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The more, the merrier or the less is more? The role of firm capabilities and industry in the knowledge spillover of innovation

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A R T I C L E I N F O

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A B S T R A C T

This study advances our understanding of the complementary and substitute relationships between investment in firm capabilities and two types of knowledge spillovers. We use three matched databases of 15,259 most innovative firms in the United Kingdom (UK) during 2002–2014 to demonstrate the joint effect of knowledge spillovers within and between industries and firm capabilities on firm innovation. This study furthers our understanding in three significant ways. First, it supports the dual nature of the R&D story. Secondly, it demonstrates that the relationship between knowledge spillovers and firm innovation is nuanced and depends on the extent to which a firm decides to invest in internal R&D, leading to either a substitution or complementarity effect between R&D and a type of knowledge spillover. Thirdly, the relationship may be different across industries. While all industries benefit from investment in internal R&D and spillovers, the creative industry does not experience the substitution effect, and knowledge-intensive business services exhibit both substitution and complementarity effects, which are accelerated by internal investment in R&D.

1. Introduction

Investigating the effect of firm capabilities (Zahra and George, 2002; Zahra et al., 2006) and localized knowledge spillovers within and between industries (Audretsch and Feldman, 1996; Audretsch and Belitski, 2022) on firm innovation with a high degree of novelty (new to the market) is highly relevant for the following reasons: First, firm capabilities determine its capacity to absorb external knowledge and innovate new products and services (Goel, 2023; Laursen and Salter, 2014; Belitski et al., 2024). Second, while the literature extensively covers knowledge spillovers and firm capabilities independently (Gesing et al., 2015), the interplay among these elements, especially across various sectors, remains underexplored and unknown (Tsai, 2009; Vanhaverbeke et al., 2014; Kobarg et al., 2019).

The extant literature may have asked the wrong question— is it localized intra-industry or, alternatively, inter-industry knowledge spillover that matters for firm innovation performance (Enkel and Heil, 2014; Hall et al., 2013; Caragliu et al., 2016), and does access to knowledge spillover should (not) be induced by an increased investment in firm R&D? (Audretsch and Belitski, 2022). While the answer to these questions has been overwhelmingly positive (Caragliu et al., 2016; Audretsch et al., 2024), the dichotomous nature of the questions may mask a more nuanced relationship. Perhaps the more relevant and compelling research question is not which one but rather to what extent the investment in firm capabilities is conducive for regional localization of intra- and inter-industry knowledge spillovers in shaping firm's radical innovation.

To address this research gap, we aim to explore how intra-industry and inter-industry knowledge spillovers interact with a firm's internal capabilities to influence new to market innovation across different industries, extending prior research on the interplay between internal and external knowledge for firm's radical innovation (Gesing et al., 2015; Battke et al., 2016; Audretsch and Belitski, 2022) and potential intra- and inter-industry differences (Liang and Goetz, 2018; Karlsson et al.,

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2021; Grashof, 2021).

A number of different mechanisms and boundary conditions under which intra-industry and inter-industry spillovers are most beneficial or detrimental to firm innovation should be explained, including the substitution and complementary effects between a firm's own R&D investment and knowledge spillovers (Nooteboom et al., 2007; Cassiman and Valentini, 2016; Denicolai et al., 2014, 2016).

Controlling for a set of firm level characteristics, including persistence of innovation, knowledge collaboration across different regions and types of collaboration partner, as well as regional characteristics where firms are located, including regional labor markets, human capital and institutions, we estimated an unbalanced Tobit panel data regressions using the micro-level data of 15,259 most innovative firms in the UK, which corresponds to 19,220 firm-year observations during 2002–2014.

We find that a firm's ability to assimilate and exploit knowledge is critical for leveraging localized knowledge spillovers. Firm capabilities, proxied by investment in internal R&D, might be substituted for intra-industry spillovers for firm innovation, if R&D intensity is above industry average. We also find that firm capabilities are complementary to inter-industry spillovers for firm innovation when R&D intensity is above industry average (Chen et al., 2016), extending the argument on "the less is more or the more is less" (Claussen et al., 2015; Gesing et al., 2015; Kobarg et al., 2019). Firms will require a substantial investment in internal capabilities to access and absorb inter-industry spillovers, while they may increase innovation performance in regions with greater localized intra-industry spillovers with minimal investment in internal R&D.

This study contributes to the knowledge transfer and innovation literatures (e.g. Roper et al., 2013, 2017; Cappelli et al., 2014; Caragliu et al., 2016) and absorptive capacity literature (Cohen and Levinthal, 1989, 1990; Hervas-Oliver et al., 2018; Audretsch and Belitski, 2020a) in two important ways. Firstly, by examining how and under what conditions internal R&D and concentration of regional knowledge within and between industries jointly shape firm innovation performance, furthering prior research (Feldman, 1999; Cassiman and Veugelers. 2002). Secondly, the paper extends prior evidence on knowledge spillover of innovation (Laursen and Salter, 2014; Audretsch and Belitski, 2022) across industries, by demonstrating how the joint effect of different types of knowledge spillovers and firm capabilities for innovation changes for knowledge intensive business services (KIBS), information and communication technologies (ICT), creative, manufacturing and the remaining industries.

Our overarching argument is that a firm's strategy on investment in developing internal capabilities should be directly related to the level and type of knowledge spillovers it can access and the industry in which the firm operates. Highlighting sector-specific dynamics, in the discussion we particularly focus on Knowledge-Intensive Business Services (KIBS) and creative industries, where the interaction between internal R&D and knowledge spillovers may differ significantly.

2. Conceptual framework and hypotheses

2.1. Firms' internal capabilities

Investment in R&D is important for innovation as it enables firms to access external knowledge and build capabilities (Teece et al., 1997; Eisenhardt and Martin, 2000). The creation of knowledge internally can significantly change the organizational and strategic routines by which firms achieve new resource configurations. This may involve recombining external and internal knowledge (Audretsch and Belitski, 2023a) in ways that "collide, split, evolve, and adapt" external knowledge (Eisenhardt and Martin, 2000: 1107).

Firm capabilities may follow different knowledge adoption paths, playing an important role in recognizing the value of external knowledge across various knowledge partners (Gesing et al., 2015) and applying this knowledge to organizational and strategic routines. One such capability is firms' absorptive capacity, which helps them benefit from available knowledge spillovers within and between industries. A firm's ability to recognize and implement knowledge spillovers largely depends on prior internal knowledge and capabilities (Zahra and George, 2002). Developing absorptive capacity means starting from a basic ability to understand and exchange information within the organization to increasing awareness of the most recent digitalization tools (Li et al., 2016; Bresnahan, 2019; Cumming et al., 2021).

Cohen and Levinthal (1990) argued that a range of capabilities improves a firm's absorptive capacity, thereby enhancing the firm's ability to exploit different types of knowledge for innovation (Griliches, 1979, 1992). Innovators place more emphasis on acquiring scientific and technical knowledge through direct investment in R&D (Belitski et al., 2024) and via R&D collaborations related to the firm's creation of new technologies, which increases the propensity to innovate new products and services (Un et al., 2010). Radical innovation, compared to incremental innovation, requires new and unfamiliar knowledge and thus relies on a larger pool of firm capabilities (Audretsch and Belitski, 2022).

Firm capabilities driven by investment in R&D and creative work are exceptionally useful and are utilized by firms when market uncertainty is high (Audretsch and Belitski, 2021a). They facilitate the absorption, adaptation, and further adoption and commercialization of knowledge for innovation (Abou-Foul et al., 2023) and serve as signals to external partners in collaboration on innovation.

2.2. Intra-industry knowledge spillovers and firm innovation

The long-standing theoretical tradition of viewing knowledge as an externality is encapsulated in the Marshall-Arrow-Romer (MAR) model (Marshall, 1890; Arrow, 1962; Romer, 1986), which emphasizes that knowledge is primarily industry-specific and that knowledge spillovers are facilitated by industry agglomeration. Marshall (1890) was the first to describe how proximity to other firms aids in recruiting employees and developing ideas. Geographic concentrations of R&D investment and interconnected companies, specialized suppliers, service providers, firms in related industries and clusters, and associated institutions create knowledge externalities (Porter, 1990, 1998). The role of knowledge externalities, mainly within agglomeration economies and spillovers for firms searching for external knowledge, and how actors harness these knowledge spillovers to transform and adopt them and develop new products and services was further explored in the earlier works of Acs and Audretsch (1988) and Acs et al. (1994).

Knowledge spillovers result from the non-excludability of knowledge and occur only if there is a specific channel of knowledge transfer has deep roots in much older theories on agglomeration, clusters, and seminal works by Arrow (1962), Griliches (1979, 1992) and Jaffe (1986, 1989). These foundational studies underscored the critical importance of R&D and geographical proximity between firms within one industry in driving economic growth and entrepreneurship through knowledge spillovers and innovation. Despite subsequent theoretical advancements and empirical investigations, significant gaps and tensions persist within the literature, calling for further research on the role of firm capabilities, spatial and technological proximity challenging shaping the scale and scope of knowledge spillover for innovation (Antonelli and Colombelli, 2017; Audretsch and Belitski, 2022). Intra-industry spillovers originate from the transfer of similar knowledge within a certain geographical location and industry, stimulating improvements in efficiency.

The effect of knowledge spillover on a firm's radical innovation may be greater for knowledge that comes from an industry with a similar knowledge base (Boschma and Frenken, 2010), often referred to as related variety. Boschma and Iammarino (2009), and later Neffke and Henning (2013), argued that knowledge would more efficiently spill over across related industries rather than industries that do not have complementarities or trade in intermediate products. In addition, knowledge spillovers can be inter-regional as they also arise from related industries located outside the focal region.

As Rigby and Brown (2015) and Delgado (2020) demonstrated, for firms to benefit from intra-industry spillovers, they usually need to be co-located within the industrial cluster. Knowledge spillovers embrace both industry and localization components.

Localized intra-industry spillovers are conduits for innovation due to potentially increased speed of knowledge transfer and implementation, a greater extent of cross-fertilization and integration, reconfiguration, and adaptation within the industry. This is due to the high familiarity and relatedness of within-industry knowledge to firm practices and routines. They increase a firm's ability to access competitors' tacit knowledge, which could never be appropriated by external firms within the industry.

Prior research also argues that high levels of cognitive and technological proximity in intra-industry spillovers may carry risks of unintended knowledge outflows (Cassiman and Veugelers, 2002, 2006). With an increase in the size of the intra-industry knowledge spillover, knowledge becomes common knowledge, which may potentially diminish its positive effect on a firm's radical innovation. We hypothesize:

H1a. An increase in intra-industry knowledge spillovers is positively associated with firm's innovation.

2.3. Intra-industry knowledge spillovers and firm capability

There is widespread agreement on the importance of investing in R&D to develop firms' internal capabilities and access external knowledge (Cohen and Levinthal, 1989, 1990) to sustain organizational evolution through innovation (Eisenhardt and Martin, 2000; Newey and Zahra, 2009). However, the joint effect of an increase in firm capabilities and access to knowledge spillovers has been less explored (Janssen et al., 2016; Audretsch et al., 2024). Only few studies have demonstrated that capabilities are directly related to a firm's ability to access and use knowledge spillovers (Kostopoulos et al., 2011; Battke et al., 2016; Denicolai et al., 2016). Firms with higher capabilities are more likely to effectively access and embed external knowledge into organizational routines, thereby boosting firm innovation.

Changes in the costs of knowledge transfer, innovation (Audretsch and Belitski, 2020b), and competition forces (Porter, 1990, 1998) may both facilitate and reduce investment in firm capabilities in industries and regions where knowledge spillovers are high (Audretsch et al., 2005, 2020). Thus, depending on the investment in firm capabilities and the type of localized knowledge spillover, spillovers and firm capabilities either complement or substitute each other in innovation (Cassiman and Valentini, 2016).

The potential substitution effect between firm capabilities and intra-industry spillover arises because both internal R&D and intra-industry knowledge spillover contribute to innovation sales as knowledge inputs, but they do so in a manner that can partially replace the need for one another.

Firstly, cost efficiency. Firms might reduce their own R&D intensity if they can effectively tap into the industry-wide knowledge base that is cognitively and technologically close. By utilizing intra-industry knowledge spillovers, firms can obtain ready-made solutions (Audretsch and Belitski, 2020a) and hence achieve innovation outcomes faster than through investment in R&D.

Secondly, resource allocation. Firms allocate resources more efficiently by balancing their own R&D efforts with the knowledge they can acquire from the industry (Denicolai et al., 2016). If intra-industry knowledge spillovers are robust and grow, and the level of cognitive and technological proximity of intra-industry spillovers with firm knowledge is high, firms might find it more cost-effective to lower R&D intensity and still maintain high innovation sales by sourcing knowledge via intra-industry spillovers (Audretsch and Belitski, 2023b).

Thirdly, signalling. The substitution effect between internal R&D and intra-industry spillover may signal that an increase in capabilities when knowledge becomes common within the industry (Hervas-Oliver et al., 2018) may reduce firms' incentives to invest in capabilities and creative works internally (Myles Shaver and Flyer, 2000). The overall returns to investment in internal R&D may drop due to knowledge leakage and involuntary knowledge transfer (Cassiman and Veugelers, 2002, 2006). This strategy might limit collaboration between firms within the sector and internalize firm capabilities if intra-industry spillovers are high (Audretsch and Belitski, 2020a, 2020b).

Finally, depending on the degree of novelty of the innovation, the level of knowledge required to successfully innovate is different. For example, In the case of incremental innovation (i.e. sales that are new to the firm) it is essential that there is a common knowledge base (the case of intra industry spillovers) to be more successful in knowledge collaborations and take advantage of internal capabilities (Chiang and Hung, 2010; Xu, 2015; Terjesen and Patel, 2017). In contrast, for radical innovation, the most appropriate type of knowledge must be more distant and heterogeneous (Narula and Zanfei, 2005; Phene et al., 2006), so there may be a substitution effect between intra-industry spillovers and firm capabilities. We hypothesize:

H1b. Firm's capabilities and intra-industry knowledge spillovers are substitutes for firm's innovation.

2.4. Inter-industry knowledge spillover and firm innovation

While prior research has demonstrated that firms benefit from horizontal and vertical knowledge spillovers for innovation (Basit and Medase, 2019), radical innovation, which involves developing new products for the industry (Laursen and Salter, 2006), compared to incremental innovation, requires new and unfamiliar knowledge (Neffke and Henning, 2013; Kneeland et al., 2020) and more distant technological collaborations. These collaborations allow for a larger breadth of knowledge and skills to be transferred (Audretsch and Belitski, 2024).

The overall context is one in which inter-industry knowledge (whether scientific or practical) is considered more important than intra-industry knowledge due to the effort required to access localized inter-industry knowledge and its novelty. Inter-industry knowledge is more likely to be strategic, whereas knowledge obtained within the industry can be strategic but can also be mundane.

Intra-industry knowledge spillovers allow innovators to explore new technological knowledge for discoveries and recombination. Unknown spillovers are a unique resource of untried technological information, offering greater opportunities for breakthrough discoveries because they unveil potential in new areas (Fleming, 2001, 2007). Although it is typically assumed that exploring unknown knowledge across industries may result in a higher failure and abandonment rate of innovation due to a lack of existing knowledge and skills in firms (Kneeland et al., 2020), such inter-industry knowledge spillover is also expected to yield more radical innovations (Cappelli et al., 2014). Some of these innovations will be exceptionally important, opening new fields of scientific opportunity and creating new directions for technological advancement.

Access to inter-industry knowledge is important for both short-term and long-term innovation strategy, as it enables firms to make significant leaps in achieving breakthrough discoveries and create new market opportunities in seemingly unknown industrial and geographical territories. Navigating through uncharted inter-industry knowledge to make breakthrough discoveries has been referred to as "long jumps" (Kauffman, 1993) and has sparked research on pioneering endeavors that can occur through systematic exploration or serendipitous events and knowledge from across industry domains (Levinthal, 1997).

Firms engage with partners across industries and clusters to explore inter-industry knowledge and interdisciplinary areas, enabling them to delve into the mechanisms that drive innovative thinking in other industries and approaches to the strategic exploration of new knowledge domains, including the emergence of new industries and new ways to appropriate knowledge (Fleming and Sorenson, 2001). Understanding how inter-industry spillover contributes to the exploration activity of firms can inform new interdisciplinary collaborations and strategies for unlocking the potential of uncharted technological spaces. We hypothesize:

H2a. An increase in inter-industry knowledge spillovers is positively associated with firm's innovation.

2.5. Inter-industry knowledge spillovers and firm capability

Firms located in regions with highly localized inter-industry knowledge spillovers are likely to experience a different relationship between firm capabilities and innovation compared to intra-industry spillovers.

A firm needs to be ready to invest further in internal capabilities and skills to understand highly distant cognitive and technological knowledge across industries (Nooteboom et al., 2007), and thus be able to acquire, assimilate, transform, and integrate diverse inter-industry knowledge into its organizational routines and practices (Eisenhardt and Martin, 2000; Denicolai et al., 2014, 2016).

In contrast, prior research has demonstrated that firms that do not invest in R&D, or do not invest in R&D that is compatible with their industry counterparts, may not be able to fully benefit from and appropriate technologically distant and highly diverse inter-industry knowledge (Griliches, 1979; Cohen and Levinthal, 1989). Thus, investment in firm capabilities is a key boundary condition for complementarity between inter-industry knowledge spillovers and firm capabilities for innovation (Claussen et al., 2015; Gesing et al., 2015). Here's how it works:

Firstly, both enhance innovation capabilities and reduce transaction costs, as firms that invest significantly in R&D are better positioned to absorb and apply new knowledge, particularly from other industries where they have less knowledge and experience. Firms that invest in R&D will be better equipped to handle increased transaction and managerial costs related to inter-industry knowledge transfer and develop knowledge recombinations for innovation (Kobarg et al., 2019; Audretsch et al., 2021). This recombination can lead to breakthroughs that neither R&D investments nor inter-industry spillovers on their own could achieve.

Secondly, it diversifies the knowledge base of a firm. Inter-industry knowledge spillovers provide diverse perspectives, technologies, and unrelated knowledge (Mascarini et al., 2023) which may become relevant for some parts of products and innovation processes in a focal industry. Development of firm capabilities allows the formalization and structuring of heterogeneous sources of knowledge inter-industry and the ability to integrate inter-industry spillovers into more systematic and homogeneous firm knowledge (Audretsch and Belitski, 2023a). This can inspire new directions for a firm's R&D efforts. This diversity can lead to more creative and effective innovation processes, reducing costs and increasing creativity.

Finally, synergistic learning between firms and external partners can increase. Firms that significantly invest in capabilities are more capable of understanding and integrating complex external knowledge (Cohen and Levinthal, 1989; Claussen et al., 2015; Gesing et al., 2015). This is because organizational routines and knowledge that are very different from a firm's own knowledge require substantial R&D investment to unpack knowledge heterogeneity and complexity (Amoroso et al., 2018). Inter-industry spillovers might provide unique, complementary insights that can significantly enhance a firm's vision and innovative projects, which intra-industry spillovers cannot do because they represent shared knowledge. Firms with high capabilities can leverage inter-industry spillovers more effectively, leading to increased innovation. Conversely, firms with low capabilities may struggle to benefit from these spillovers due to high transaction and knowledge integration costs. We hypothesize:

H2b. Firm's capabilities and inter-industry knowledge spillovers are complementary for firm's innovation.

2.6. Industry-specific effect of knowledge spillover innovation

The joint effect of firm capabilities and intra- and inter-industry knowledge spillovers on firm innovation may vary across industries as firms employing different knowledge search strategies in highly process heterogeneous industries vis-à-vis more homogeneous industries, and industries that are more heterogeneous on knowledge inputs are more likely to introduce innovations (Terjesen and Patel, 2017). Prior research has called for incorporating industry structures in understanding firm innovation (Lenox et al., 2007; Balasubramanian, 2011; Audretsch and Belitski, 2023) and, specifically, the need to consider various innovation types (Xu, 2015). Here are the key reasons for industry-specific effects of knowledge spillover innovation.

Firstly, the nature of industry knowledge. Industries such as high-tech manufacturing, rely heavily on complex, tacit knowledge that is difficult to codify and transfer. In such industries, firms hire diverse labor and employ capital to enable heterogeneous innovation input-output conversion processes (Terjesen and Patel, 2017), develop firm capabilities to absorb and integrate external knowledge. Conversely, in industries where knowledge is more homogeneous and explicit, such as administrative services or low-tech manufacturing, and where the innovation is mainly incremental, could have higher intra-industry spillovers.

Secondly, industries such as ICT and KIBS such as R&D and scientific services and experiments are highly technology-intensive, tacit and rapidly evolving. Firms in these industries benefit significantly from inter-industry spillovers as they provide access to diverse technological advancements and new ideas (Tether and Tajar, 2008).

Thirdly, internal investment in R&D can help firms to better leverage external knowledge via spillovers and direct collaborations (Audretsch et al., 2024) as they have the necessary absorptive capacity to assimilate and utilize external knowledge. Industries with a high concentration of skilled labor, such as KIBS, are particularly effective at absorbing both intra- and inter-industry spillovers, as their workforce is adept at integrating new knowledge (Muller and Doloreux, 2009). This ability is less pronounced in industries like agriculture or furniture repair, where the knowledge intensity and the need for rapid innovation are lower.

Fourthly, in industries where collaboration networks are robust, such as the creative industries, firms primarily benefit from intra-industry spillovers, facilitating the exchange of ideas and best practices within the industry (Grabher, 2001). In contrast, industries with well-established clusters, like the automotive sector, often benefit from localized intra-industry spillovers before engaging in collaborations with firms from other industries, such as design, aerospace, and ICT (Lorenzen and Mahnke, 2002; Beaudry and Schiffauerova, 2009).

Fifthly, the average firm size within an industry can significantly influence how capabilities and spillovers affect innovation, particularly due to differences in resource availability, absorptive capacity, organizational structure, and external interactions. Larger firms, which are more common in certain industries, have more financial and human resources to invest in R&D and innovation, allowing them to exploit economies of scale in these areas (Cohen and Klepper, 1996; Dosi, 1988). Such firms typically exhibit greater absorptive capacity, owing to their extensive R&D activities and diverse expertise, enabling them to recognize, assimilate, and apply external knowledge more effectively (Zahra and George, 2002).

On the contrary, industries with firms of smaller size often face resource constraints, limiting their ability to invest in R&D (De Massis et al., 2018). This makes them more dependent on external knowledge spillovers for radical innovation and pushes them to focus on niche areas or emerging markets and technologies. Smaller firms have more variable absorptive capacity due to fewer dedicated R&D resources, reducing their ability to reach inter-industry spillovers. The absorptive capacity of firms is crucial to apply external knowledge (Cohen and Levinthal, 1990). Industries where a broad external search of knowledge and creativity is common, allows firms to become aware of variations in industry processes and identify novel recombinations of knowledge and resources, facilitating innovation. Broad knowledge bases could also prevents firms in specific sectors from being constrained by a specific resource base, enabling them to innovate more effectively and independently (Terjesen and Patel, 2017). Industries where process of knowledge creation is more heterogeneous (Audrestch & Belitski, 2023a, 2023b) are likely to experience more dynamic and varied knowledge spillovers, as firms in such industries continuously adapt to a wider range of external sources for innovation.

Finally, the level of competition is different between industries affecting how firms leverage external knowledge and whether they rely on intra-industry spillovers or coopetition. In highly competitive industries, such as crative industry and KIBS, firms may prioritize speed over quality in utilizing knowledge spillovers (Kuratko et al., 2020) as they race to enter the market faster than their competitors. This intense competition can drive firms to invest heavily in internal capabilities to differentiate themselves and integrate external knowledge (Phene et al., 2006), thereby creating a unique dynamic where the focus may shift from collaborative knowledge sharing to more competitive strategies (Ritala and Hurmelinna-Laukkanen, 2009). This understanding helps to explain why knowledge spillovers can vary so significantly between industries based on their firm's capabilities and competition.

3. Data and method

3.1. Sample selection

We matched together three firm-level datasets and two regional-level datasets. First, we used the Business Registry (BSD) for data on firm ownership, firm status, age since the establishment year, number of full-time employees, exports, industry information, and geographical location. Second, we utilized the Community Innovation Survey data (UKIS), which provides information on knowledge collaboration across different types of external partners, and data related to innovation performance, such as the share of products new to the market. It also includes data on innovation outputs like expenditure on innovation training, marketing, acquiring external equipment and facilities, and investing in and acquiring knowledge. Third, the Business Expenditure in Research and Development (BERD) database provides information on the number and share of researchers and employees with higher education, as well as data on internal R&D investment and acquisition. Together, these three datasets form a powerful survey tool to test our research hypothesis, with data available after cleaning for the 2002–2014 period. The total number of firms over this period is 15,259, corresponding to 19,220 firm-year observations. The unit of analysis is the firm, while we also control for the number of subsidiaries if a firm has any. Only a small fraction of the 1451 firms were observed more than twice in our six-year survey sample. The list of variables in this study appears in Table 1, and their correlation matrix is shown in Table 2. The distribution of the sample by region, industry, year, and firm size is provided in Appendix A1.

To perform our analysis by industry, we created a set of binary variables associated with six main sectors: KIBS, ICT, creative, manufacturing low and medium-low technology, manufacturing high and medium-high technology and other industries. Our first industry is low-tech and medium-low tech manufacturing (SIC 10.1, 10.5, 13.9, 15.2, 16.1, 22.1, 22.2, 23.1, 24.4, 25.9). Our second industry is high-tech and medium-high-tech manufacturing (SIC 20.3, 25.4, 28.2, 30.2, 32.5, 21.1, 26.1, 26.3, 27.3, 30.3). Our third industry is ICT and services (SIC 58 - SIC 63), excluding publishing (SIC 58), film, TV, video, radio, and photography (SIC 59–60). Our fourth industry is KIBS, which includes scientific and professional services (SIC 69 - SIC 74) and excludes design, graphic, and fashion (SIC 74), advertising and marketing (SIC

Table 1
Description of variables.

Variable (source)	Definition	Mean	St. dev.	Min	Max
Firm-level characteristics					
New product sales (UKIS)	% of a firm's total turnover from goods and services that were new to the market (%)	4.021	12.662	0	100
Age (BSD)	Age of a firm in years, in logarithms	2.662	0.729	0	3.98
Employment (BSD)	Number of full-time employees, in logarithms	4.076	1.495	0.69	10.77
Human capital (UKIS)	Share of workers (full-time employed) with a university degree in science, technology, and engineering scaled between zero and one	0.068	0.164	0	1
Exporter (UKIS)	Binary variable = 1 if a firm sells its products in foreign markets, 0 otherwise	0.374	0.483	0	1
Survival (BSD)	Binary variable = 1 if a firm was still in the market without death or merge in 2018, 0 otherwise	0.548	0.497	0	1
Herfindahl Index (BSD)	Herfindahl Index calculated using concentration in sales by 2 SIC digit industry.	0.072	0.077	0.01	0.83
Foreign MNE (BSD)	Binary variable = 1 if MNE has headquarters abroad, 0 otherwise	0.489	0.499	0	1
National MNE (BSD)	Binary variable = 1 if MNE headquarters in the United Kingdom, 0 otherwise	0.338	0.473	0	1
Internal R&D intensity (BERD)	Amount spent internally on research and development (000s) taken from the BERD data to total sales (000s pound sterling) taken from BSD data for t-1	0.011	0.046	0	0.56
External R&D intensity (BERD)	Amount spent externally (purchased) on research and development (000s) from the BERD data to total sales (000s pound sterling) taken from BSD data for t-1	0.001	0.013	0	0.50
Training intensity (UKIS)	Amount spent internally on training for innovation (000s) to total sales (000s pound sterling)	0.111	0.201	0	0.61

(continued on next page)

Table 1 (*continued*)

Variable (source)	Definition	Mean	St. dev.	Min	Max
	over the last 3 years				
Process innovation (UKIS)	Binary variable = 1 if a firm has introduced new ways (methods, approaches) to innovate over the last 3 years, zero otherwise	0.262	0.440	0	1
Abandoned innovation (UKIS)	Binary variable = 1 if a firm has any innovation activities that were abandoned over the last 3 years, zero otherwise	0.049	0.217	0	1
Persistent innovation (UKIS)	Binary variable = 1 if a firm has any innovation activities that were started but yet incomplete over the last 3 years, zero otherwise	0.071	0.258	0	1
Regional collaboration (UKIS)	Binary variable = 1 if a firm collaborates on innovation with at least one external partners regionally, 0 otherwise	0.146	0.353	0	1
National collaboration (UKIS)	Binary variable = 1 if a firm collaborates on innovation with at least one external partner within national borders (UK)	0.192	0.393	0	1
Global collaboration (UKIS)	Binary variable = 1 if a firm collaborates on innovation with at least one external partner internationally	0.081	0.272	0	1
Suppliers collaboration (UKIS)	How efficient was collaboration on innovation with suppliers from 0 – not used to 1 – low, 2 – medium and 3 – high	1.478	1.095	0	3
Customers collaboration (UKIS)	How efficient was collaboration on innovation with customers and clients from 0 – not used to 1 – low, 2 – medium and 3 – high	1.722	1.201	0	3
Competitors collaboration (UKIS)	How efficient was collaboration on innovation with competitors from 0 – not used to 1 – low, 2 – medium and 3 – high	1.257	1.058	0	3
Consultants collaboration (UKIS)	How efficient was collaboration on innovation with consultants from 0 – not used to 1 – low, 2 – medium and 3 – high	0.686	0.882	0	3
Universities collaboration (UKIS)	How efficient was collaboration on innovation with universities and R&D labs from 0 – not used to 1 – low, 2 – medium and 3 – high	0.433	0.754	0	3
Government collaboration (UKIS)	How efficient was collaboration on innovation with local and national government from 0 – not used to 1 – low, 2 – medium and 3 – high	0.429	0.729	0	3
Appropriability (UKIS)	Sum of scores of the effectiveness of the following methods for protecting new products and processes: secrecy, complexity of goods and services, lead time advantages, patenting, design, copyright, trademarks, lead, complexity, secrecy (rescaled between zero and one).	0.09	0.16	0	1
Regional characteristics (country data at NUTS3 level)					
Tertiary education (ONS)	Working age population with a qualification at NVQ4 or above (%) of total. Qualifications of working age population (16–64), and proportion of people aged 25–64 with each level of qualification.	26.481	7.217	15.20	66.50
Russel group university	Binary variable equals one if a firm is located in a city 0region with the University that belongs to the Russel group (leading research higher education institutions in the UK), zero otherwise	0.129	0.341	0	1
Business churn (ONS)	The churn rate, also known as the rate of business entry minus business exit It is most commonly expressed as the percentage	2.429	2.324	−6.12	13.07
Region population (ONS)	Population of local district postcode district in logarithm.	12.699	0.803	11.52	16.07

(*continued on next page*)

Table 1 (*continued*)

Variable (source)	Definition	Mean	St. dev.	Min	Max
Business density (ONS)	Business stock (per 10,000 population) which is a number of businesses per 10,000 population in leading cities in the United Kingdom (UK) and is used as a measure of regional networking	279.82	50.15	178.35	490.83
GVA per capita (ONS)	Gross value added in a region per capita, in 000, British Pounds in constant 2005 prices	22.755	7.101	13.132	48.335
Region resources	Share of large-scale manufacturing and mining workers in a local district (by 2 letter postcode) in 1891. An increase in the share means an increase in the share of large-scale manufacturing workers and mining, and vice versa (Stuetzer et al., 2016).	0.181	0.137	0.03	0.60
EQI	The regional European Quality of Government Index (EQI) which includes corruption, impartiality and rule of law pillars (Charron et al., 2013)	0.738	0,258	0.002	1.167
Intra-industry knowledge spillover (BSD)	Dependent variable: Intra-industry knowledge spillover by 2 digit SIC and a local district is calculated using firm level data on R&D expenditure. This is a ratio of R&D expenditure within a sector at 2 digit SIC (excluding a firm's own R&D expenditure) and a local district to a total R&D expenditure in sector at 2 digit SIC in a country.	0.093	0.156	0	1
Inter-industry knowledge spillover (BSD)	Dependent variable: Inter-industry knowledge spillover by 2 digit SIC and a local district is calculated using firm level data on R&D expenditure. This is a ratio of R&D expenditure outside firm sector at 2 digit SIC level and a local district (this calculation does not include firm's own R&D) to total a R&D expenditure in all sectors in a country (excluding a 2 digit SIC where firm is located).	0.087	0.082	0	0.48

Note: Number of observations: 19,220 obs.
Source: Office of National Statistics (2017, 2018, 2023), Business Demography Population Estimates (2020); Annual Population Survey (2020).

70), and architecture (SIC 71). Our fifth industry is the creative industry, which includes music, performing and visual arts (SIC 59, 85, 90), museums, galleries, and libraries (SIC 91), publishing (SIC 58), film, TV, video, radio, and photography (SIC 59–60), design: product, graphic, and fashion design (SIC 74), advertising and marketing (SIC 70), architecture (SIC 71), and crafts (SIC 32). The rest of industries (our sixth industry) is coded as other industries (Office for National Statistics, 2023).

3.2. Variables

3.2.1. Dependent variable

Our dependent variable is radical innovation measured as a percentage of firm's revenues from new to market products in its total sales. This indicator is based on CIS question 810: 'percentage of total turnover over the last 3 years from goods and services that are new to the market,' with an average of 4.96 percent of sales being new-to-market products and a standard deviation of 14.70. A value of zero for innovation performance means the firm has not developed any innovation in year t, while a value of 100 percent means that all sales in year t were associated with new product creation. This variable has been used in prior research as a proxy for innovation (Laursen and Salter, 2006; Nieto and Santamaría, 2007; Belitski et al., 2024) and is different from incremental innovation which is measured as a percentage of firm's revenues from new to firm products in its total sales (Xu, 2015; Kobarg et al., 2019).

3.2.2. Independent variables

Our independent variables are at the industry-regional level, specifically within (intra-) and between (inter-) industry knowledge spillovers (Knott et al., 2009; Bloom et al., 2013), which serve as proxies for external knowledge valuable to a firm. Intra-industry spillover is calculated as firms' internal R&D expenditure within the 2-digit SIC 2007 industry and 2-letter postcodes, excluding the firm's own investment in internal R&D based on the BERD dataset.

We started with the assumption that firms within the same industry will equally benefit from other firms' R&D expenditure using equal weights within the same 2-digit ($w_{ii} = 1$) sector (Keller, 2002), using the following equation:

$$S_{ir} = w_{ii}\left(R_{ir} - R_f\right) / \left(R_{i\_country}\right) \tag{1}$$

where subscript i indicates the industry of a knowledge spillover; R is a measure of knowledge stock as the R&D expenditure by 2-digit SIC2007 and w_{ii} is an intra-industry weight.

Inter-industry spillover is calculated following Griliches (1992) as the total of R&D expenditures in other industries by 2-digit SIC 2007 and 2 letter postcode j distinct from industry i. We applied weights for

Table 2
Correlation matrix.

Variables		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23		24	25
1	New product sales	1																									
2	Age	−0.11*	1																								
3	Employment	−0.01*	0.19*	1																							
4	Human capital	0.29*	−0.10*	0.01	1																						
5	Exporter	0.17*	0.08*	0.19*	0.24*	1																					
6	Survival	0.01	0.06*	−0.26*	−0.01	−0.02	1																				
7	Herfindahl Index	003*	−0.09*	−0.01	0.12*	−0.01	−0.01	1																			
8	Foreign MNE	−0.02	0.25*	0.51*	0.04*	0.21*	−0.18*	0.01*	1																		
9	National MNE	0.12*	−0.21*	−0.32*	0.04*	−0.04	0.14*	0.01*	−0.65*	1																	
10	Internal R&D	0.37*	−0.12*	−0.04*	0.40*	0.19*	0.01	0.09*	−0.02*	0.10*	1																
11	External R&D	0.28*	−0.08*	−0.02*	0.20*	0.08*	0.01	0.08*	−0.01	0.06*	0.46*	1															
12	Training intensity	0.16*	−0.17*	−0.07*	0.16*	0.04*	0.02	0.07*	−0.08*	0.21*	0.17*	0.10*	1														
13	Process innovation	0.21*	0.01*	0.15*	0.14*	0.21*	−0.02*	0.04*	0.07*	0.10*	0.13*	0.07*	0.20*	1													
14	Abandoned innovation	0.14*	0.01*	0.04*	0.13*	0.13*	0.05*	0.02*	0.01	0.05*	0.15*	0.08*	0.05*	0.14*	1												
15	Persistent innovation	0.19*	0.01*	0.02*	0.17*	0.18*	0.02	0.03*	−0.02*	0.11*	0.22*	0.18*	0.08*	0.18*	0.56*	1											
16	Regional collaboration	0.16*	0.03*	0.04*	0.11*	0.10*	0.01	0.01	−0.02*	0.13*	0.12*	0.08*	0.13*	0.24*	0.15*	0.20*	1										
17	National collaboration	0.23*	0.03*	0.12*	0.20*	0.23*	0.01	0.04*	0.05*	0.09*	0.20*	0.15*	0.13*	0.33*	0.21*	0.28*	0.51*	1									
18	Global collaboration	0.22*	0.01	0.13*	0.26*	0.29*	0.01	0.02*	0.09*	−0.01	0.29*	0.16*	0.07*	0.23*	0.22*	0.26*	0.33*	0.48*	1								
19	Suppliers collaboration	0.16*	0.01	0.12*	0.10*	0.19*	0.01	0.01	0.05*	0.27*	0.09*	0.06*	0.23*	0.33*	0.10*	0.14*	0.20*	0.27*	0.16*	1							
20	Customers collaboration	0.19*	−0.02*	0.14*	0.16*	0.25*	−0.03*	0.01	0.05*	0.28*	0.15*	0.08*	0.24*	0.29*	0.14*	0.19*	0.22*	0.31*	0.20*	0.62*	1						
21	Competitors collaboration	0.16*	0.01	0.18*	0.12*	0.21*	−0.03*	0.01	0.09*	0.21*	0.12*	0.06*	0.18*	0.25*	0.13*	0.17*	0.19*	0.26*	0.18*	0.58*	0.62*	1					
22	Consultants collaboration	0.14*	−0.02*	0.19*	0.21*	0.23*	−0.01	0.03*	0.10*	0.12*	0.19*	0.14*	0.20*	0.27*	0.15*	0.20*	0.22*	0.32*	0.24*	0.46*	0.43*	0.47*	1				
23	Universities collaboration	0.21*	−0.01	0.13*	0.29*	0.26*	−0.02*	0.03*	0.08*	0.09*	0.22*	0.13*	0.17*	0.24*	0.15*	0.22*	0.25*	0.33*	0.29*	0.22*	0.34*	0.35*	0.54*	1			
24	Government collaboration	0.17*	−0.02*	0.15*	0.24*	0.17*	−0.03*	0.05*	0.08*	0.09*	0.15*	0.10*	0.16*	0.23*	0.12*	0.16*	0.24*	0.28*	0.21*	0.34*	0.36*	0.39*	0.52*	0.65*	1		
25	Appropriability	0.15*	0.04*	0.03*	0.13*	0.09*	0.02*	0.01	−0.02*	0.12*	0.11*	0.09*	0.11*	0.20*	0.01	0.01	0.23*	0.23*	0.15*	0.13*	−0.19*	−0.12*	0.09*	0.15*	0.04*	1	
26	Intra-industry spillover	0.05*	−0.01	0.08*	0.07*	0.07*	−0.03*	0.01	0.06*	−0.03*	0.04*	0.03*	−0.01	0.03*	0.03*	0.05*	0.02*	0.04*	0.07*	0.03*	0.03*	0.02*	0.06*	0.03*	0.07*	0.02*	1
27	Inter-industry spillover	0.06*	−0.02*	0.05*	0.02*	−0.02	0.01	0.06*	0.03*	−0.09*	−0.02	0.02	−0.01	0.02	0.02*	0.02*	0.01	0.01*	0.02*	0.01	0.01	0.02*	0.02*	−0.01	0.02*	0.01	0.21*

Note: Significance level: *$p < 0.05$. Number of observations: 19,220 obs.
Source: Office of National Statistics (2017, 2018, 2023), Business Demography Population Estimates (2020); Annual Population Survey (2020).

inter-industry spillovers using input-output matrix for intermediate products between 2-digit SIC 2007 industries for each corresponding year of the survey.

We further calculated the *inter-industry* of firm in industry j as a weighted sum of internal R&D expenditure for all industries i, excluding s 2-digit SIC2007 industry where a firm is located, using the following equation:

$$S_{jr} = \sum_{j \neq i}^{n} w_{ij} \left(R_{jr} - R_{ir} \right) / \left(R_{j\_country} - R_{i\_country} \right) \quad (2)$$

where subscript j indicates the industry of R&D expenditure; R is a measure of knowledge stock proxied by R&D expenditure by 2-digit SIC2007; w_{ij} is an inter-industry weight proportional to the inter-industry input-output consumption of intermediate goods. R_{jr} is R&D expenditure in industry j in a region r; R_{ir} is R&D in industry i in region r by 2 letter postcodes. Both intra- and inter-industry spillovers are normalized by the total amount of R&D expenditure in the economy for each survey year.

We use one period lag in localized intra- and inter-regional knowledge spillovers. For example, for the period of 2012–2014, the knowledge spillover was calculated using R&D expenditure data from the BERD for year 2012. Using one period lag for the biannual UKIS survey, provides an additional control for intertemporal effect of localized knowledge spillovers on firm innovation output. For example, investment in R&D by localized firms (within 2 letter postcode) within and between industries in year 2012 is likely to change innovation strategy and output of a focal firm in the region in the next 2 years (2012–2014). The UKIS data 2012–2014 period is reported by firm managers in 2015.

To operationalize *firm's capabilities*, we use R&D to sales ratio measured as the total amount spent on internal R&D, derived from the BERD dataset for year t-1 divided by total sales (BSD dataset) for the year t-1 (R&D intensity). This measure is known as R&D intensity (Denicolai et al., 2014; Hall et al., 2013; Audretsch et al., 2024) and we use one-year lagged value of R&D intensity to deal with potential endogeneity between R&D investment and innovation output. The list of control variables appears in Table 1 with the detailed definition for each variable. We use interactions of R&D intensity and intra- and inter-industry knowledge spillovers to measure the joint effect of firm's capabilities and access to external knowledge via spillovers for firm innovation. This is the way to test whether firm's capabilities are complements or substitutes to a specific type of knowledge spillover.

3.2.3. *Control variables*

At the firm level, we started by using a set of control variables related to the role of knowledge collaboration nationally and internationally to enhance innovation activity (Boschma, 2005; Boschma and Frenken, 2010). We included three binary variables indicating whether a firm collaborates on innovation with at least one external partner within the region, nationally, or internationally, coded as 1, and 0 otherwise. Additionally, we controlled for the diversity of knowledge collaboration and the type of collaboration partner, drawing on Audretsch and Belitski (2024), who the diversity of knowledge and specific collaboration partner increase radical innovation. Thus, we created six collaboration binary variables for six types of external partners: suppliers, customers, consultants, competitors, universities, and government, measuring the importance of such collaboration as perceived by a firm (from 0 – not important to 3 – highly important). The development of the collaboration scale followed Terjesen and Patel (2017), Kobarg et al. (2019) and Audretsch et al. (2024), who demonstrated that knowledge breadth and depth may under certain conditions bolster or inhibit radical innovation. Knowledge collaborations entail knowledge transfer and may capture part of the impact of spillovers, contributing to the further effect of intra- and inter-industry spillovers on innovation performance. This inclusion minimizes potential estimation bias when evaluating the effect of both types of knowledge spillovers.

We controlled for firm size and age drawing on prior research (Audretsch et al., 2021) taken logarithm of firm number of full-time employees as smaller firms are known to be more flexible and innovative than larger firms which allows them to innovate more rapidly. We build on Coad et al. (2018) who investigated the non-linear effect of firm age on innovation and thus we took the logarithm of the number of years since establishment. Exporters were found to innovate more than non-exporters (Rugman and Verbeke, 2001) and we add binary variable coded 1 if firms export their products and services, 0 otherwise, and whether the firm belongs to a national or foreign (international) MNE group. To control for the role of process innovation as an input for product innovation we draw on prior research of Terjesen and Patel (2017), who demonstrated that both are interrelated, by creating a binary variable if firm has innovated new processes, zero otherwise. Schamberger et al. (2013) study demonstrated that there is a persistence in innovation activity. We included two binary variables: abandoned innovation (coded 1 if the firm had any innovation activities abandoned over the last 3 years, 0 otherwise) and persistent innovation (coded 1 if the firm had any innovation activities started but yet incomplete over the last 3 years, 0 otherwise) to control has had prior innovation. Human capital, such as share of university-degree workers is positively associated with innovation as firms has higher internal capabilities to enable knowledge transfer and collaboration (Eisenhardt and Martin, 2000; Zahra and George, 2002). We used a share of employees with university degrees in STEM fields out of the total full-time employment.

Prior research has found that firms investing in internal R&D and buying R&D from external providers are more innovative (Cassiman and Veugelers, 2002). We included external R&D intensity, calculated as the R&D expenditure-to-sales ratio, and training intensity, as well as the training expenditure-to-sales ratio, drawing on Belitski et al. (2020) as controls for additional innovation inputs. We also included a binary variable "survival" indicating if a firm survived until the end of our observation period (year 2016). This draws on prior research of Antonelli and Colombelli (2018) who found that innovation could help fuirms to survive longer in market. Finally, firms apply different innovation regimes, meaning some firms innovate at such a high speed that it is unnecessary to patent because they generate a steady stream of new/improved products. Other firms protect their innovations using patents, design, copyright, trademarks, and other informal protection methods such as lead time advantage, complexity, and secrecy - altogether these forms of innovation appropriability are known to increase firm's radical innovation effort (Hall et al., 2013). We added a measure of appropriability to our model, calculated as a sum of scores for the effectiveness of the following methods for protecting new products and processes: secrecy, complexity of goods and services, lead time advantages, patenting, design, copyright, and trademarks (rescaled between 0 and 1).

Each model we estimate includes controls for year and industry (two-digit SIC, 2007). We included a set of regional (NUTS3-based) controls. All variables are illustrated and explained further in Table 1.

At the firm-industry level, we also measured the effects of industry competition on firm innovation with firms in more competitive environment are expected to innovate more (Porter, 1998; Coad et al., 2018). We calculated the Herfindahl Index, which squares the market share in sales for each firm by two-digit SIC and then sums the squares. An increase in the index indicates a shift from very competitive markets to almost monopoly markets.

Finally, regional economic and institutional characteristics were included drawing on prior research of regional scholars such as Audretsch and Feldman (1996, 1999), Balland et al. (2015) who demonstrated that availability of regional resources facilitates innovation activity and growth. We included a set of regional control variables that can either facilitate or impede firm's innovation and indirectly affect the size of knowledge spillovers. First, we included a measure of regional human capital, which is the share of the working-age population in a region with a qualification at NVQ4 (tertiary education) or above (%) of the total. We included a binary variable indicating the presence of a Russell Group university in the region, which increases research funding availability and attracts leading researchers (Audretsch et al., 2022).

We included the business churn rate, also known as the net rate between business entry and business exit, as a proxy for market dynamics and the breadth of networking (Belitski et al., 2023). It is most commonly expressed as a percentage to demonstrate the dynamics of business. We controlled for business density as a proxy for business networking, calculated as the number of businesses per 10,000 population in a region which was found to increase innovation activity of firms (Boschma, 2005). We included a control for regional gross value added per capita (GVA) in a region using the production approach as regions that are more economically developed also innovate more (Florida, 2014). Regional GVA is the value generated by any unit engaged in the production of goods and services, a useful way of comparing regions of different sizes, taken in constant 2005 prices. It is not a measure of regional productivity but rather regional economic development and availability of resources. Drawing on Stuetzer et al. (2016) and to control for the presence of large manufacturing and historical persistence on innovation we controlled for the share of large-scale manufacturing and mining workers out of the total employed in a region in a local district (by two-letter postcode) in 1891, a historical indicator measuring the origins of regional specialization and economic development based on regional resource endowment. Finally, we used regional population in logarithm as a proxy for the market size of a region as in prior research (Boschma and Frenken, 2010). Regional data was sourced from the Office of National Statistics (ONS) regional data combined by the Centre for Cities such as Business Demography Population Estimates (2020).

The list of region-time controls is completed with a measure of institutional quality in a region. A body of literature argues that the institutional environment is a determinant of knowledge creation and innovation (Bennett and Nikolaev, 2020a, 2020b). A weak institutional environment affects entrepreneurial judgment (Casson, 1982) and reduces innovation activity (Audretsch and Belitski, 2021a). Thus, changes in the quality of governance in a region create economic incentives that make entrepreneurs embrace uncertainty and risk. In particular, the quality of governance is an important concept associated with the extent of formal and informal institutions. The Quality of Governance index at the NUTS2 level was developed by Charron et al. (2013) and includes corruption and the rule of law. Given the challenges of compatible data across UK regions, we used the European Quality of Government Index (EQI) by NUTS2 regions for the UK during 2005–2017, also used in prior research (Charron et al., 2013, 2020). We interpolated EQI for periods of 2002–2004 and 2004–2006.

3.3. Estimation strategy

We are interested in estimating a firm's innovation sales. Therefore, we use Tobit regression (Wooldridge, 2009) as follows:

$$y_{it} = \beta_0 + \beta_1 x_{it} + \beta_2 S_{irt-1} + \beta_2 S_{jrt-1} + \beta_3 \varphi_{it-1} + \beta_5 S_{irt-1}\varphi_{it-1} + \beta_6 S_{jrt-1}\varphi_{it-1}\omega_r + \rho_j + a_t + u_{it} \quad (3)$$

Equation (2) contains S_{jrt-1} and S_{irt-1} as explanatory variables of intra- S_{ir} and inter-industry S_{jr} knowledge spillover in t-1 calculated by industry/region; x_{it} is a vector of the lagged value of R&D intensity φ_{it-1} at time t-1 for firm i; u_{it} is an error term. S_{jrt-1} and S_{irt-1} are exogenous and are not correlated with u_{it}. and $S_{irt-1}\varphi_{it-1}$ and $S_{jrt-1}\varphi_{it-1}$ are interaction terms of intra- and inter-industry knowledge spillovers with R&D intensity for firm i in time t-1. Vectors ω_r, ρ_j, a_t are set of regional controls as well as industry and time fixed effects.

While our primary focus is on understanding the general relationship across industries, we perform sector-specific analyses to check the robustness and consistency of our findings. This helps us identify whether the hypothesized relationships hold across different sectors or if there are sector-specific nuances. We add to model (3) triple interactions of sector/spillover/firm capability when we test the relationship for each of six sectors.

4. Findings

4.1. Main findings

As one would expect from the literature (Laursen and Salter, 2006; McCann and Folta, 2011; et al., 2019) we find firm's capabilities are positively associated with firm innovation. An increase in R&D intensity by one percent (e.g., from 1% to 2% of R&D to total sales) is, on average, associated with a 54.21 to 72.03 percentage point increase in innovation sales (Table 3, specifications 1–6). This means that a firm initially achieving 1% of sales from new products to market can now achieve between 1.5% and 1.7% of sales for every 1 percentage point increase in R&D intensity. Compared to external R&D intensity and training intensity, the results are higher. A one percentage point change in external R&D intensity increases new product sales by between 34.95 and 46.20 percentage points. In comparison, a one percentage point change in training to sales ratio increases new product sales by between 9.87 and 10.56 percentage points (Table 3, specifications 1–6).

Furthermore, we estimated the effect of intra-industry spillovers on firm innovation. Our results support H1a, which states that an increase in intra-industry spillovers is associated with an increase in firm innovation. A one percentage point increase in intra-industry spillovers increases innovation sales by between 3.83 and 5.63 percentage points (Table 3, specifications 1–6), demonstrating a clear and important link between related knowledge variety for firms and their innovation performance. Our findings also support H1b, which states that firm capabilities and intra-industry spillovers are substitutes for firm innovation when R&D intensity reaches at least one standard deviation above the mean. Indeed, for firms above the mean R&D intensity in the industry, an increase in R&D intensity by one percentage point, jointly with an increase in intra-industry knowledge spillovers by one percentage point, is associated with a reduction in innovation sales of between 60.85 and 69.03 percentage points (Table 3, specifications 4 and 6). Economically, this means that a firm (above average internal R&D intensity) with 10% of innovative sales will have 3–4% of innovative sales if they increase R&D intensity by one percentage point and intra-industry spillovers by one percentage point.

For firms below or at the mean of R&D intensity, a joint increase in R&D intensity and intra-industry spillovers is associated with an increase in firm innovation (complementarity effect). This finding demonstrates that firms with lower levels of internal capabilities can still benefit from intra-industry spillovers, but these benefits are likely to have diminishing returns. As long as the firm continues its investment in internal capabilities, an increase in intra-industry spillovers may be perceived as a threat or as a substitute for its own R&D.

The results displayed in Table 3 (spec. 4 and 6) on the interaction terms demonstrate that the relationship between intra-industry spillovers and firm innovation changes with firm capabilities, advancing our knowledge about the recombination of innovation resources (Antonelli and Colombelli, 2018) and knowledge spillovers of innovation (Cappelli et al., 2014; Audretsch and Belitski, 2022). To visualize the relationship, we calculated the predictive margins of product innovation for intra-industry knowledge spillovers and R&D intensity (see Fig. 1).

We also estimated the impact of inter-industry spillovers on firm innovation. Our results do not support H2a, which states that an increase in inter-industry spillovers is associated with an increase in firm innovation, assuming the direct effect of inter-industry spillovers on innovation. Our coefficients of inter-industry knowledge spillovers are insignificant (Table 3, specifications 4–6). It is plausible to assume that the effect of inter-industry knowledge spillovers on firm innovation may be indirect and depend on the firm's investment in internal capabilities,

Table 3
Tobit regression results for all sectors. Dependent variables – innovation sales.

Industry	Firm controls	+ regional controls	+ knowledge spillovers	+ intra-industry interactions	+ inter-industry interactions	all controls
Specification	(1)	(2)	(3)	(4)	(5)	(6)
Firm-level characteristics						
Age	−2.23*** (0.61)	−2.84*** (0.61)	−2.84*** (0.62)	−2.82*** (0.62)	−2.84*** (0.62)	−2.82*** (0.62)
Employment	−0.85** (0.35)	−1.04*** (0.35)	−1.05*** (0.35)	−1.05*** (0.35)	−1.04*** (0.35)	−1.04*** (0.35)
Human capital	18.28*** (2.43)	18.51*** (2.54)	18.37*** (2.54)	18.47*** (2.54)	18.32*** (2.54)	18.39*** (2.54)
Exporter	10.22*** (0.94)	9.22*** (1.00)	9.17*** (1.00)	9.07*** (1.00)	9.16*** (1.00)	9.04*** (1.00)
Survival	0.12 (0.88)	0.02 (0.89)	0.04 (0.89)	0.07 (0.89)	0.04 (0.89)	0.07 (0.89)
Herfindahl Index	−20.23*** (5.44)	−18.10*** (6.20)	−18.03*** (6.20)	−17.71*** (6.19)	−18.21*** (6.20)	−19.91*** (6.19)
Foreign MNE	9.06*** (1.99)	8.92*** (1.99)	8.87*** (1.96)	8.87*** (1.99)	8.87*** (1.99)	8.88*** (1.99)
National MNE	11.82*** (1.93)	12.04*** (1.94)	12.00*** (1.94)	11.96*** (1.95)	12.00*** (1.94)	11.94*** (1.94)
Internal R&D intensity	59.84*** (8.23)	63.24*** (8.23)	63.01*** (8.23)	72.03*** (8.23)	54.21*** (10.95)	61.67*** (11.42)
External R&D intensity	34.95*** (11.11)	46.08*** (11.77)	45.95*** (11.75)	45.15*** (11.73)	46.20*** (11.77)	45.37*** (11.73)
Training intensity	9.87*** (1.98)	10.46*** (2.00)	10.46*** (2.00)	10.53*** (2.01)	10.47*** (2.01)	10.56*** (2.00)
Process innovation	11.40*** (0.93)	11.42*** (0.93)	11.42*** (0.93)	11.39*** (0.93)	11.43*** (0.93)	11.40*** (0.93)
Abandoned innovation	5.42*** (1.80)	1.65 (1.83)	1.62 (1.83)	1.59 (1.83)	1.57 (1.83)	1.52 (1.83)
Persistent innovation	4.94*** (1.53)	−1.30 (1.71)	−1.30 (1.71)	−1.32 (1.71)	−1.22 (1.71)	−1.29 (1.70)
Regional collaboration	1.27 (1.17)	2.15* (1.18)	2.13* (1.18)	2.15* (1.18)	2.12* (1.18)	2.13* (1.18)
National collaboration	7.60*** (1.16)	6.50*** (1.16)	6.49*** (1.18)	6.47*** (1.18)	6.45*** (1.18)	6.42*** (1.18)
Global collaboration	2.93** (1.44)	2.15* (1.18)	2.13 (1.40)	2.21 (1.44)	2.13 (1.44)	2.22 (1.44)
Suppliers collaboration	1.87*** (0.52)	1.65*** (0.52)	1.64*** (0.52)	1.60*** (0.52)	1.65*** (0.52)	1.61*** (0.52)
Customers collaboration	4.91*** (0.58)	4.71*** (0.58)	4.72*** (0.58)	4.73*** (0.58)	4.71*** (0.58)	4.72*** (0.58)
Competitors collaboration	−0.31 (0.56)	−0.60 (0.56)	−0.58 (0.56)	−0.56 (0.56)	−0.59 (0.56)	−0.57 (0.56)
Consultants collaboration	0.71 (0.57)	0.37 (0.57)	0.35 (0.57)	0.37 (0.57)	0.36 (0.57)	0.39 (0.57)
Universities collaboration	1.42** (0.68)	1.21* (0.69)	1.21* (0.69)	1.21* (0.69)	1.24* (0.69)	1.24* (0.69)
Government collaboration	0.55 (0.71)	0.31 (0.71)	0.31 (0.71)	0.30 (0.71)	0.31 (0.71)	0.28 (0.71)
Appropriability	0.228*** (0.03)	0.270*** (0.02)	0.271*** (0.03)	0.274*** (0.02)	0.275*** (0.03)	0.274*** (0.02)
Regional -level characteristics						
Tertiary education		0.14* (0.08)	0.14* (0.08)	0.12* (0.07)	0.14* (0.08)	0.12* (0.07)
Russel group university		4.92** (1.98)	4.97** (1.98)	4.99** (1.98)	4.62** (1.97)	4.99** (1.98)
Business churn		−0.32 (0.30)	−0.30 (0.30)	−0.30 (0.30)	−0.29 (0.30)	−0.29 (0.30)
Region population		−2.04** (0.66)	−2.05** (0.66)	−2.10** (0.66)	−2.05** (0.66)	−2.10** (0.66)
Business density		0.02** (0.01)	0.02** (0.01)	0.02** (0.01)	0.03** (0.01)	0.02** (0.01)
GVA per capita		0.04*** (0.01)	0.03*** (0.01)	0.02*** (0.01)	0.03*** (0.01)	0.03*** (0.01)
Region resources		−4.73 (3.81)	−4.76 (3.84)	−4.80 (3.84)	−4.56 (3.85)	−4.55 (3.85)
EQI		−0.24 (1.73)	0.03 (1.79)	0.07 (1.79)	0.07 (1.79)	0.03 (1.79)
Intra-industry spillover (H1a)			3.83** (2.01)	5.40** (2.70)	3.85* (2.50)	5.63** (2.76)
Intra -industry spillover X Internal R&D intensity (H1b)				−60.85** (30.18)		−69.03** (30.66)
Inter-industry spillover (H2a)			−5.16 (5.74)	−5.42 (5.74)	−7.21 (5.99)	−8.15 (6.01)
Inter-industry spillover X Internal R&D intensity (H2b)					105.34 (79.59)	118.61* (67.59)
Constant	−57.57*** (2.77)	−20.65 (15.05)	−20.08 (15.72)	−19.83 (15.72)	−20.01 (15.72)	−19.70 (15.72)
Error variance	787.63*** (25.77)	763.78*** (25.30)	763.48*** (25.38)	762.81*** (25.35)	763.27*** (25.37)	762.47*** (25.34)
Number of obs.	19220	19220	19220	19220	19220	19220
Uncensored	4156	4156	4156	4156	4156	4156
Left-censored	15064	15064	15064	15064	15064	15064
Chi2	2694.75	2925.29	2927.90	2931.90	2929.35	2935.01
Pseudo R2	0.09	0.10	0.10	0.10	0.10	0.11
Log-likelihood	−12529.09	−12413.29	−12412.53	−12410.42	−12411.33	−12409.19

Note: Significance level: *p < 0.05. Number of observations: 19,220 obs.
Source: Office of National Statistics (2017, 2018, 2023), Business Demography Population Estimates (2020); Annual Population Survey (2020).

such as in-house R&D expenditure, which facilitates the recognition, absorption, assimilation, and adaptation of external knowledge from across industries (Zahra and George, 2002). Additionally, a key challenge of such knowledge sourcing remains the time needed for knowledge adjustment, adaptation, and lab trials, diminishing the immediate effect on innovation.

This empirical finding furthers our understanding of prior research on the importance of diverse knowledge for innovation and firm performance (Cappelli et al., 2014; Amoroso et al., 2018), while also highlighting potential conditions that need to be maintained to enable inter-industry spillover short- and long-term effects on innovation. The empirical findings of these studies suggest heterogeneity in the role of spillovers, with some studies reporting positive and others negative or no effect of knowledge spillovers on innovation (Lööf and Heshmati 2002; Amoroso and Audretsch, 2022).

On the contrary, our findings support H3b, which states that firm capabilities and inter-industry spillovers are complementary for firm innovation (Table 3, specifications 5 and 6). Our results demonstrate that an increase in R&D intensity by one percentage point, jointly with an increase in inter-industry knowledge spillovers by one percentage point, is associated with an increase in innovation sales of between 105.34 and 118.61 percentage points (Table 3, specifications 5 and 6). Economically, this means that firms with 10% of their innovation sales can increase their innovation sales to 20–22 percentage points if they

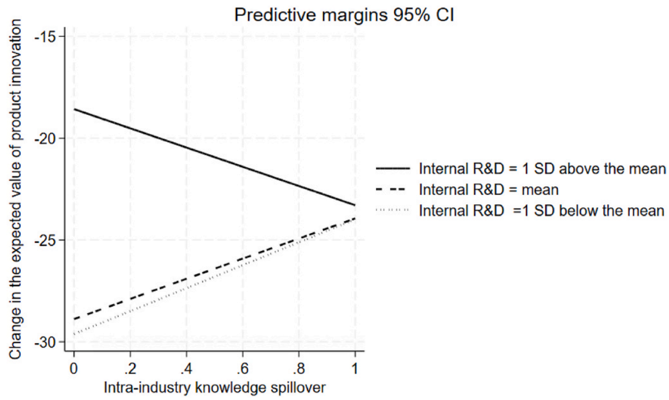

Fig. 1. Predictive margins for change in the expected value of product innovation for intra-industry spillovers for different levels of firm's capabilities.
Source: Office of National Statistics (2017, 2018, 2023).

increase R&D intensity by one percentage point for every one percentage point increase in inter-industry spillovers.

Interestingly, for firms below or at the mean of R&D intensity, an increase in inter-industry spillovers is associated with a decrease in firm innovation. This finding demonstrates that firms with lower levels of internal capabilities are unable to benefit from increasing inter-industry spillovers. As long as a firm continues its investment in internal capabilities and reaches above the mean R&D intensity in the industry, an increase in inter-industry spillovers will result in an increase in firm innovation, supporting H2b.

These findings advance the understanding of "two faces of R&D" (Cohen and Levinthal, 1989), where a firm's investment in internal capabilities is needed to absorb external knowledge spillovers (Kobarg et al., 2019; Audretsch et al., 2021). Our study demonstrates that the ability to benefit from knowledge spillovers depends on the type of knowledge spillover (intra or inter-industry) and the matched level of firm capabilities. To absorb intra-industry spillovers, a minor investment in internal R&D is expected, while to absorb inter-industry spillovers, a firm is expected to significantly invest in internal R&D. We plotted the predictive margins of product innovation for R&D intensity and inter-industry knowledge spillovers (see Fig. 2).

4.2. Other findings

Table 3 provides further interesting and unexpected findings on the direct effect of different firm-specific characteristics on firm innovation. An increase in employment and firm age is negatively associated with the likelihood of innovation sales. Younger firms are more likely to

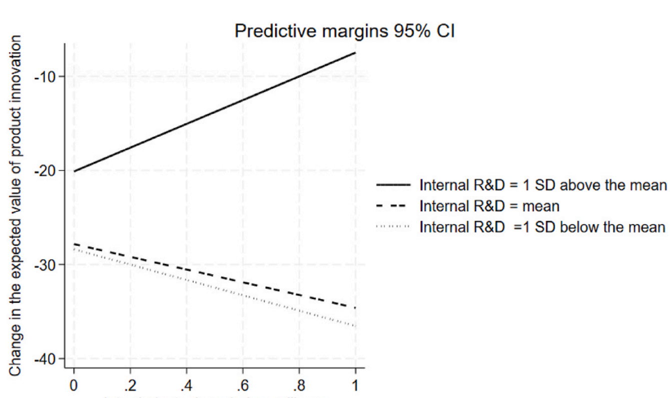

Fig. 2. Predictive margins for change in the expected value of product innovation for inter-industry spillovers for different levels of firm's capabilities.
Source: Office of National Statistics (2017, 2018, 2023).

introduce new products and services compared to more mature firms in the market.

Collaborations with external partners regionally increase innovation sales on average by between 2.13 and 2.15 percentage points, while collaboration with partners in national markets increases innovation sales on average by between 6.42 and 7.60 percentage points (Table 3, specifications 1–6). Collaboration with international partners, on average, is not associated with innovation sales; however, this result is likely conditional on the type of partner. Interestingly, an increase in the perceived importance of collaboration with suppliers by one unit (e.g., from none to low importance or from medium to high) increases innovation sales on average by 1.61–1.87 percentage points. An increase in collaboration with customers by one unit increases innovation sales by 4.72–4.91 percentage points. An increase in collaboration with universities by one unit increases innovation sales by 1.21–1.42 percentage points. Collaboration with other external partners, such as competitors, consultants, and government, is not associated with changes in innovation sales, contrasting with prior research (Bouncken et al., 2020; Audretsch et al., 2024).

Additionally, firms that are foreign-owned and nationally-owned by MNEs have on average 8–9 percentage points (foreign MNEs) to 11–12 percentage points (national MNEs) higher innovation sales compared to individual firms that are not part of MNEs. Exporters have on average 9.04–10.22 percentage points higher innovation sales compared to those that do not export. Human capital, proxied by the share of scientists, is positively associated with innovative sales (Table 3, specifications 1–6). In economic terms, this means that a 1% increase in the share of university graduates increases product innovation by between 18.28 and 18.57 percentage points. Firms located in industries with less competition have on average lower innovation sales. In economic terms, this means an increase in the Herfindahl index by 1 unit reduces innovation sales by between 18.21 and 20.23 percentage points. Finally, firms involved in process innovation have on average 11.40 percentage points higher innovation sales.

While we expected a positive effect on innovation sales, the fact that a firm has abandoned innovation in the past or started but not completed innovation, as a proxy for persistent innovation, does not show statistically significant coefficients. In addition, surviving firms and firms that merged or exited the market had on average the same level of innovation sales.

4.3. Post-hoc sector analysis

Prior research has argued that the effect of knowledge spillovers on innovation can vary across industries due to product and service specificity and differences in reliance on and access to external knowledge (Audretsch and Belitski, 2020a, 2023a). Without specifying a particular form of relationship, we estimate equation (3) to test the hypothesized relationship in H1 and H2 for each of six aggregated sectors - KIBS, ICT, creative, low and medium-low tech manufacturing, high and medium-high tech manufacturing and other industries.

Analysing the findings by sector allows us to examine whether our hypotheses hold across sectors and exhibit any differences when a sector-specific interaction variable is used. Our estimation results are presented in Table 4. We find that firm capabilities increase innovation performance across all industries. Furthermore, we find sectoral differences in the relationship between R&D intensity and innovation with the effect positive and significant for ICT and manufacturing, while the interaction coefficients of R&D intensity with other sectors are insignificant. This suggests potential differences in the role that internal and external resources play for innovation in these sectors extending prior research (see Audretsch and Belitski, 2020a, 2023a).

The interactions between intra- and inter-industry knowledge spillovers and sector dummy variables indicate whether the size effect of intra and inter-industry knowledge spillovers is different across sectors.

The results suggest positive and significant effects of internal and

Table 4
Tobit regression results across six aggregated sectors. Dependent variables – innovation sales.

Industry	Manufacturing low and medium-low tech	Manufacturing high and medium-high tech	ICT	KIBS	Creative	Rest sectors
Specification	(1)	(2)	(3)	(4)	(5)	(6)
Firm-level characteristics						
Age	−2.62*** (0.42)	−2.66*** (0.43)	−2.33*** (0.61)	−2.47*** (0.60)	−2.45*** (0.60)	−2.42*** (0.60)
Employment	−1.07** (0.25)	−1.03** (0.25)	−1.00** (0.35)	−1.04** (0.35)	−1.01** (0.35)	−1.05** (0.35)
Human capital	13.61*** (1.87)	13.69*** (1.81)	15.87*** (2.47)	17.78*** (2.45)	16.79*** (2.49)	17.20*** (2.49)
Exporter	9.33*** (0.70)	9.20*** (0.73)	9.26*** (0.94)	9.24*** (0.94)	9.35*** (0.94)	9.21*** (0.95)
Survival	0.33 (0.67)	0.33 (0.67)	0.19 (0.88)	0.18 (0.88)	0.19 (0.88)	0.16 (0.88)
Herfindahl Index	−15.77*** (3.91)	−16.55*** (3.93)	−21.94*** (5.43)	−18.06*** (5.43)	−23.08*** (5.43)	−22.01*** (5.48)
Foreign MNE	10.27*** (1.48)	10.29*** (1.50)	8.95*** (1.98)	9.03*** (1.98)	9.00*** (1.99)	8.92*** (1.99)
National MNE	11.99*** (1.44)	12.04*** (1.48)	11.93*** (1.93)	12.08*** (1.93)	12.02*** (1.93)	11.94*** (1.93)
Internal R&D intensity	75.68*** (8.83)	80.35*** (8.97)	73.01*** (13.54)	63.76*** (11.86)	67.13*** (13.83)	52.01*** (13.83)
External R&D intensity	79.88** (21.73)	82.58** (20.50)	43.56*** (13.54)	48.25** (24.15)	53.89** (26.05)	48.77** (24.78)
Training intensity	7.88*** (1.49)	9.96*** (1.49)	9.80*** (1.98)	10.28*** (1.99)	9.76*** (1.99)	9.53*** (2.00)
Process innovation	11.58*** (0.70)	11.65*** (0.70)	11.32*** (0.92)	11.59*** (0.92)	11.40*** (0.92)	11.39*** (0.92)
Abandoned innovation	2.53 (1.37)	3.39** (1.67)	1.88 (1.83)	1.73 (1.83)	1.88 (1.83)	1.88 (1.84)
Persistent innovation	−1.60 (1.24)	−1.63 (1.30)	−1.24 (1.71)	−1.10 (1.71)	−1.26 (1.71)	−1.10 (1.71)
Regional collaboration	1.32* (0.89)	1.30 (0.86)	1.98* (1.17)	1.92* (1.16)	2.09* (1.17)	2.00* (1.18)
National collaboration	7.83*** (0.89)	7.31*** (0.89)	6.31*** (1.18)	6.46*** (1.18)	6.47*** (1.18)	6.42*** (1.18)
Global collaboration	4.25*** (1.09)	3.93*** (1.10)	2.17 (1.43)	2.10 (1.43)	2.25 (1.44)	2.20 (1.43)
Suppliers collaboration	1.94*** (0.39)	1.90*** (0.40)	1.60*** (0.52)	1.66*** (0.52)	1.67*** (0.52)	1.65*** (0.52)
Customers collaboration	4.45*** (0.43)	4.59*** (0.49)	4.76*** (0.58)	4.71*** (0.58)	4.80*** (0.58)	4.78*** (0.58)
Competitors collaboration	−0.40 (0.42)	−0.49 (0.44)	−0.58 (0.56)	−0.60 (0.56)	−0.57 (0.56)	−0.56 (0.56)
Consultants collaboration	1.09** (0.42)	1.05** (0.44)	0.47 (0.57)	0.49 (0.56)	0.42 (0.57)	0.46 (0.57)
Universities collaboration	1.57** (0.51)	1.66** (0.60)	1.32** (0.68)	1.24** (0.68)	1.26** (0.68)	1.30** (0.68)
Government collaboration	0.29 (0.52)	0.22 (0.66)	0.21 (0.70)	0.29 (0.70)	0.19 (0.70)	0.21 (0.70)
Appropriability	0.279*** (0.04)	0.283*** (0.03)	0.273*** (0.02)	0.271*** (0.03)	0.269*** (0.02)	0.271*** (0.03)
Regional-level characteristics						
Tertiary education	0.11 (0.07)	0.13* (0.08)	0.12 (0.08)	0.13* (0.08)	0.14* (0.08)	0.13* (0.07)
Russel group university	4.81** (1.87)	5.88*** (1.65)	4.56** (1.96)	4.67** (1.95)	4.45** (1.96)	4.77** (1.96)
Business churn	−0.36 (0.28)	−0.32 (0.30)	−0.22 (0.30)	−0.27 (0.30)	−0.28 (0.30)	−0.27 (0.30)
Region population	−1.95** (0.63)	−1.99** (0.68)	−2.13** (0.67)	−2.02** (0.67)	−2.06** (0.67)	−2.05** (0.67)
Business density	0.02** (0.01)	0.03** (0.01)	0.03** (0.01)	0.03** (0.01)	0.02** (0.01)	0.02** (0.01)
GVA per capita	0.01 (0.01)	0.02** (0.01)	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)
Region resources	−4.18 (3.48)	−4.58 (3.88)	−3.46 (3.84)	−3.45 (3.84)	−3.51 (3.85)	−3.87 (3.85)
EQI	0.14 (1.56)	0.08 (1.60)	0.08 (1.79)	0.10 (1.79)	0.11 (1.79)	0.04 (1.79)
Intra-industry spillover (H1a)	2.39 (2.00)	4.65** (2.01)	6.31** (2.95)	6.28** (2.83)	4.85* (2.87)	10.89** (4.66)
Intra -industry spillover X Internal R&D intensity (H1b)	−61.59*** (25.53)	−75.32** (26.33)	−98.24*** (32.78)	−68.37*** (30.95)	−0.83 (6.70)	−76.45** (33.16)
Inter-industry spillover (H2a)	−1.10 (4.42)	−1.54 (4.32)	−8.68 (6.18)	−8.09 (6.13)	−7.34 (6.50)	−10.16 (10.41)
Inter-industry spillover X Internal R&D intensity (H2b)	125.43* (72.80)	120.72** (54.56)	161.78* (90.83)	93.42 (90.98)	66.71 (70.24)	187.05** (88.52)
Sector identifier	2.02 (1.97)	3.64*** (1.19)	7.67*** (2.53)	−3.62 (2.54)	0.79 (3.57)	−0.58 (1.41)
Sector identifier X R&D intensity	106.31* (75.65)	14.31*** (4.94)	59.02** (24.00)	−68.74 (43.27)	−20.70 (23.35)	81.51** (32.39)
Sector identifier X Intra -industry spillover	4.33 (9.45)	−7.80 (6.73)	−2.37 (7.80)	−4.99 (11.26)	−16.07 (14.76)	−7.54 (5.78)
Sector identifier X Inter-industry spillover	−9.92 (16.66)	−4.49 (5.01)	−12.34 (19.98)	−11.52 (20.74)	−3.48 (10.60)	4.54 (12.02)
Sector identifier X Intra -industry spillover X R&D intensity	***−141.71 (94.11)***	***−138.21 (93.01)***	***−1.55 (14.98)***	***−232.71** (121.21)***	***116.83 (88.84)***	***−21.70 (99.14)***
Sector identifier X Inter -industry spillover X R&D intensity	***115.12 (80.13)***	***170.87** (69.13)***	***−105.72 (175.98)***	***133.08** (40.48)***	***182.37 (102.19)***	***−281.50 (161.68)***
Constant	−22.64 (14.13)	−24.64 (13.99)	−22.02 (14.75)	−23.54 (14.69)	−22.98 (14.85)	−22.08 (15.05)
Error variance	762.58*** (24.71)	765.45*** (25.44)	765.13*** (25.96)	763.29*** (25.95)	764.45*** (25.44)	764.87*** (25.43)
Number of obs.	19220	19220	19220	19220	19220	19220
Uncensored	4156	4156	4156	4156	4156	4156
Left-censored	15064	15064	15064	15064	15064	15064
Chi2	2998.17	2967.17	2922.48	2928.18	2905.09	2909.76
Pseudo R2	0.09	0.10	0.10	0.10	0.10	0.10
Log-likelihood	−12466.19	−12432.19	−12415.23	−12420.29	−12423.92	−12421.59

Note: Significance level: *p < 0.05. Number of observations: 19,220 obs.
Source: Office of National Statistics (2017, 2018, 2023), Business Demography Population Estimates (2020); Annual Population Survey (2020).

external R&D as well as investment in innovative training for all sectors (Table 4, specifications 1–6). We find the direct effect of intra-industry spillovers is positive and significant, supporting H1a, with no significant differences in the effect of intra-industry spillover on innovation (Table 4, specifications 1–6), supporting the general view on the role of knowledge spillovers for innovation (Xu, 2015; Kobarg et al., 2019). The only sector where the effect is insignificant is low tech manufacturing (Table 4, specifications 1). All interaction coefficients of internal R&D intensity and intra-industry spillovers are negative and significant, but creative sector (Table 4, specification 5), supporting the substitution effect in H1b. This result demonstrates that creative sector benefits equally from intra-industry spillovers and expanding firm capabilities.

We find that the direct effect of inter-industry spillovers on innovation is insignificant, not supporting H2a across all sectors, consistent with prior findings in Table 3. The joint effect of internal R&D intensity and inter-industry spillovers remains positive for all sectors except for creative industries and KIBS, not supporting H2b for these sectors. Unlike sectors where radical innovation is heavily reliant on formal R&D activities, in creative industries and KIBS, innovation frequently emerges from non-R&D based activities such as design, learning by doing, and leveraging external knowledge sources. These sectors thrive on the iterative process of creativity (Audretsch and Belitski, 2013; Florida, 2014), where the development of new products or services is often driven by the continuous adaptation and recombination of existing and new ideas, rather than through structured R&D processes.

For instance, in creative industries, design thinking plays a pivotal role in fostering innovation and this approach focuses on user-centric innovation, where understanding consumer needs and preferences drives the creation of new products (Brown, 2009). In KIBS, knowledge spillovers and external collaborations are critical, as firms in these industries often rely on absorbing and applying knowledge generated externally to create innovative services (Muller and Doloreux, 2009). Additionally, the concept of "learning by doing" is particularly relevant in these sectors as firms engage in day-to-day creative operations, accumulating significant tacit knowledge through face-to-face practical interactions that becomes a key driver of innovation. This form of experiential learning allows firms to adapt and refine their offerings continuously, leading to incremental but significant innovations over time (Lundvall and Johnson, 1994).

Finally, our triple interactions of internal R&D intensity and spillovers with each sectoral dummy demonstrated an accelerated effect of firm capabilities and inter-industry spillovers for KIBS and high-tech manufacturing industry. Our triple interactions with sector dummies, firm capabilities and intra-industry demonstrated the negative (substitution effect) for KIBS (Table 4, specification 4). To visualize key differences in the relationship for firms in KIBS, we calculated the predictive margins of product innovation for intra- and inter-industry knowledge spillovers and R&D intensity (see Figs. 3 and 4).

Finally, we found that creative industries can benefit from intra-industry spillovers and internal R&D, while increasing their investment in R&D and accessing intra-industry spillovers may not be the condition for innovation, not supporting H1b (Table 4, specification 5). This unexpected finding is closely related to the nature of knowledge creation and transfer in this industry. Our results demonstrate that investment in R&D and other creative works internally and the availability of R&D intra-industry spillovers are independent for firm innovation. Creative firms can continue investing in R&D internally and access intra-industry knowledge via spillovers while growing their innovation.

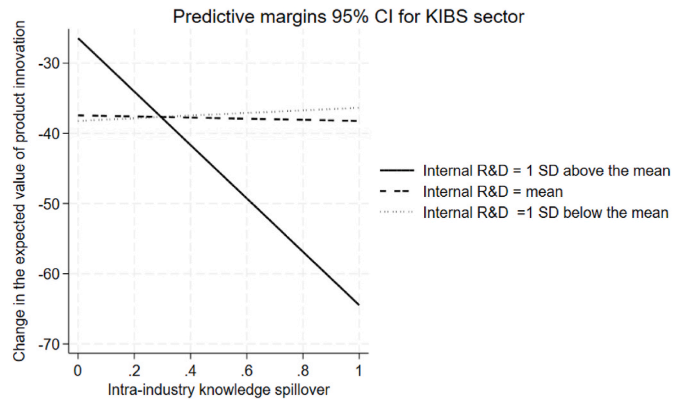

Fig. 3. Predictive margins for change in the expected value of product innovation for intra-industry spillovers for different levels of firm's capabilities – in KIBS sector.
Source: Office of National Statistics (2017, 2018, 2023).

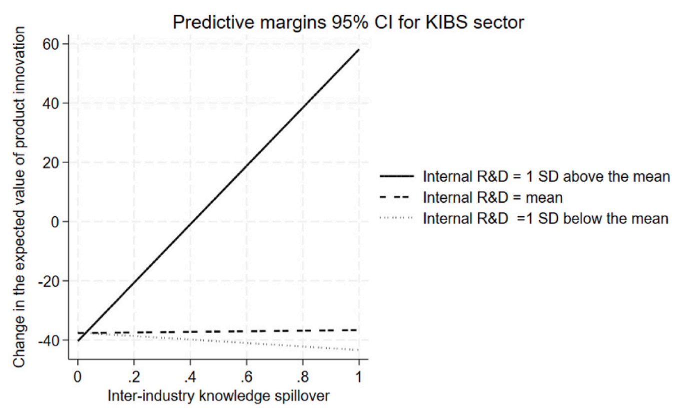

Fig. 4. Predictive margins for change in the expected value of product innovation for inter-industry spillovers for different levels of firm's capabilities - in KIBS sector.
Source: Office of National Statistics (2017, 2018, 2023).

5. Discussion

Drawing on open innovation literature explaining the role of knowledge spillovers in facilitating and sustaining innovation (Laursen and Salter, 2006; Nooteboom et al., 2007; Kobarg et al., 2019) we researched how the interplay between firm's capabilities and two types of industry spillovers shapes innovation activity amongst the most innovative UK firms and across six distinct sectors, extending recent research on knowledge spillover of innovation (Audretsch and Belitski, 2022).

Investment in internal R&D has traditionally been sought as a mechanism to develop firm's capabilities which plays a dual role as a source of innovation (Cohen and Levinthal, 1990). Firstly. it grants the ability to access, adopt and adapt external knowledge such as knowledge spillovers (Qian and Acs, 2013; Qian and Jung, 2017). Secondly it creates conditions within a firm to produce innovation. However, in contrast to prior research our argument is that an increase in investment in R&D when industry's level of R&D investment is high, and intra-industry knowledge spillovers increases may hamper firm's innovation and diminish incentives to invest in R&D. We would like to explain this effect further.

Firms strategically focus their internal R&D on areas where they can maximize unique contributions, and what is not available as knowledge spillover from the localized firms in the same industry, relying on intra-industry spillovers for more general innovations. This allows them to optimize their innovation process and costs. We find that firms with low level of R&D investment benefit by intra-industry spillover until a certain point, when further increase in R&D enables firms to internalize their capabilities and reduce reliance on intra-industry knowledge spillovers. Alternatively, firms that do not invest in R&D will use spillovers within industry to maintain or even increase innovation sales while optimizing internal resource use and minimizing costs of R&D.

Our findings challenge Noteboom's et al. (2007: 1028) argument that "larger technological capital generally shows better performance in dealing with cognitive distance", as we show that the boundary condition for innovation and inter-industry spillovers is investing in firm capabilities at least above the average industry level. The complementarity effect arises when investment in R&D reaches above the average in the industry, so that increase in firm's capabilities can complement inter-industry knowledge spillovers and enhance firm's innovation. Our study also extends our understanding of prior research (Chen et al., 2016) that finds complementarity between firm's R&D effort and collaborations with universities and research labs that generates university to industry spillovers. It is likely that only those firms, that are able to invest substantially in R&D are able to source knowledge from universities directly via collaboration and knowledge transfer partnerships, and via spillovers. While we do not find the significant effect of inter-industry spillover on firm's innovation, we believe the effect is long-term as most breakthrough innovations with a profound impact on industry have been the result of exploring unknown technological landscapes and the critical role of novel knowledge in driving within industry innovation (Levinthal, 1997; Kneeland et al., 2020).

The divergent and sometimes unexpected findings of this study build on complementary and substitution effects of firm's capabilities empirically findings a threshold where the relationship between R&D investment and availability of knowledge spillovers may change.

Firms with low level of capabilities rely on intra-industry knowledge spillover for innovation (Audretsch et al., 2021, 2024), which explains the positive slope (Fig. 1), while firms with a high capabilities, may perceive intra-industry spillovers as a competition threat or simply substitute them by an increasing firm capabilities, as firms invest in R&D and may seek for procedures to restrict knowledge outflows and innovate with own capabilities, leading to a substitution effect and negative slope (see Fig. 1). Our empirical findings identify the flipping point where positive effect may switch to negative for firm innovation.

Firms need to be aware that investment in capabilities in clusters where intra-industry knowledge spillovers are high could become a common knowledge and open to rivals, thus wearing off the competitive advantage of firms (Bloom et al., 2013; Grebel and Nesta, 2020). We identify it as an important condition why firms may fold their investment in R&D if they are located in industrial clusters where intra-industry spillovers are usually high (Rigby and Brown 2015; Delgado, 2020).

Firms with low capabilities in a location with an increasing inter-industry spillovers are unable to absorb it resulting in lower firm innovation. Firms that are able to invest in internal capabilities to recognize inter-industry knowledge spillovers find complementary effect leading to increase in firm innovation (see Fig. 2).

When analysing the joint effect of firm's capabilities proxied by internal R&D and both types of spillovers across sectors we find for KIBS the joint effect is accelerated compared to other sectors in our sample (see Figs. 3 and 4). This effect may be attributed to the unique characteristics of the KIBS industry, including its reliance on specialized knowledge, close client interactions, highly skilled workforce, collaborative networks, and dynamic environment, contribute to a greater effect of firm capabilities and knowledge spillovers on innovation compared to other industries. Let us elaborate further. Firstly, KIBS has higher dependency on knowledge and specialized expertise related to use of advanced knowledge and technology for providing a service. Their services often involve complex problem-solving, consultancy, IT services, and R&D, which require continual knowledge acquisition and application. This high dependency on variety of knowledge makes them more responsive to innovation. Employees in KIBS firms are usually highly educated and possess specialized skills that demands more investment in R&D as well as increases firm's capabilities for every unit of R&D expenditure. These firms invest significantly in continuous learning and professional development, enhancing their capability to absorb, integrate, and apply new knowledge and hence are better able to absorb inter-industry spillover, and on the contrary, may have all needed resources internally and not engage with related variety of knowledge available as intra-industry spillover.

Secondly, KIBS firms typically work closely with clients, which facilitates frequent and intense knowledge exchanges allowing for synergetic effects of R&D investment and external knowledge sourcing. Through these interactions, KIBS firms gain deep insights into client needs, industry trends, and emerging problems which may further increase sales of innovative products. KIBS firms frequently tailor their services to meet specific client needs, requiring innovative approaches and solutions. This focus on customization drives them to leverage their capabilities and any new knowledge they acquire, fostering a culture of continuous innovation.

Finally, close collaboration with customers, firms in KIBS often operate within extensive networks of other businesses within enterprise group, research institutions, suppliers and universities. These networks are fertile grounds for intra and inter-industry knowledge spillovers, as these networks further facilitate the flow of knowledge and help to better absorb inter-industry spillover, while equipping firms in KIBS with necessary resources to make intra-industry spillover obsolete due to abundance of ideas and best practices within organizational boundaries.

Another unexpected finding is that firms in the creative industries can effectively use both internal R&D and intra-industry spillovers to innovate. In many aspects this could be a result of the nature of creative work, such as design, film, music, fashion, and media sectors thrive on creativity, originality, and the continuous development of new ideas. The nature of creative work inherently involves experimenting with new concepts that requires both firm's capabilities and investment in skills and R&D as well as copying and imitating others, searching for new ideas from the industry. The constant need for novelty and differentiation drives these firms to seek investment in internal capabilities as well as learning from peers (Belitski and Herzig, 2018; Fisher and Barrett, 2019), incorporate a wide range of inspirations and innovations within the sector. For example, musicians can learn from other musicians on the methods how to play and on establishing and setting the performance.

Furthermore, firms in creative industries often have a highly collaborative culture where experts in the field frequently work together on projects, as jazz musicians randomly get together and improvise and jam (Audretsch et al., 2023), share ideas, and play together. This organizational, industry specific culture fosters an environment where knowledge spillovers are commonplace, and individuals are welcomed to borrow from peers and firms in general are more open to competitors to improvise and co-create ideas and learning than firms in other industries.

Many creative industries operate on a project-based structure, where teams are assembled for specific projects and disbanded upon completion. This structure encourages a continuous flow of new ideas intra-industry, while also making firms to invest in capabilities for the project and for their employees. Interestingly, that creative sector firms may have more fluid and adjustable boundaries than firms in the sector, meaning that employees frequently move between different firms and projects learning from peers to a greater extent than in other sectors (Belitski and Herzig, 2018) adding to further mobility and transfer of knowledge and skills within the creative industry.

Unlike other sectors, where both tacit and explicit knowledge are commonplace (Audretsch and Belitski, 2020b), it is tacit knowledge that is personal and context-specific plays a crucial role in creative industries. Learning from artists, programmers, musicians, architects is often through shared through face-to-face interactions and experiences, living through the project where both internal knowledge accumulated in companies is merged with knowledge from networks, making intra-industry spillovers more effective and more relevant to the creative project.

6. Conclusion

6.1. Theoretical implications

Prior research on the role of external and internal knowledge for firm innovation is still emerging, with arguments ranging from “the more is less” (Hervas-Oliver et al., 2018; Kobarg et al., 2019) to “the less is more” (Claussen et al., 2015). Our study advances this research and clearly demonstrates two boundary conditions for firm innovation: the type of knowledge spillover (intra- and inter-industry spillovers) and R&D intensity within the industry context where a firm is located.

Our study extends prior research on the heterogeneity of knowledge spillovers in innovation (Cassiman and Veugelers, 2006; Amoroso et al., 2018) by focusing on the role of investment in firm capabilities and the industrial context, where effects may differ due to the nature of the knowledge and industry (Liang and Goetz, 2018). Our findings help understand how firms can cross-fertilize knowledge by combining intensive R&D efforts with diverse external knowledge from other industries, contributing to prior research on internal and external knowledge capabilities and their efficiency in recombination fir firm innovation (Denicolai et al., 2016; Antonelli and Colombelli, 2018). This clarification is important to determine the specific type of knowledge spillovers needed for innovation in various industries (Audretsch and Belitski, 2023a). The differences between creative, KIBS, and other industries clearly demonstrate that firm capabilities, knowledge spillovers, and innovation are interrelated.

We also advance Hervas-Oliver et al.’s (2018) research, which aimed to transfer the concept of knowledge leakage (Myles Shaver and Flyer, 2000) and learning à la Marshall (1890). We suggest that there exists a nonlinear effect between internal and external knowledge for firm innovation. In other words, the interaction between internal and external knowledge on innovative performance should consider the extent of internal knowledge investment in the industry, the type of spillover (intra- or inter-industry), and the specific industry in which a firm is located.

The industry perspective provides further insights into the differences in the interplay between firm capabilities and knowledge spillovers for firm innovation. This may explain the heterogeneity in firm decisions to invest in internal knowledge or to seek knowledge from external sources (Audretsch et al., 2024).

6.2. Managerial implications

Given the key findings of this study, our message to C-level and innovation managers is as follows. Firstly, location choice matters. Innovation managers must decide how much R&D to invest in developing firm skills and capabilities based on whether they source regional knowledge within or between industries and the specific characteristics of information and knowledge in their industry. Secondly, reducing R&D intensity may result from an abundance of localized intra-industry knowledge spillovers and developing regional collaborations with other firms in the industry, such as techno parks, science parks, or industrial clusters. Increasing R&D intensity could result from expected increased regional knowledge available via inter-industry spillovers in the short and long term and the need to access, absorb, and integrate inter-industry knowledge spillovers into firm routines and practices. By considering this complex relationship, the “more, the merrier” finding is related to a condition when a firm’s investment in capabilities (Eisenhardt and Martin, 2000) enables access to localized inter-industry knowledge (Enkel and Heil, 2014) to bolster long-term innovation. The “less is more” approach is valid when a firm’s investment in capabilities may remain low as long as localized intra-industry knowledge spillovers are high and increasing.

Managers in creative industries are often subject to rapidly changing trends and consumer preferences, motivating them to continually adapt and innovate to keep up with these changes. Protecting ideas is less common than sharing creative ideas due to the collaborative nature of the work. Investment in internal R&D provides the means to create such networks and foster knowledge exchange rapidly compared to lengthy legal procedures related to knowledge transfer in other sectors with higher appropriability of knowledge and longer manufacturing cycles (Audretsch and Belitski, 2023a). An abundance of new ideas within the creative sector could be exploited by innovation managers along with further investment in internal R&D to develop innovation capabilities and enhance cross-dependence between firm capabilities and external knowledge, potentially making firms more resilient if they learn from each other, as many did during the COVID-19 pandemic (Khlystova et al., 2022).

KIBS firms experience an accelerated effect of complementarity between internal and external knowledge, likely related to rapid changes and high competition. KIBS managers must continuously innovate and improve their services, pushing these firms to be proactive in seeking collaborations within and outside the industry and looking for ways to more rapidly integrate external inter-industry spillovers into firm routines compared to firms in other sectors. KIBS firms could choose to rapidly implement new knowledge via intra-industry spillovers, as they benefit more from within-industry knowledge, or invest in firm capabilities and reduce collaborations within the industry.

6.3. Limitations and further research

This study has several limitations. Firstly, the data has a significant cross-sectional element, with approximately 60 percent of the firms entering the sample only once, resulting in an unbalanced panel. Future research may address this by limiting the sample to panel data and checking for robustness by comparing data from different countries. This will allow to explore in more details and over time a firm’s ability to recognize and implement knowledge spillovers and its subsequent effect on innovation given firm’s prior internal knowledge and capabilities. It would be important to further examine how prior experience in the use of external knowledge (e.g. previous knowledge collaborations) helps in this absorptive capacity and thus better exploit external knowledge (inter- and inter-industry spillovers) for firm innovation and performance.

Secondly, a key limitation of this study remains its focus on the moderation effect of internal R&D intensity, which may not fully capture the complexity of how firms’ capabilities facilitate knowledge spillover innovation. Innovation is often the result of multiple factors beyond internal R&D, such as buying knowledge and technology externally, employee training for innovation, hiring industry experts and consultants, strategic knowledge collaborations, the adoption of advanced technologies. By concentrating solely on internal investment in R&D, this study may overlook the contributions of these other firm’s capabilities and the role they play in facilitating the effect of knowledge spillovers on innovation.

While this study provides valuable insights into the interactions between internal R&D and knowledge spillovers for innovation, future research could broaden the scope by exploring how other firm capabilities interact with intra- and inter-industry knowledge spillovers in shaping innovation. Investigating other firm capabilities, individually or in combination with knowledge spillovers will contribute to innovation literature by providing a more holistic understanding of the mechanisms that drive firm innovation.

Additionally, there are many industries in which other mechanisms such as market scanning, design, hiring specialized labor or learning by doing and using advanced technology-led products, service and/or process innovation. Future research could explore sector-specific dynamics, as the relative importance of internal R&D versus other capabilities may vary significantly across different industries.

Thirdly, the dynamics between firm capabilities and knowledge spillovers could depends on the novelty of the innovation (Xu, 2015). For incremental innovations (i.e., innovations that are new to the firm but not the market), a shared knowledge base is crucial for successful collaboration and leveraging internal capabilities, thus the complementarity effects could be present, unlike substitution effects for radical innovation. This suggests that future research should study, compare and contrast the interaction between various firm internal capabilities and knowledge spillovers for radical and incremental innovations. This would help determine whether the substitution or complementarity effects observed with radical innovations hold true for incremental innovations, where a common knowledge base plays a more pivotal role.

While some of our findings align with the arguments of Hervas-Oliver et al. (2018), Kobarg et al. (2019), and Audretsch and Belitski (2022) on the existence of both positive and negative effects, further research should continue to explore the U-shaped relationship between knowledge spillovers and firm innovation. This should include controlling for different types of innovation capabilities and various innovation outcomes (e.g., process and product innovation, organizational internal and external innovation, imitation, and first-mover advantage).

We call for further research into the "net effect" of knowledge spillovers, which will unpack the diminishing marginal returns to knowledge spillovers (Kobarg et al., 2019) and provide novel insights differentiating between intra- and inter-industry spillovers and industry context. At the regional level, further research should focus on understanding the role that intra- and inter-industry knowledge spillovers play in firm innovation and growth across different sectors, as well as in determining firms' geographical location choices to learn from peers and benefit from knowledge spillovers.

CRediT authorship contribution statement

David Bruce Audretsch: Supervision, Investigation, Conceptualization. **Maksim Belitski:** Resources, Methodology, Investigation, Formal analysis, Data curation. **Anna Spadavecchia:** Visualization, Validation, Investigation. **Shaker A. Zahra:** Supervision, Investigation, Conceptualization.

Data availability

The data that has been used is confidential.

Appendix A1. Industrial, regional and firm size distribution of the firm level sample

Industry distribution	Firm sample	
	Firms	Share, %
1 - Mining & Quarrying	165	0.86
2 - Manufacturing low tech and medium-low	1140	5.93
3 – Manufacturing high-tech and medium-high	3675	19.12
4 - Electricity, gas and water supply	140	0.73
5 - Construction	1990	10.35
6 - Wholesale, retail trade	3115	16.20
7 - Transport, storage	1121	5.83
8 - Hotels and restaurants	1038	5.40
9 - ICT	1244	6.47
10 - Financial intermediation	693	3.60
11 - Real estate and other business activity	2335	12.14
12 - Public admin, defence	1951	10.15
13 – Education	186	0.96
16 - Other community, social activity	427	2.22
Total	**19220**	**100.00**
Regional distribution		
North-East	1055	5.48
North-West	1787	9.29
Yorkshire and The Humber	1550	8.06
East Midlands	1544	8.03
West Midlands	1691	8.79
Eastern England	1687	8.77
London	1841	9.57
South-East	2095	10.90
South-West	1594	8.29
Wales	1271	6.61
Scotland	1474	7.66
Northern Ireland	1631	8.48
Total	**19220**	**100.00**
Firm size distribution		
small firms (10–49 FTEs)	10389	54.05
medium small (50–99 FTEs)	4548	23.66
medium large (100–249 FTEs)	4166	21.67
large (250+ FTEs)	117	0.61
Total	**16914**	**100.00**

Source: Office of National Statistics (2017, 2018, 2023), Business Demography Population Estimates (2020); Annual Population Survey (2020).

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