.69)
R&D collaboration international (H2)	1.98 (2.08)	19.97** (4.92)	7.55 (5.32)	20.55 (16.82)	2.68 (2.42)	20.53** (5.80)
Incoming basic knowledge spillover × R&D collaboration domestic (H3)		−27.10*** (7.01)		−51.85*** (15.41)		−32.35*** (7.75)
University basic knowledge spillover × R&D collaboration domestic (H3)		−13.11 (9.06)		−12.12 (8.56)		−15.59 (10.25)
Incoming basic knowledge spillover × R&D collaboration international (H3)		−11.30** (5.52)		−41.12*** (13.02)		−7.64 (6.25)
University basic knowledge spillover × R&D collaboration international (H3)		−18.60*** (6.69)		−46.55*** (11.45)		−14.29** (6.11)
Age	−0.63*** (0.12)	−0.60*** (0.12)	−0.53*** (0.15)	−0.56*** (0.15)	−0.68*** (0.13)	−0.66*** (0.13)
Age squared	0.01*** (0.00)	0.01*** (0.00)	0.01*** (0.00)	0.01*** (0.00)	0.01*** (0.00)	0.01*** (0.00)
Employment	−3.34*** (0.25)	−3.36*** (0.25)	−3.28*** (0.32)	−3.21*** (0.32)	−3.69*** (0.30)	−3.71*** (0.30)
Training	5.85*** (0.64)	5.46*** (0.65)	8.83*** (0.76)	8.69*** (0.76)	5.57*** (0.71)	5.37*** (0.71)
Organizational innovation internal	4.09*** (0.68)	3.96*** (0.68)	4.20*** (0.82)	4.08*** (0.80)	4.47*** (0.77)	4.35*** (0.77)
Organizational innovation external	3.35*** (0.69)	3.23*** (0.69)	4.21*** (0.83)	4.11*** (0.83)	3.87*** (0.78)	3.71*** (0.78)
Process innovation	9.59*** (0.63)	9.36*** (0.63)	10.47*** (0.76)	10.32*** (0.76)	9.33*** (0.71)	9.15*** (0.71)
R&D expenditure	3.90*** (0.15)	3.85*** (0.15)	3.78*** (0.18)	3.75*** (0.18)	4.38*** (0.17)	4.34*** (0.17)
Patents	6.11*** (0.68)	5.88*** (0.68)	9.31*** (0.83)	9.40*** (0.83)	7.21*** (0.77)	6.95*** (0.75)
Scientist	0.11*** (0.01)	0.11*** (0.01)	0.12*** (0.01)	0.13*** (0.01)	0.10*** (0.01)	0.10*** (0.01)
Exporter	7.63*** (0.65)	7.20*** (0.65)	6.72*** (0.81)	5.86*** (0.79)	7.83*** (0.72)	7.40*** (0.70)
Foreign	−2.87*** (0.70)	−2.97*** (0.70)	−1.54*** (0.88)	−1.87*** (0.89)		
Survival	0.67 (0.60)	0.63 (0.61)	0.13 (0.73)	0.24 (0.73)	0.96 (0.68)	0.92 (0.67)
Reporting units	0.01 (0.05)	0.01 (0.05)	−0.06 (0.11)	−0.04 (0.11)	–	–

(Continues)

Table 6. (Continued)

Specification	(1)	(2)	(3)	(4)	(5)	(6)
Industry, year, and city region fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Constant	−26.29*** (1.41)	−27.88*** (1.42)	−29.16*** (1.96)	−33.56*** (2.64)	−28.29*** (1.56)	−29.55*** (1.59)
N	19,043	19,043	21,702	21,702	18,434	18,434
Left censored	13,898	13,898	15,260	15,260	13,595	13,595
Log-likelihood	−27,447.88	−27,347.02	−18,015	−17,999	−24,624.18	−24,587.02
LR (chi^2)	5,397.12	5,497.87	4,027.12	4,059.05	4,971.02	5,044.57

Reference category for legal status is company (limited liability company), industry (mining), region (North East of England) instead of industry dummies in this estimation employment (in logs is used). Robust standard errors are in parenthesis. The coefficients of the Tobit and Probit regressions are the marginal effect of the independent variable on the probability of knowledge spillover, R&D collaboration, ceteris paribus. For dummy variables, it is the effect of a discrete change from 0 to 1.
BSD, Business Structure Database; UKIS, UK Innovation survey.
**$p<0.01$; ***$p<0.001$.

that international R&D collaboration primarily benefits firms within the Greater London area, where market internationalization is higher, as well as foreign firms or those with multiple subsidiaries, due to their likely involvement in exports and knowledge transfers with various partners, particularly abroad. Our findings also validate H3b, suggesting that knowledge spillover and R&D collaboration serve as substitutes due to the high costs associated with both activities (specifications 5–6, Table 5). Interestingly, certain combinations of basic and applied knowledge may promote innovation output when embedded in local collaborations or complemented by international partnerships. The picture becomes significantly more nuanced once we account for enterprise group and location in Greater London (specifications 5–6, Table 5).

5.2. *Understanding the propensity to innovate*

In our final robustness check, we test Hypotheses 1–3 (H1–H3) using a sample of product innovators. Here, a product innovator is defined as a binary variable that equals one if a firm has innovated new products and services over the past 3 years, and zero otherwise. This robustness check enables us to expand the available sample to 26,908 observations (refer to Table 7). We estimate function (1) using a probit regression, where the dependent variable of innovative sales is replaced with the binary variable of a product innovator.

Our findings affirm H1, suggesting that firms accessing knowledge spillovers will bolster their innovation output. In economic terms, this indicates that an increase in incoming knowledge spillover by one standard deviation boosts the propensity to innovate new products and services by 1.97 to 2.02 times ($\beta = 1.97–2.02$, $p < 0.01$) (specifications 1–3, Table 7). Moreover, an elevation in university knowledge spillover by one standard deviation enhances the propensity to innovate new products and services by 2 to 21 percentage points ($\beta = 1.02–1.21$, $p < 0.01$) (specifications 1–3, Table 7). Hypothesis 2 (H2) is supported, as we observe that firms collaborating with external partners on R&D, both domestically and internationally, are more likely to innovate new products and services than firms which do not. In economic terms, a one standard deviation increase in domestic R&D collaboration escalates the propensity to innovate between 6 and 8 times ($\beta = 6.33–8.69$, $p < 0.01$) (specifications 1–3, Table 7). Additionally, a one standard deviation increase in international R&D collaboration augments the propensity to innovate between 1.5 and 5.3 times ($\beta = 1.51–5.38$, $p < 0.01$) (specifications 1–3, Table 7).

We support Hypothesis 3b (H3b) as we found that the complementarity effect holds for incoming knowledge spillover and domestic R&D collaboration ($\beta = 0.14$, $p < 0.01$), university spillover and domestic R&D collaboration ($\beta = 0.41$, $p < 0.01$), and university knowledge spillover and international R&D collaboration ($\beta = 1.15$, $p < 0.01$).

6. Discussion

This study enriches R&D management and knowledge spillovers literature, and builds upon the recent contributions of Bernal et al. (2022), explaining how incoming knowledge spillovers can either amplify or constrain R&D collaboration and its impact on

Table 7. Results of Probit models for product innovation in pooled sample (all firms). Dependent variable – Product innovator. Results are ported in odd ratios

	(1)	(2)	(3)
Specification method	Logit	Logit	Logit
Incoming knowledge spillover (H1)	2.02*** (0.14)	1.74*** (0.12)	1.97*** (0.15)
University knowledge spillover (H1)	1.11*** (0.07)	1.02*** (0.07)	1.21*** (0.07)
R&D collaboration domestic (H2)		6.33*** (0.64)	8.69*** (2.70)
R&D collaboration international (H2)		1.51*** (0.25)	5.38*** (1.91)
Incoming basic knowledge spillover × R&D collaboration domestic (H3)			0.14*** (0.06)
University basic knowledge spillover × R&D collaboration domestic (H3)			0.41** (0.15)
Incoming basic knowledge spillover × R&D collaboration international (H3)			0.47 (0.23)
University basic knowledge spillover × R&D collaboration international (H3)			0.15*** (0.07)
Age	0.97*** (0.01)	0.97*** (0.01)	0.97*** (0.01)
Age squared	1.00*** (0.01)	1.00*** (0.01)	1.00*** (0.01)
Employment	0.89*** (0.03)	0.88*** (0.03)	0.88*** (0.03)
Training	1.72*** (0.05)	1.67*** (0.05)	1.65*** (0.05)
Organizational innovation internal	1.67*** (0.03)	1.61*** (0.03)	1.59*** (0.03)
Organizational innovation external	1.30*** (0.04)	1.24*** (0.04)	1.24*** (0.04)
Process innovation	3.71*** (0.13)	3.78*** (0.12)	3.77*** (0.12)
R&D expenditure	1.34*** (0.02)	1.32*** (0.02)	1.31*** (0.02)
Patents	1.26*** (0.04)	1.36*** (0.04)	1.36*** (0.04)
Scientist	1.00 (0.04)	1.00 (0.04)	1.00 (0.04)
Exporter	1.65*** (0.05)	1.63*** (0.05)	1.60*** (0.04)
Foreign	0.90*** (0.04)	0.92*** (0.04)	0.92*** (0.04)
Survival	1.16** (0.05)	1.15** (0.05)	1.14** (0.05)
Reporting units	1.00 (0.04)	1.00 (0.04)	1.00 (0.04)
Industry, year and city-region fixed effects	Yes	Yes	Yes
Number of obs.	26,908	26,908	26,908
Log-likelihood	−13,425.88	−13,196.02	−13,142.82
Chi^2	9,532.62	9,985.97	10,093.16
Pseudo R^2	0.26	0.27	0.27

Reference category for legal status is COMPANY (limited liability company), industry (mining), region (North East of England). Robust standard errors are in parenthesis.
BSD, Business Structure Database; UKIS, UK Innovation survey.
$^{**}p<0.01$; $^{***}p<0.001$.

performance. By theoretically exploring the mechanisms of R&D collaboration and knowledge spillovers for innovation, our goal is to further distinct the complementary and substitutive effects, with a focus on the types of knowledge involved – basic versus applied – and the geographical scope of collaboration, whether domestic or international. Our findings support the positive and significant effects of both domestic and international R&D collaboration, as well as knowledge spillovers from external open sources and universities on innovation, thereby extending the analysis of Bernal et al. (2022) through an examination of the interplay among various external sources of knowledge for innovation.

The incorporation of new data sources and critical measures of basic and applied knowledge has provided unprecedented insights into the innovation process, challenging the conclusions of seminal studies by Jaffe (1989), Acs et al. (1992), Bloom et al. (2013), and more recent works by Koch and Simmler (2020) and Bernal et al. (2022) regarding the roles of knowledge spillovers and R&D collaboration.

6.1. Theoretical implications

In our study, we build on prior research indicating that geographic proximity increases the likelihood of collaborations, potentially due to face-to-face interactions (Rybnicek and Königsgruber, 2019; Koch and Simmler, 2020). We explore the role of digital technologies in facilitating knowledge transfer beyond regional boundaries and examine how geographic proximity between a firm and its external partners influences innovation performance for both basic and applied knowledge. In doing so, we contribute to the knowledge spillover theory (Jaffe, 1989; Bloom et al., 2013; Audretsch et al., 2021), reinforcing the complex relationship between types of R&D collaboration, knowledge spillovers, and innovation (Bernal et al., 2022), and by connecting it with evolutionary economic geography (Boschma, 2005).

Our study demonstrates that the impact of basic knowledge from universities, through spillovers, can be enhanced when firms are located near competitors, customers, and suppliers, thereby learning from them and integrating this knowledge with the basic knowledge obtained through spillovers (Faulconbridge, 2007). This study explicitly assumes that R&D collaboration and knowledge spillovers can be facilitated using digital technologies, both domestically and internationally.

6.2. Managerial implications

We demonstrate that both basic and applied knowledge enhance a firm's propensity for innovation and facilitate access to knowledge, both locally and from a distance. We found that firms must decide whether to utilize both types of knowledge (basic and applied), thereby enhancing the complementary effect, or to make a distinct choice between knowledge spillovers and R&D collaboration, considering the cost implications of knowledge transfer. This decision is influenced by the firm's specific needs, its stage of development, and the availability of resources. Both types of knowledge are shown to increase firms' propensity to innovate.

Firms are confronted with both complementary and cost effects of knowledge sourcing for innovation (Williamson, 1979). Certain combinations of spillovers and R&D collaboration may be particularly advantageous, either reducing or enhancing the returns on basic and applied knowledge. For example, firms that acquire knowledge through university spillovers while also engaging in domestic R&D collaboration experience a lower cost effect of knowledge collaboration and they are more likely to secure equity funding (Audretsch et al., 2024). It appears that collaborating on R&D with customers, suppliers, and competitors nationally, where applied knowledge is sourced alongside university spillovers, serves as a conduit for innovation.

The cost effect, leading to substitution, is likely to predominate in the combined effect of knowledge spillovers and R&D collaboration, except in cases where university knowledge spillovers are combined with firm R&D. In these instances, the substitution effect dissipates with regard to a firm's propensity to innovate. Interestingly, we also observed nonsignificant results, indicating that the cost of collaboration was offset by a complementarity effect, for innovation in general. These results remained robust when controlling for firms located outside London, firms without subsidiaries, and potential endogeneity bias.

6.3. Future research and limitations

The choice firms make between knowledge spillovers and R&D collaboration, in addition to the cost effect, could also be constrained by factors such as knowledge appropriability, intellectual property, intangible assets, and trust issues among others (Hussinki et al., 2017). In industries and regions where knowledge spillovers are high, it becomes challenging for firms involved in R&D collaboration to increase the intensity of interactions and learning. Furthermore, potential reverse knowledge spillovers or undesirable information leakage pose an issue in collaboration (Bernal et al., 2022). This may diminish a firm's innovation efforts and discourage R&D collaboration (Cassiman and Veugelers, 2002; Frishammar et al., 2015). Future research will incorporate the appropriability and strategic innovation protection elements and will seek to unpack the reasoning and complexity behind a manager's choice between different types of knowledge transfer.

Due to the anonymous nature of the UK Innovation survey, no additional information on external partners could be added to the database to examine the quality, breadth, and intensity of collaborations, as well as the extent of collaboration with each partner. Subsequent studies may utilize individual (manager) data to demonstrate whether the cost effect could be mitigated by increasing managerial capacity (Helfat and Martin, 2015; Cassiman and Valentini, 2016).

Future research will also differentiate the motives, persistence, and duration of collaborations across different types of partners (suppliers, customers, competitors). An effort will be made to select longitudinal data on R&D collaboration and knowledge spillovers over time and during periods of economic growth and shocks. This will help to examine how these effects change (Di Minin et al., 2021).

7. Conclusion

Acknowledging the importance of both internal and external knowledge investments for innovation, this study highlights the critical role of externally sourced knowledge, including both basic and applied types, for highly innovative firms. This knowledge, often crucial for product development, can be accessed through knowledge spillovers and R&D collaboration. We argue and empirically demonstrate that investments in R&D collaboration and access to knowledge spillovers are essential for fostering innovation. However, there is a cost associated with knowledge transfer, both through spillovers and R&D collaboration. This underscores how firms might recombine different types of spillovers and R&D collaboration partners to maximize their innovation potential.

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Data availability statement

Data associated with the article were collected from the authors. They are provided if requested.

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APPENDIX

Table A1. Results of the first stage regression used for constructing the predicted values of knowledge spillovers and R&D collaboration

Dependent variable	Incoming knowledge spillover	University knowledge spillover	R&D collaboration domestic	R&D collaboration international
Model	(1)	(2)	(3)	(4)
Incoming knowledge spillover industry	0. 97*** (0.03)			
University knowledge spillover industry		1.02*** (0.03)		
R&D collaboration domestic industry			0.93*** (0.04)	
R&D collaboration international industry				0.88*** (0.04)
Number of plants	−0.01*** (0.00)	−0.01*** (0.00)	−0.01*** (0.00)	−0.01*** (0.00)
Age (in logs)	−0.008** (0.00)	−0.008** (0.00)	−0.008** (0.00)	−0.008** (0.00)
Employment (in logs)	0.02*** (0.00)	0.02*** (0.00)	0.01*** (0.00)	0.01*** (0.00)
Turnover (in logs)	0.006*** (0.00)	0.006*** (0.00)	0.003*** (0.00)	0.002*** (0.00)
Foreign	0.02** (0.00)	0.01** (0.00)	0.01** (0.00)	0.01** (0.00)
Year and firm legal status fixed effects	Yes	Yes	Yes	Yes
Constant	−0.10*** (0.03)	−0.08*** (0.03)	−0.01*** (0.00)	−0.03*** (0.01)
No. of obs.	21,702	21,702	21,702	21,702
F-stat	325.01	393.25	75.69	65.87
Log-likelihood	−375.03	−1,432.77	−1,420.40	−2,687.50

Reference category for legal status is company (limited liability company) year (2002). Robust standard errors are in parenthesis. The coefficients of the regressions demonstrate the marginal effect of the industry instruments on knowledge spillovers and R&D collaboration. For dummy variables, it is the effect of a discrete change from 0 to 1.
BSD, Business Structure Database; UKIS, UK Innovation survey.
$^{**}p<0.01$; $^{***}p<0.001$.

