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REGULAR ARTICLE

The multifaceted nature of cooperation for innovation, ICT and innovative outcomes: evidence from UK Microdata

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Abstract
Cooperation in innovation activities is a key building block in forming entrepreneurial innovation networks. However, the impact on innovation of different forms of cooperation among multiple stakeholders composing a firm's relational environment can be dramatically different, depending on whether the modalities of cooperation are tacit or explicit and the type of functional relations between the cooperating organizations. Information and Communication Technologies (ICTs) facilitate cooperation and innovation outcomes. The main aim of this paper is to disentangle the effects of *explicit* vs. *tacit and complementarity* vs. *competitive* modalities of cooperation in innovation activities on innovation outputs. Based on pooled UK Microdata from 2004 to 2010, this paper's main finding is that tacit cooperation, emerging from R&D and ICTs spillovers, increases firms' likelihood to introduce process, product, and organizational innovations. We also find that a firm's functional relation with its cooperating peers determines the sign of the association with innovation outcomes: explicit cooperation among competitors lowers the level of innovations. In contrast, cooperation along the value chain brings more innovations.

Keywords Tacit cooperation · Explicit cooperation · ICTs · Innovation networks · Geographic and sectoral spillovers

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1 Introduction

Cooperation in innovation activities provides the linkages that underlie *innovation networks*—the collaborative arrangements through which firms benefit from their *knowledge-sourcing* activities when introducing innovative products or services (Huggins et al., 2015). These cooperative relations can be seen as the links along which innovation-relevant knowledge travels across these networks. Information and communication technologies (ICTs) have been radically transforming the context of such networks as the links required for knowledge sourcing between two organizations become progressively decoupled from geographic proximity due to the significant reductions in transmission costs and the widening of the scope of codifiable knowledge through digitization. ICTs, on the other hand, might also indirectly help spread innovation knowledge through spillovers. This is especially true given the importance of innovative activities in the ICT sector for the diffusion of R&D spillovers across all sectors of an economy (Moncada-Paternò-Castello, 2022).

This paper explores the separate roles of ICTs and of different cooperation modalities in shaping the likelihood of firms' product, process, and organizational innovation outcomes. The data are based on four waves of the UK innovation surveys, integrated with other UK business, geographic, and intersectoral trade data sets.

Concerning the modalities of cooperation, our focus is on capturing the differences in their impact on innovation along two key dimensions:

1. The competitiveness vs. complementarity (C-C) one expresses the relational kind of cooperation, such as cooperating with clients, suppliers (both complements), or market rivals (Cassiman & Veugelers, 2002; Audretsch & Belitski, 2020a, b); and,
2. The explicit vs. tacit (E-T) dimension separating between explicit, acknowledged cooperation, which is typically captured in the literature on open innovation networks (Enkel et al., 2009), and tacit cooperation (Lam, 2000; Polanyi, 1958), arising from spillovers, due to ICTs and R&D innovation activities, weighted according to the proximity in either geographic (Audretsch & Feldman, 1996) or production spaces (Aldieri et al., 2022).

The main aim of this paper is to disentangle the effects of *explicit* vs. *tacit, and complementarity* vs. *competitive* modalities of cooperation in innovation activities on innovation outputs, hence characterizing the effectiveness of the UK *innovation network* in transforming explicit cooperation, ICTs and R&Ds into firm-level innovation outputs. Many contributions (see Freire and Gonçalves, 2021 for a recent survey) assess the impact of various forms of cooperation on innovation outcomes. This paper fills a critical gap in this literature by estimating the impact of various forms of cooperation according to the two-dimensional taxonomy, C-C / E-T, while separately considering the role of spillovers caused by ICTs. Additionally, for each of the three main types of innovations—process, product, and organizational—the various effects of diverse forms and modalities of cooperation, investments in intangible capital, and ICTs are jointly estimated. This distinction is especially important because different types of innovations have varied effects on employment, with process innovations having a labor-saving benefit and product innovations having an opposite labor-increasing effect (Dosi et al., 2021).

Finally, this paper's contribution goes beyond simply differentiating between the competitiveness vs. complementarity and the explicit vs. tacit dimensions of cooperation in innovation networks. Rather, it also studies these effects according to distinct types of intangible innovative activities (Corrado et al., 2005) in the first stage of its estimation process, and then assesses the effects of these innovative activities on the product, process, and organizational innovations.

Since tacit cooperation results from unintended by-products of innovative activities within the relevant innovation networks, rather than being the direct result of strategic managerial decisions like explicit cooperation, it is important for managers and policymakers to better understand how different cooperation modalities affect innovations. Additionally, this paper's insights will offer helpful pointers for innovation managers and policymakers by decoupling the effects on innovation across various intangible investments and ICTs because these effects can be specifically attributed to each of the three typologies of innovation: process, product, and organizational ones. Therefore, dependent on the type of innovation they intend to introduce, our findings will provide managers with crucial information on how to target their investments in intangible capital and ICTs, and their collaborative methods.

Following this Introduction, Section 2, which addresses the contextual framework, goes over some of the most relevant literature insights pertinent to formulating the main hypotheses examined in this paper. The data, key variables of interest, estimation strategy and results from the two-stage model are introduced in Section 3. Section 4 discusses the key findings and provides a detailed analysis of the direct and indirect effects of the various modalities of cooperation in innovative activities and ICTs on innovation outcomes. The discussion of the ensuing managerial strategies, policy implications, and limitations in Section 5 brings the paper to a close.

2 Conceptual framework

This section introduces the relevant conceptual framework leading to the main hypotheses assessed in the paper. All these hypotheses will focus on assessing the potentially different effects on innovation outcomes due to cooperation within *innovation networks*, according to the two separate dimensions of cooperation discussed above. The competitiveness vs. complementarity dimension, indicating whether firms are product competitors or are linked through complementarity relations, is addressed by hypotheses H1 and H2 below, while H3 and H4 will focus on the role played by tacit cooperation, through R&D and ICT spillovers, in affecting innovation outcomes.

2.1 Innovation networks

Many associated terms are used in the literature to express that a network of external interactions is necessary to successfully transfer the information required by innovation processes. Among these terms are *innovation ecosystems*, the set of formal and informal collaborative arrangements through which firms combine their activities into (innovative) products or services, generating value by addressing new solutions for customers' needs (Adner, 2006), often also described as the business equivalent of an ecological habitat (Moore, 1993); *open innovations* (Enkel et al., 2009; Gassmann et al., 2010) that may emerge as the result of the interaction through multiple R&D collaboration relations (Tether, 2002); and *open innovation ecosystems* focusing on the complementarity between the previous two concepts (Rohrbeck et al., 2009). The concept of *inter-organizational networks* (Huggins et al., 2012), which includes the interactions and connections organizations employ to gain knowledge outside of their market relationships, is also in line with our approach. Given the emphasis on the impact of cooperation on innovation results, the whole set of cooperation relations investigated will be addressed with the more general but all-encompassing concept of innovation networks.

2.2 Explicit cooperation

As mentioned in the introduction, this study considers cooperative activities to be the fundamental links for knowledge sourcing in innovation networks. In a study on the West Midlands of the United Kingdom, for instance, De Propris (2002) observed that explicit vertical cooperation along the supply chain facilitates innovation, while Freel and Harrison (2006) reached similar conclusions in a study covering innovations in a larger area in Northern England and Scotland.

The positive impact on innovation of explicit cooperation outside a company's boundaries is one of the distinguishing characteristics that emerge from the vast literature on open innovation networks (Gassmann et al., 2010). According to Pellegrino and Piva (2020), explicit, formal cooperation in innovation is viewed as a short-term strategy for coping with complexity and lack of experience. Consequently, explicit cooperation in innovative activities is frequently found to benefit innovation (Cassiman & Veugelers, 2002; Fritsch & Franke, 2004; Piga & Vivarelli, 2004; Parker, 2008).

The first two hypotheses of this paper deal with explicit cooperation and can be traced back to Cournot's (1838) findings on the mutually beneficial effects of integration (here viewed as an extreme form of cooperation) between two vertically separated monopolists linked by a supplier/customer relationship to avoid double marginalization inefficiencies.

In this context, our hypotheses focus on differentiating the possible impact on innovation of various relational forms of explicit cooperation based on the organizations' location along the C-C dimension.

In more detail, the paper's first hypothesis, H1, will focus on the expected positive effects of relationships where explicit cooperation occurs between a firm and its customers or suppliers along the complementary links of an *innovation network*.

H1: Explicit complementarity cooperation in innovative activities facilitates the introduction of innovations.

The second hypothesis, H2, focuses on the potentially negative impact of explicit cooperation on innovation, specifically the explicit cooperation among competitors for the final product. The introduction of innovations may have negative profitability effects on output market competitors, as it may intensify *price-competition* by increasing the innovating firm's efficiency due to process innovations, *quality-competition* due to the improved characteristics of product innovations, and the overall competitive pressure due to the efficiency gains resulting from organizational innovations.

The awareness of these potentially negative profit externalities resulting from innovations may incentivize product market competitors to collaborate in reducing their innovative output and, consequently, market competitiveness. Similar outcomes emerge, for instance, from models of spatial competition in which proximity to innovators may negatively impact profitability (Giovannetti, 2013) or from findings that diversity in external collaborations may negatively impact internal innovation efforts (Gkypali et al., 2017).

Katz et al. (1990) provide a clear description of the market competition aspects of this incentive, stating: "When the firms conducting R&D are product-market rivals, R&D investment by one firm may harm the profitability of the others. In this case, the externality across firms may be a negative one, so that the effect of cooperation is to reduce the incentive to conduct R&D." (Katz et al., 1990, p. 145). Similarly, Iammarino et al. (2012) using UK innovation data, discovered that "while innovation seems to be reinforced by collaborations along the supply chain, once attention is turned to the horizontal dimension, rivalry seems to dominate." (Iammarino et al., 2012, p. 1290). These coordination incentives are also captured by a "Dominator strategy," which is based on horizontal network integration aimed at collective takeover that reduces the innovation outputs (Insiti & Levien, 2004). Similarly, based on Korean data, Park & Lee (2022) conclude that horizontal cooperation in R&D harms a firm's R&D intensity due to the decrease in R&D appropriability and the incentives for opportunism. Moreover, R&D collaboration with rivals may enable companies to use the partners' contributions as a substitute for their own inventive efforts rather than as a supplement.

The following hypothesis, H2, captures these insights and incentives by focusing on the expected negative effects of explicit cooperation among competitors on the outcomes of innovation networks.

H2: Explicit competitive cooperation in innovative activities with competitors reduces the outcomes of innovation networks.

2.3 Tacit cooperation: spillovers from investment in R&Ds and ICT

The next two hypotheses examine the effects of spillovers due to interaction in innovative activities, including investment in R&D and ICTs. These are intended to capture the unique role that tacit cooperation plays in fostering innovation networks. Intangible capital (Corrado et al., 2005), including various innovative activities such as expenditure on R&D, training towards innovation, and ICTs, has been identified as a key enabler in building a firm's capacity for absorbing knowledge produced elsewhere (Cohen & Levinthal, 1989), thereby facilitating cooperation towards innovations. The role of R&D activities, from a resource-based view of the firm, was recently summarized by Lehmann et al. (2022) as "The more firms invest in R&D activities, the more knowledge is produced, leading to both an increase of the absorptive capacity as well as the total pool of tacit and hitherto unexplored knowledge that could be then exploited and transformed into economic knowledge. The internal endowment of resources and capacities has since then widely been considered as a strategic source of performance, made popular by the so-called resource-based view of the firm" (Lehmann et al., 2022 p. 130).

The following hypotheses aim to evaluate the effects of tacit cooperation, as captured by the spillovers resulting from investment in innovative activities, including ICTs, due to proximity (Knoben & Oerlemans, 2006), either in geographical or in production space.

Marshall (1890) attributed geographical proximity's relevance to the tacit dimension of knowledge (Polanyi, 1958), which requires face-to-face interaction and informal contacts (Jaffe, 1989; Audretsch & Feldman, 1996; Acs et al., 2002. See also Crescenzi and Rodriguez-Pose (2012) for an early review on spillovers effects on innovative outcomes).

This paper will evaluate the effects on innovations of cooperation due to geographical proximity, utilizing the Travel to Work Areas (TTWAs). These geographic units developed by the UK Office for National Statistics (ONS) capture the effective radius of influence of spatial interaction due to workers' commuting patterns. The TTWA level of aggregation expresses the notion of a "region" that captures "systemic elements external to the firm that influence its technological capabilities and growth…and have an influence on the firms' R&D and innovative competences and capabilities, resulting into a specific regional innovation pattern" (Iammarino et al., 2012. p. 1286).

Specifically, the geographic relationship between tacit cooperation and firm innovation is captured by weighing intangible innovative activities as inversely proportional to the distance between the TTWAs where such activities occur and the TTWA where the recipient firm is located. Research and Development and Training expenditures are the first group of geographically weighted intangible innovative activities considered.

A second crucial source of tacit cooperation is due to interindustry spillovers resulting from the proximity of production space. The significance of trade-proximity spillovers as an additional source of tacit cooperation stems from the fact that: the more firms in an industry buy from and sell to other firms, the more these firms can benefit from the technological spillovers originating from either downstream or upstream trade links (Von Hippel, 1988; Nadiri, 1993; Keller, 2002; Bartelsman et al., 1994; Los & Verspagen, 2000, for an overview, see Medda & Piga, 2012). Based on this literature's findings and using the intensity of bilateral interindustry trade flows obtained from the Input-Output Tables of the UK Economy, this paper measures tacit cooperation resulting from the spillovers due to proximity in production space.

The following hypothesis, H3, summarizes the key insights gained from the literature on the role of spillovers in facilitating the introduction of innovations.

H3: Investment in intangible R&D activities within an innovation network facilitates the introduction of innovations through spillovers due to proximity in both geographic and production spaces.

The final hypothesis presented in this paper examines the role of ICT investments in facilitating the introduction of innovations. Investment in ICTs has been identified as a key enabler for intangible innovative activities to exert their effects on process and product innovations for small and medium-sized enterprises (SMEs) in the United Kingdom (Higón, 2012) and, more generally, for productivity growth (Hall et al., 2012).

Diverse strategies have been proposed to counteract the potential source of endogeneity due to investment in ICTs potentially being both the cause and effect of innovations. Authors have suggested utilizing time-delayed ICT variables or estimating structural models (Brynjolfsson & Hitt, 1995; Hempell, 2005; Röller & Waverman, 2001). Czernich et al. (2011) proposed using a two-stage approach in modeling the effects of ICTs. This paper will also use a two-stage approach to deal with the sources of endogeneity due to the simultaneity of the possible direction of causality. The first stage estimates the intensities of innovation intangibles and ICTs. The second stage uses the predicted values of these variables to estimate their impact on the likelihood of introducing different innovation typologies.

Moncada-Paterno-Castello (2022) highlights the importance of considering the sectoral distribution of R&D spillovers, specifically that of R&D in the ICT sector, on firms' R&D performance, due to the role that ICTs play in shifting the boundaries between various knowledge-sourcing modalities. Indeed, by introducing, for instance, multimedia-enabled video conferencing and e-learning, it is easy to see how ICTs, transform the geographic reach of the *doing, using and interacting* mode of sourcing knowledge (Jensen et al., 2007), which is based on informal learning and experience-based know-how.

These arguments are captured by the final hypothesis, H4, which focuses on the impact of direct and indirect spillover effects from the ICTs sector on innovation.

H4: A firm's investment in ICTs, the localized spillovers of ICT expenditure, and the spillovers from R&D performed in the ICT sector facilitate the introduction of innovations.

3 Data

3.1 Data sources

Our empirical analysis, limited to innovation data from the United Kingdom, is based on secondary data obtained from different merged databases, providing micro-evidence of firms' innovation outputs, innovation activities, and the other relevant covariates used in the analysis and discussed in detail below. Most of these databases provide anonymized micro-evidence at the firm level.

The first set of data is collected from the four waves of the Community Innovation Survey (CIS)[1], a voluntary postal survey conducted by the Office for National Statistics every two years. The sample is designed to be statistically representative of twelve regions of the UK, most industrial sectors covering the production and the service sectors and all sizes of firms with more than ten employees. The four UK innovation Surveys (CIS) used were the following:

1. CIS 4 (2002–2004) with 16,445 initial valid responses,
2. CIS 5 (2004–2006) with 14,872 initial valid responses.
3. CIS 6 (2006–2008) with 14,281 initial valid responses and,
4. CIS 7 (2008–2010) with 14,342 initial valid responses.

The Business Expenditure on Research and Development (BERD)[2] and the Annual Respondent Database (ARD)[3] were used to construct total annual R&D intensities aggregated at the sectoral or geographical level in the UK. Sectorial spillovers variables used in the model, described below, were constructed by weighing the aggregate sector data using a matrix of sectoral weights based on the intersectoral trade flows obtained from the Input-Output Tables of the UK economy[4] that provides details linking industries' inputs and outputs; supply and demand for products; components of gross value added and the composition of uses and resources across institutional sectors.

Finally, geo-data[5] were used to construct the geographical spillover variables, using weights based on the inverse of the geographical distance between the centres of any two Travel to Work Areas (TTWAs).

[1] Department of Business Innovation and Skills, Office for National Statistics, Northern Ireland. Department of Enterprise, Trade and Investment (2013). UK innovation Survey, 1994–2010: Secure Access. [DATA COLLECTION] 3rd EDITION. UK Data Service. SN 66,909. DOI https://doi.org/10.5255/UKDA-SN-6699-3eli.

[2] Office for National Statistics (2013). Businesses Expenditure on Research and Development, 1995–2011: Secure Access. [DATA COLLECTION] 2nd EDITION. UK Data Service. SN 6690 BERD. DOI https://doi.org/10.5255/UKDA-SN-6690-2.

[3] Office for National Statistics (2012). Annual Respondent Database, 1973–2008: Secure Access. [DATA COLLECTION] 3rd EDITION. UK Data Service. SN 6644. DOI https://doi.org/10.5255/UKDA-SN-6644-5.

[4] Office for National Statistics, (2011). Input-output supply and use tables. [Online] Available at: https://webarchive.nationalarchives.gov.uk/ukgwa/20120108114604/http://www.ons.gov.uk/ons/publications/re-reference-tables.html?edition=tcm%3A77-240418&format=contrast.

[5] Office for National Statistics, (2011). Travel to Work Areas UK 2011 map V2. [Online] Available at: https://geoportal.statistics.gov.uk/Docs/Maps/Travel_to_Work_Areas_UK_2011_map_V2.pdf .The TTWAs subdivide the UK into 243 non-overlapping, contiguous areas inside which a substantial proportion of the resident working population commutes to work.

3.2 Main variables

3.2.1 Dependent variables

The dependent variables for the final estimation stage were obtained from the CIS questions on a firm's market introduction of three possible, not mutually exclusive, innovation outcomes, namely:

- *Product innovations*, as "new or significantly improved goods or services."
- *Process innovations*, as "new or significantly improved methods for the production or supply of goods or services" and,
- *Organizational innovations*, as "new business practices for organizing procedures and new methods of organizing work responsibilities and decision making or new methods of organizing external relationships with other firms or public institutions."

Iammarino et al. (2012) and Zoia et al. (2018) used positive answers to product and process innovation questions to indicate firms with *technological capabilities*. Similarly, these authors considered negative answers to these questions, indicating the lack of innovative output, coupled with the presence of an investment in innovative activities, as characterizing firms with *technological competencies* but lacking *capabilities* to transform their *competencies* into innovations.

In our model, we focus, instead, on estimating the impact on *product*, *process*, and *organizational* innovations, of varied innovation activities, including their geographic and sectorial spillovers, to capture the innovation effects of the tacit dimension of cooperation while also considering the impact of explicit forms of cooperation.

3.2.2 Main covariates

For each firm, we considered three sets of main covariates of interest to assess our hypotheses:

The first group of covariates, obtained from the firms' answers to the CIS questionnaires, captures the intensity of a firm's investment in intangible *innovation activities* and *ICTs* and includes:

- *Internal R&D intensity*: internal R&D expenditure, divided by firm sales.
- *External R&D intensity*: external R&D expenditure, divided by firm sales.
- *Training intensity*: training expenditure toward innovative activities, divided by firm sales, and,
- *ICTs intensity*: ICTs expenditure, again, divided by firm sales.

The second group of covariates, also obtained from the firms' answers to the CIS questionnaires, includes a set of variables capturing *explicit cooperation*. This group of variables was decomposed into two categories to diversify the competitive vs. the complementary dimensions of explicit cooperation. The first focuses on *explicit competitive cooperation*, based on the firms' answers on whether they cooperated towards innovation with other firms operating in the same market (*Coop - Other firms)*.

The second category, instead, is composed of the covariates capturing all other forms of *explicit complementarity cooperation*:

- Cooperation towards innovation with other firms operating in the same business group (*Coop - Group)*;
- Cooperation towards innovation with suppliers in a firm's value chain (*Coop – Suppliers*);
- Cooperation towards innovation with customers in a firm's value chain (*Coop – Customers*);
- Cooperation towards innovation with consultants (*Coop – Consultants)*;
- Cooperation towards innovation with universities (*Coop – Universities*)[6] ; and
- Cooperation towards innovation with public bodies (*Coop – Government*).

The third group of covariates includes a set of variables capturing tacit cooperation via R&D and ICTs spillovers based on firms' proximity in either geographic or production spaces. In detail, *tacit cooperation* is captured through the following variables:

- *Trade-mediated R&D spillovers*: the effects of each sector's aggregated R&D are weighted according to the level of trade between origin and destination sectors obtained from the *Input-Output tables* (ONS, 2011). In this framework, to identify specific effects due to R&D in the ICTs sector, we have considered two different R&D sector spillovers covariates:
  - *R&D sector spill. net of ICT sector*: reporting each R&D sector spillovers weighted according to production space proximity, based on the full economy R&D activities excluding the ICT sector, and,
  - *R&D sector spill. from the ICT sector*: capturing only the sector spillovers based on R&D activities performed in the ICTs sector, again weighted to reflect production space proximity between the ICT and the destination sector.
- *Geographic spillovers*: where the effects of different intangible innovative activities arising from the 243 separate TTWAs covering the United Kingdom (ONS, 2011) are normalized with weights that are inversely proportional to the geographic distance between the centers of these areas. In this category, we considered the following:
  - *R&D Geographic Spillovers*: based on the geographic weighing of R&D expenditures, obtained by merging the BERD, ARD and TTWAs datasets,
  - *Training Geographic Spillovers*: given by geographically weighted training expenditures, also obtained from by merging the BERD, ARD and TTWAs dataset, and,

[6] On the role of Cooperation towards innovation with Universities, see also Lehmann et al. (2022).

- *Local ICT expenditure Spillovers*, based on the level of ICTs investment performed by other firms in the same TTWA, excluding a firm's own ICTs investment.

3.2.3 Control variables

In addition to the main covariates focussing on different forms of cooperation, other firm-level control variables were considered in the analysis. These include *Firm size*, captured by the log of firms' employment, to control for the Schumpeterian notion that large firms are more likely both to undertake and to succeed in innovative activities (see, for example, Pellegrino & Piva, 2020 and Breschi et al., 2000). *Internationalization*: capturing the extent of internationalization of a firm, in terms of whether the firm sells products/services in Regional, National, EU or Rest of the World markets. These variables are widely used in the innovation literature to control for the impact that global competition exerts on innovations (see, for example, Zoia et al.,2018 and Archibugi and Iammarino, 1999). *Age*: capturing linear and quadratic effects of the age of a firm, also based on a wide literature pointing towards the innovative role of young companies (see, for example, Moncada-Paternò-Castello, 2022). *Motivation for innovation* was also considered as a control. This includes possible drivers for innovation, the intention to achieve: *Better products, Better production, Improve Profit and Meeting Regulation* (see, for example, Piening and Salge (2015) and Crépon, Duguet and Mairesse, 1998). *State subsidies* at the firm level and as a proportion of Turnover were also included as an additional control (see, for example, Pellegrino and Piva, 2020). Regional and sectoral effects (see Iammarino et al. 2012) were controlled by introducing, in the first stage of estimation:

- Eleven Regional dummies including, for England: *North West, Yorkshire and the Humber, East Midlands, West Midlands, Eastern England, London, South East, South West*, plus *Wales, Scotland* and *Northern Ireland* using *North East of England* as the base category. And,
- Thirteen dummies for the industrial and services sectors: *Manufacturing, Electricity & Gas, Water, Construction, Wholesale and Retail Services, Transport & Storage, Hotel & Restaurant, ICTs, Financial Services & Insurance, Professional Services, Public Administration & Defence, Health & Social Work Services, Art and Creative activities* and *Other services*, using *Agriculture* as the base category.

3.3 The model

To test the hypotheses developed in Sect. 2, we will use a two-stage modeling approach, whereby in the first stage we estimate the determinants of a firm's investment in innovative intangibles: internal R&D, external R&D, training and ICTs, while in the second stage, we use the innovative intangibles predicted values from the first stage as innovation inputs, to estimate the probability that a firm will introduce any combination of the three possible types of innovations outputs: *product*, *process* or *organizational* innovations.

The seminal work on the multi-stage approach was introduced by Crépon et al. (1998) to estimate a knowledge production function (Griliches, 1979; Pakes & Griliches, 1984), while Giovannetti and Piga (2017) used a three-stage approach focussing on UK productivity drivers and Hall et al. (2012) used multiple estimation steps focussing on the complementarities between innovation intangibles and ICTs to reduce the estimation problems typically associated with endogeneity due to simultaneity. Pellegrino & Piva (2020) motivate the choice of using the predicted values of the diverse innovation activities as innovation inputs in the second stage, as this helps avoid selection bias (Griffith et al., 2006) while also controlling for potential endogeneity of the innovative inputs.

The two stages of estimations and the key covariates used are represented in Fig. 1.

3.3.1 First stage: estimation of the intangibles

In the first stage, we estimate the intensities of individual firms' expenditures on internal and external R&D, Training and ICTs. Given the censored nature of these

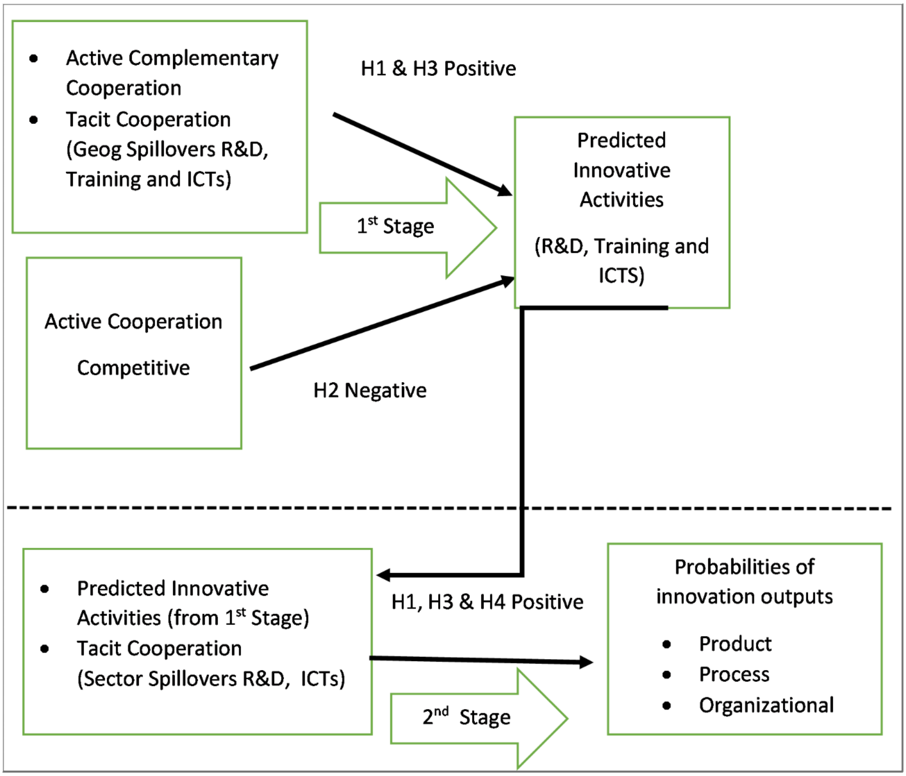

Fig. 1 Model stages

dependent variables, we consider four separate Tobit regressions, using pooled[7] data from four separate UK-CIS waves covering the period 2002–2010. These dependent variables, discussed in Sect. 3.2 above, are *Internal R&D intensity*; *External R&D intensity*; *Training intensity* and *ICTs intensity*.

The key regressors used in this first stage can be divided into the following groups:

- *R&D Geographic Spillovers,Training Geographic Spillovers,* and *Local ICT expenditure Spillovers*, used to capture the effects of implicit cooperation.
- *Coop - Other firms* focusing on *explicit competitive cooperation*.
- *Coop – Group; Coop – Suppliers,Coop – Customers,Coop – Consultants, Coop – Universities,* and *Coop – Government*, capturing different forms of explicit complementarity cooperation.

In addition to the main covariates focussing on different forms of cooperation, other firm-level variables were considered in the first estimation stage: *Firm size*, *Internationalization; Age*; *Motivation for innovation* and *State subsidies.*

Finally, in this first stage of estimation, regional and sectoral effects were controlled by introducing eleven *UK Regional* and thirteen *UK Sectors* dummies.

The key estimation results for the first stage are reported in Table 1.

3.3.2 Second stage: from innovation activities to innovation outputs

In the second stage, an innovation production function is estimated based on the predicted values of *R&D*, *Training* and *ICTs intensities*, estimated in the first stage, together with the usual variables capturing tacit and explicit, c*omplementary* and *competitive* cooperation. In this second stage, *Tacit cooperation* is calculated through two diverse spillovers derived from proximity in the production space:

- *R&D sector spill. net of ICT sector*, reporting each R&D sector spillovers weighted according to production space proximity to the sector of the receiving firm and calculated based on the R&D activities in all sectors of the UK economy excluding the ICT sector, and,
- *R&D sector spill. from the ICT sector*, capturing only the spillovers based on R&D activities performed in the ICTs sector, again weighted to reflect production space proximity between the ICT and the destination sector.

In this second stage, we also control other firms' specific features, such as *internationalization* and the *firm's employment, size, age, subsidies* and *motivation* for innovation.

[7] As suggested by an anonymous referee, it is important to emphasize that we used disjoint cross-sections pooled together, which is quite common in CIS and similar surveys. However, this means that whenever the same firms are present in two or more surveys, they are 'treated' as different companies.

Table 1 First Stage: Tobit estimations of internal R&D, external R&D, Training, and ICTs expenditure intensities

First Stage: Tobit Pooled estimation UK CIS (2004–2010)	Internal R&D expenditure over Turnover	External R&D expenditure over Turnover	Training Expenditure over Turnover	ICTs Expenditure over Turnover
Explicit Cooperation Covariates				
Coop - Other firms	–0.8572***	–0.4356***	0.1152**	0.0019
	(0.1285)	(0.1078)	(0.0470)	(0.0173)
Coop – Suppliers	0.4711***	0.5321***	0.1788***	0.1039***
	(0.1026)	(0.0906)	(0.0391)	(0.0144)
Coop – Customers	0.5531***	–0.0048	–0.0200	–0.0185
	(0.1030)	(0.0960)	(0.0400)	(0.0147)
Coop – Consultants	0.7566***	1.0626***	0.1047**	0.0076
	(0.1244)	(0.1019)	(0.0478)	(0.0181)
Coop – Universities	1.1534***	0.6297***	0.1084**	0.0119
	(0.1897)	(0.0604)	(0.0495)	(0.0283)
Coop - Government	–0.1485	0.0895	0.0448	0.0169
	(0.1500)	(0.1226)	(0.0567)	(0.0217)
Tacit Cooperation Covariates				
R&D Geog. Spillovers	0.0101	0.0108	–0.0467***	0.0120***
	(0.0306)	(0.0277)	(0.0105)	(0.0037)
Local ICT expenditure Spillovers	–0.0006**	–0.0002	0.0001	0.0001***
	(0.0002)	(0.0003)	(0.0001)	(0.0000)
Training Geog. Spillovers	0.0053	–0.0205	0.0400***	–0.0169***
	(0.0331)	(0.0315)	(0.0117)	(0.0040)
Other Control Variables				
Motive: Better products	0.5707***	0.3527**	0.2589***	0.0277
	(0.1751)	(0.1664)	(0.0535)	(0.0192)
Motive: Better production	–0.0266	0.0227	0.1810***	0.0859***
	(0.1267)	(0.1195)	(0.0447)	(0.0165)
Motive: Improve Profit	1.04600***	0.7900***	0.2500***	0.0457**
	(0.1738)	(0.1684)	(0.0568)	(0.0204)
Motive: Meet Regulation	–0.0490	–0.0887	0.1219***	0.0092
	(0.1140)	(0.1044)	(0.0396)	(0.0148)
Motive: Expansion	0.8379***	0.1152	–0.0196	–0.014
	(0.1289)	(0.1164)	(0.0400)	(0.0152)
Subsidies over Turnover	0.0061	–0.0653	–0.0028	–0.0008
	(0.0203)	(0.0477)	(0.0076)	(0.0029)
Age	0.0214*	–0.0085	–0.0053	0.0018
	(0.0129)	(0.0116)	(0.0043)	(0.0015)
Age squared	–0.0009***	–0.0001	0.0001	–0.0001
	(0.0003)	(0.0005)	(0.0001)	(0.0001)
Log Total Employment	–0.7738***	–0.7735***	–0.2972***	–0.0893***
	(0.0254)	(0.0243)	(0.0089)	(0.0032)
Regional Markets	0.5024***	0.0218	0.3448***	0.1252***
	(0.0732)	(0.0661)	(0.0259)	(0.0089)
National Markets	0.9575***	0.2205***	0.2786***	0.1133***
	(0.0787)	(0.0723)	(0.0249)	(0.0087)

Table 1 (continued)

First Stage: Tobit Pooled estimation UK CIS (2004–2010)	Internal R&D expenditure over Turnover	External R&D expenditure over Turnover	Training Expenditure over Turnover	ICTs Expenditure over Turnover
EU Markets	0.5195***	0.3709***	0.0459	0.0038
	(0.0870)	(0.0832)	(0.0314)	(0.0112)
International Markets	1.0396***	0.6139***	0.0158	–0.0051
	(0.0831)	(0.0779)	(0.0322)	(0.0116)
Observations	23845	23845	23845	22401
Pseudo R-squared	0.1360	0.1520	0.1000	0.0730

* p<0.10, ** p<0.05, *** p<0.01

The standard errors are presented in parentheses.

Additional controls: **Regional dummies** including, for England: *North-West, Yorkshire and the Humber, East Midlands, West Midlands, Eastern England, London, South East, South West*, plus *Wales, Scotland and Northern Ireland* and the *North East of England* as the base category.

Sector dummies: *Manufacturing, Electricity & Gas, Water, Construction, Wholesale and Retail Services, Transport & Storage, Hotel & Restaurant, ICTs, Financial Services & Insurance, Professional Services, Public Administration & Defence, Health & Social Work Services, Art and Creative activities and Other services*, using *Agriculture* as the base category.

In more detail, in this stage, we consider three, not mutually exclusive, types of innovations outputs: *product*, *process* and *organizational innovations*[8] for firm *i*:

$$y_{i,j} \in \{0,1\}, and\ \ j = \{New\ Product, New\ Process, Organizational\ Innovation\}$$

We estimate an innovation production function where the predicted values of *Total R&D*[9], *Training* and *ICT* intensities, estimated in the first stage, are used as the relevant explanatory variables for $y_{i,j}$. These discrete choices are assumed to express an underlying system of latent innovations propensities:

$$y*_{i0} = x'_i\beta_0 + u_{i0},$$

$$y*_{i1} = x'_i\beta_1 + u_{i1},$$

$$y*_{i2} = x'_i\beta_2 + u_{i2}.$$

We can only observe an indicator function taking a value one when the latent variable is greater than zero and zero otherwise:

$$y_{i0} = 1\left(y*_{i0} > 0\right),$$

[8] This decomposition is possible as the CIS questionnaires allow to select any combination of answers about these three different innovation typologies.

[9] Obtained as the sum of predicted internal and predicted external R&D intensities estimates from the first stage.

$$y_{i1} = 1\left(y*_{i1} > 0\right),$$

$$y_{i2} = 1\left(y*_{i2} > 0\right).$$

Also, we allow for these decisions, whether to introduce any combination of these three forms of innovation, to be correlated so that we assume that the random error terms: u_{i0}, u_{i1}, u_{i2} are jointly trivariate normal[10] with a symmetric Variance-Covariance matrix given by:

$$\Sigma = \begin{bmatrix} 1 & \rho_{01} & \rho_{02} \\ & 1 & \rho_{12} \\ & & 1 \end{bmatrix}.$$

The estimation of the probabilities of introducing process, product and organizational innovations is, therefore, a joint estimation that exploits the correlations between these binary variables.

The results for the first stage are reported in Table 2 and further discussed concerning our hypotheses in the next section.

Table 2 Multivariate Probit estimations for *Processes*, *Product* and *Organisational* Innovations

Second Stage, Multivariate Probit, Pooled data CIS (2004–2010)	Processes Innovations	Product Innovations	Organisational Innovations
Covariates			
Predicted Variables from the First Stage			
Pred. Tot. R&D exp/Sales	0.0221*	0.0546***	–0.0049
	(0.0113)	(0.0120)	(0.0086)
Pred. Training exp/Sales	0.0287	–0.0639	0.2570***
	(0.0683)	(0.0666)	(0.0529)
Pred. ICT exp/Sales	0.3540***	0.4990***	0.1200**
	(0.0679)	(0.1040)	(0.0490)
Explicit Cooperation Variables			
Coop - Group	0.1380**	0.1190*	0.2400***
	(0.0627)	(0.0661)	(0.0661)
Coop - Suppliers	0.2810***	0.2320***	0.1530**
	(0.0640)	(0.0648)	(0.0654)
Coop - Customers	0.1850***	0.3280***	0.2450***
	(0.0638)	(0.0620)	(0.0623)
Coop - Other firms	–0.0269	0.0047	–0.0680
	(0.0791)	(0.0783)	(0.0791)

[10] Thus, the joint probability of a triplet of firm's choices: $\{Yi{=}yi,\ i{=}1,\ 2,\ 3\}$ is conditional on the coefficients β, the covariances $\sum$ and the set of explanatory variables, X. The estimation of the probabilities of introducing process, product and organizational innovations is therefore a joint estimation that exploits the correlations between these binary variables. $Pr\left[Y_i = y_i,\ _{i=0,1,2}/\beta, \Sigma\right] = \iiint_{A0,A1,A2} \varphi\left(z_0, z_1, z_2, \rho_{01}, \rho_{02}, \rho_{12}\right) dz_0\, dz_1\, dz_2$ where φ is the density function of a multivariate normal distribution with mean (0,0,0) and variance covariance matrix $\sum$ and Ai for *i=0,1,2*, is the interval:($-\infty, \beta\prime_i X\prime_i$) if $y_i = 0$ and ($\beta\prime_i X\prime_i, \infty$) if $y_i = 1$

Table 2 Multivariate Probit estimations for *Processes*, *Product* and *Organisational* Innovations

Second Stage, Multivariate Probit, Pooled data CIS (2004–2010)	Processes Innovations	Product Innovations	Organisational Innovations
Coop - Consultants	0.0219	0.0166	0.2290***
	(0.0782)	(0.0790)	(0.0792)
Coop - Universities	0.0987	–0.0811	0.0241
	(0.0897)	(0.0911)	(0.0927)
Coop - Government	–0.0802	–0.1280	–0.0816
	(0.0966)	(0.0970)	(0.0949)
Implicit Cooperation Variables			
R&D sector spill net of ICT Sector	0.0479***	0.0128*	0.0275***
	(0.0079)	(0.0076)	(0.0068)
R&D sector spill from the ICT Sector	0.0147**	0.0095*	0.0028
	(0.0058)	(0.0053)	(0.0046)
Other Control Variables			
Subsidies over Turnover	0.0192**	0.0304***	0.0024
	(0.0090)	(0.0070)	(0.0090)
Log Total Employment	0.1550***	0.1180***	0.2200***
	(0.0181)	(0.0173)	(0.0136)
Age	–0.0083	–0.0097	–0.0152**
	(0.0079)	(0.0074)	(0.0065)
Age squared	0.0002	0.0002	0.0002
	(0.0002)	(0.0002)	(0.0002)
Motive: Better products	0.5530***	0.7460***	–0.1350
	(0.1197)	(0.0818)	(0.0854)
Motive: Better production	0.6700***	0.0023	0.1830**
	(0.0923)	(0.0777)	(0.0718)
Motive: Improve Profit	0.3160***	0.3410***	0.0946
	(0.1153)	(0.0883)	(0.0901)
Motive: Meet Regulation	–0.2975***	–0.3338***	0.2200***
	(0.0705)	(0.0664)	(0.0591)
Motive: Expansion	0.0312	0.3920***	0.3040***
	(0.0709)	(0.0670)	(0.0598)
Regional Markets	0.0071	–0.1380***	0.0890***
	(0.0442)	(0.0414)	(0.0342)
National Markets	0.1110**	0.0263	0.2760***
	(0.0478)	(0.0453)	(0.0366)
EU Markets	0.0901*	0.1950***	0.0229
	(0.0536)	(0.0496)	(0.0449)
International Markets	0.0087	0.1640***	0.1550***
	(0.0544)	(0.0517)	(0.0480)
Constant	–2.5530***	–1.5130***	–1.7180***
	(0.1136)	(0.1115)	(0.0921)

Table 2 Multivariate Probit estimations for *Processes*, *Product* and *Organisational* Innovations

Second Stage, Multivariate Probit, Pooled data CIS (2004–2010)	Processes Innovations	Product Innovations	Organisational Innovations
Observations	23828	23828	23828
*ρ (2,1) = 0.3626069***, ρ (3,1) = 0.2384411***, ρ (3,2) = 0.24816****	* p < 0.10 ** p < 0.05 *** p < 0.01	Wald chi2 (75) = 6072.55 Log pseudolikelihood = -215441.52 Prob > chi2 = 0.0000	

The standard errors are presented in parentheses.

4 Discussion of the results

4.1 First-stage results

This section discusses the results of the first stage estimates, focussing on the determinants of the four innovation activities: internal R&D, external R&D, Training and investment in ICTs.

4.1.1 Explicit cooperation

The first set of results explores the effects of *explicit* cooperation on innovative activities. The estimates in Table 1 show that *explicit complementarity* cooperation with "Suppliers of equipment, materials, services or software" (Coop – Suppliers) and with "Clients, customers or end users" (Coop – Customers) both have a positive association with internal R&D intensity (column 2). In contrast, external R&D is only affected by *explicit* cooperation with suppliers (column 3). These results confirm that total R&D intensity benefits from cooperation with downstream customers and upstream suppliers. *Explicit* cooperation with suppliers also positively affects a firm's ICT expenditure (column 5), confirming that investment in ICTs benefits from explicit upstream cooperation, most likely to help with implementing the ICTs investment. These results provide initial evidence supporting H1, focussing on the positive role of *explicit complementarity* cooperation on innovations through its positive effects on innovation activities, such as R&D and ICT intensities, as it will become clearer after exploring the second stage results[11].

Contrary to these results on *explicit complementarity* cooperation, our findings also show that *explicit competitive* cooperation, captured by the variable: "Competitors or other businesses in your industry" (Coop - Other firms), shows a negative and significant association with both *internal* and *external R&D intensities*. This result provides supporting evidence to H2 that *explicit* collaboration towards innovation among product market competitors is lowering R&D levels, suggesting that *explicit competitive* cooperation in innovation could be used as a coordination device to soften competitive pressure.

[11] A qualitatively similar finding applies to *Cooperation with other firms of the same group*.

4.1.2 Tacit cooperation

The results from Table 1 also show that *tacit cooperation*, in this first stage captured by geographic spillovers of R&D activities, improves ICTs intensity and that the local (same TTWA) expenditure in ICTs also exerts a positive localized externality on a firm's ICTs intensity[12]. These results provide initial evidence supporting H3, on the positive role played by *tacit* cooperation on innovation activities, and H4, on the positive effects of localized ICTs' level of expenditure on innovation activities, an effect that will be further confirmed in the analysis of the second stage of estimation, discussed next.

4.2 Second stage results

This stage focuses on the introduction of innovations. We jointly estimate the impact of different forms of cooperation according to the Competitive-Complementarity (C-C) and Explicit-Tacit (E-T) dimensions on three dependent variables, capturing whether a firm had introduced a *process*, a *product*, or an *organizational* innovation.

The effects of *explicit* and *tacit* cooperation can now be analyzed through their indirect and direct effects. The indirect effects are those arising through the effects on the innovation inputs (estimated in the first stage). In contrast, the direct effects measure their direct impact on process, product and organizational innovations.

4.2.1 Direct effects

Concerning the direct effects of *explicit* cooperation, our estimates show that *explicit complementarity* cooperation with *customers* and with *suppliers* are both significant in their positive associations with all types of innovations, providing empirical evidence supporting H1. Moving to the direct effects of *tacit cooperation* on the product, process and organisational innovations, this second stage estimates the *spillovers* of R&D due to proximity in the production space. Table 2 shows that the total amount of R&D expenditure performed by other firms in the economy, outside the ICT sector, and weighted with trade intensities among sectors (*R&D sector spill net of ICT Sector*) has a positive and significant effect on the probability that a firm introduces a process, a product and an organisational innovation. In this second stage, we separately capture the spillovers due to R&D performed in the ICTs sector only, again, weighted with the trade intensities between the ICT and the other sectors of the economy (*R&D sector spill from the ICT Sector*), finding a positive association with the probability of introducing both process or product innovations. These results provide empirical evidence supporting hypotheses H3 and H4 on the positive role tacit cooperation plays in R&D, economywide, and specifically in the R&D performed in the ICT sector, in facilitating innovations.

[12] The intersectoral spillovers arising from production proximity, as an additional component of tacit cooperation, are analyzed in the second stage.

4.2.2 Indirect effects

The indirect effects are those captured by combining the two stages of the analysis. In the first stage, we noticed the impact of *tacit* and *explicit* cooperation on the predicted levels of intangible innovation activities, which were then used to estimate innovation outputs in the second stage.

Table 2 shows that the predicted *total R&D* intensity[13] has a positive and significant association with product and process innovations, confirming the expected positive role of R&D on product and process innovation outputs. Table 2 also shows that the level of a firm's *predicted ICTs* intensity has significant positive associations with all types of innovations, while the level of *predicted training expenditure* is only significantly and positively associated with introducing *organizational* innovations. Moving one step back, the first stage results showed that *tacit cooperation* based on R&D geographic spillovers positively affects other firms' ICTs investment and that localized ICTs expenditure increased individual firms' ICTs expenditure. These two diverse geographic spillovers capture tacit cooperation's positive indirect effect on innovation outputs. Based on R&D geographic spillovers, the first effect supports hypothesis H3 on the positive impact of *tacit cooperation* in intangible R&D on innovations. The second effect (based on localized ICT spillovers) supports hypothesis H4 on the positive effects on innovations of localized ICTs spillovers.

The first stage results also showed that *explicit complementarity* cooperation with suppliers was positively correlated with all the innovations inputs: R&D, training, and ICTs intensities, while *explicit complementarity* cooperation downstream with customers was positively associated with internal R&D intensity. These findings on the indirect effects of *explicit complementarity* cooperation provide additional support for hypothesis H1 on the positive impact exerted by *explicit complementarity* cooperation on innovations.

Finally, in the first stage estimates, *explicit competitive* cooperation with product market competitors was found to be significantly lowering the predicted level of both external and internal R&D intensity, exerting an indirect negative impact on both process and product innovations, as hypothesized in H2, on the negative impact of *explicit competitive* cooperation on innovative outcomes.

5 Conclusions, limitations and strategic and policy implications

This paper focused on the UK *innovation network* and the role of spillovers in innovation activities and ICTs, diffusing along two dimensions: geography, based on the commuter-related concept of *Travel to Work Areas*, and production proximity, based on the inter-sectorial trade flows. The main aim of this paper was to disentangle the effects of *explicit* and *tacit, complementarity* and *competitive* modalities of cooperation in innovation activities on three different types of innovation outputs,

[13] The second stage uses the sum of the predicted levels of internal and external R&D intensities, as total R&D intensity.

hence characterizing the effectiveness of the UK *innovation network*, in transforming explicit cooperation, ICTs and R&Ds into firm level's innovation outputs.

Our results show that *tacit* cooperation due to inter-sector trade-weighted spillovers of R&D performed both in the ICTs sector and all other sectors percolate through the informal links provided by trade flows, facilitating the introduction of *process*, *product*, and *organisational* innovations.

The main strategic, but also policy, insight to be derived from this finding, relates to the need to identify the key sectors that can maximize the range for the exploitation of this *tacit* cooperation due to their centrality in the trade flows of the relevant *innovation network*. This will be critically relevant in improving the probability of introducing *product* and *process* innovations. Similarly, *due to R&D and ICTs spillovers diffusing through geographic proximity, tacit cooperation* indirectly fosters an *innovation network's* success in bringing innovations to the market. Hence, targeted strategies and policies need to incentivize these spillover effects that might otherwise not be captured by the private incentives to perform R&D. Hence, without public support, the innovation system will underperform due to the *public good* nature of these spillovers.

Explicit cooperation along the *complementarity* dimension of the innovation chain exerts both direct and indirect positive effects on innovation outcomes. Hence, an additional key role for innovation policy is to provide the required soft and hard infrastructures for *innovation networks* to thrive, increasing trust to reduce their potential vertical coordination failures and providing insurance against the risks posed by free riding.

Finally, our empirical evidence supports the hypothesis that *explicit competitive cooperation* among competitors reduces the innovation output of an *innovation network*. This explicit *competitive* cooperation strategy acts as a form of "*collective dominance*" within the economy, and policymakers and excluded competitors should be wary of its impact. From a business perspective, this coordination strategy might occur within R&D consortia comprised of output market competitors, acting as coordination devices and possibly softening product market competition by reducing innovation outputs.

This work has, of course, different limitations. Firstly, it is based on pooled UK Microdata only; hence it would be inappropriate to generalize the findings to different contexts. Also, many hard choices had to be made when selecting the appropriate ways of constructing spillovers variables, for example, by choosing the TTWAs as basic geographic units, and their centers' distances as a proxy for spillovers loss. Similarly, only UK intersectoral spillovers were considered without integrating possible international R&D spillovers arising through international trade.

Moreover, the innovation output variables are dichotomic and might not capture the full complexity of innovative outputs. Finally, the CIS data does not consider firms with less than ten employees. These might form a relevant part of the UK innovation ecosystem, those for whom innovation, particularly digital innovations, might be critical for economic survival. Some of these issues need to be addressed in future work. However, it might be challenging to consider them all at once.

The 2008 financial crisis brought a general reduction in innovation-related investment in the UK[14]. However, this adverse macroeconomic framework showed that this reduction was accompanied, at the European level, by a change of the key actors driving innovations, finding small firms and new entrants to be the successful innovators (Archibugi et al., 2013), according to the Schumpeterian paradigm of creative destruction (Schumpeter, 1911). These are the innovators that are most likely to depend on, and entrepreneurs that may successfully emerge from, the set of loose interactions formed within the *innovation networks* studied in this paper, as they are the most likely beneficiaries from the presence of spillovers due to their lack of a well-established network of formal, *explicit* cooperation relations. Future work should explore even deeper the innovative behaviors of these small innovators and startups to fully understand the potential of R&D and ICT spillovers.

6 Appendix summary statistics

Table A1 Mean, Standard Deviation and Observations for the key variables

Variable	Mean	Standard Deviation	Observations
Processes Innovations	0.1755	0.3804	26,572
Organizational Innovations	0.3437	0.4750	26,572
Product Innovations	0.2759	0.4470	26,572
Subsidies over Turnover	0.1013	1.9166	26,572
Log Total Employment	4.8872	1.5840	26,572
Age	20.2725	10.1341	24,027
Motive: Better Products	0.4511	0.4976	26,572
Motive: BetterProduction	0.4137	0.4925	26,572
Motive: Improve Profit	0.4356	0.4958	26,572
Motive: Meet Regulation	0.4122	0.4922	26,572
Motive: Expansion	0.4107	0.4920	26,572
Regional Markets	0.6865	0.4639	26,572
National Markets	0.6254	0.4840	26,572
EU Markets	0.3326	0.4711	26,572
International Markets	0.2384	0.4261	26,572
Coop - Group	0.1149	0.3190	26,551
Coop - Suppliers	0.1422	0.3492	26,551
Coop - Customers	0.1509	0.3579	26,552
Coop - Other firms	0.0669	0.2498	26,551
Coop - Consultants	0.0766	0.2660	26,551
Coop - Universities	0.0580	0.2337	26,551
Coop - Government	0.0470	0.2117	26,551

[14] See, for example Department of Business Innovation and Skills, (2014)

Table A2 Correlation Table for the key variables

	Processes Innovations	Organi-zational Innovations	Product Innovations	Subsi-dies over Turnover	Log Total Employment	Age	Motive: Better Products
Processes Innovations	1						
Organi-zational Innovations	0.3125	1					
Product Innovations	0.4432	0.342	1				
Subsi-dies over Turnover	0.0123	-0.0037	0.0129	1			
Log Total Employment	0.0882	0.1576	0.053	0.0047	1		
Age	-0.0133	-0.0445	-0.0238	-0.0131	0.1155	1	
Motive: Better Products	0.4268	0.3975	0.5218	0.0056	0.0319	-0.0434	1
Motive: Better Production	0.4436	0.3972	0.4924	0.0003	0.0469	-0.0403	0.89
Motive: Improve Profit	0.4345	0.4048	0.5123	-0.0003	0.0433	-0.0418	0.9256
Motive: Meet Regulation	0.3936	0.3917	0.4559	0.0073	0.0405	-0.0323	0.8696
Motive: Expansion	0.4138	0.3992	0.523	0.0029	0.0576	-0.0278	0.892
Regional Markets	0.0673	0.0982	0.0708	0.0003	-0.1237	-0.0134	0.1604
National Markets	0.1806	0.2439	0.2226	-0.0086	0.0942	0.0121	0.2686
EU Markets	0.2001	0.2057	0.2696	-0.0103	0.0673	0.0717	0.2516
Internation-al Markets	0.1793	0.192	0.2537	-0.0102	0.0704	0.0773	0.2229
Coop - Group	0.2852	0.2768	0.3138	-0.007	0.1109	0.0086	0.3217
Coop - Suppliers	0.3414	0.2952	0.3601	-0.0034	0.0832	0.0137	0.3815
Coop - Customers	0.3301	0.3128	0.3818	0.0008	0.0813	0.0067	0.3971
Coop - Other firms	0.2193	0.1998	0.2329	0.0001	0.0496	-0.0054	0.2401
Coop - Con-sultants	0.2552	0.2352	0.2674	-0.0025	0.0822	0.0009	0.2674
Coop - Uni-versities	0.2218	0.1893	0.2337	0.0062	0.0604	0.0134	0.224
Coop - Government	0.183	0.1679	0.1958	-0.0029	0.053	0.001	0.199

Table A2 Correlation Table for the key variables

	Processes Innovations	Organizational Innovations	Product Innovations	Subsidies over Turnover	Log Total Employment	Age	Motive: Better Products
	Motive: Better Production	**Motive: Improve Profit**	**Motive: Meet Regulation**	**Motive: Expansion**	**Regional Markets**	**International Markets**	**Coop - Suppliers**
Motive: Better Production	1						
Motive: Improve Profit	0.9049	1					
Motive: Meet Regulation	0.8573	0.8888	1				
Motive: Expansion	0.8541	0.88	0.8258	1			
Regional Markets	0.1424	0.1506	0.1413	0.1363	1		
National Markets	0.2677	0.2735	0.2434	0.2844	0.0562		
EU Markets	0.2519	0.256	0.2244	0.2702	0.234		
International Markets	0.2169	0.2271	0.1963	0.2425	0.1836	1	
Coop - Group	0.3217	0.3208	0.3161	0.3226	0.0523	0.1862	
Coop - Suppliers	0.3776	0.384	0.3706	0.3807	0.0557	0.1625	1
Coop - Customers	0.3932	0.397	0.3881	0.3996	0.0528	0.1854	0.6974
Coop - Other firms	0.2384	0.2394	0.2325	0.2365	0.0478	0.1011	0.5166
Coop - Consultants	0.2684	0.2676	0.2646	0.2666	0.0431	0.1647	0.5409
Coop - Universities	0.2263	0.2249	0.224	0.2288	0.0484	0.1834	0.4265
Coop - Government	0.198	0.1979	0.2011	0.1948	0.0394	0.1111	0.421
	Coop - Customers	**Coop - Customers**	**Coop - Customers**	**Coop - Customers**	**Coop - Customers**		
Coop - Customers	1						
Coop - Other firms	0.5309	1					
Coop - Consultants	0.5175	0.5028	1				
Coop - Universities	0.4475	0.46	0.5689	1			
Coop - Government	0.4292	0.5022	0.538	0.6002	1		

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2. Office for National Statistics (2013) Businesses Expenditure on Research and Development, 1995–2011: Secure Access. [DATA COLLECTION] 2nd EDITION. UK Data Service. SN 6690 BERD. DOI https://doi.org/10.5255/UKDA-SN-6690-2.
3. Department of Business Innovation and Skills, Office for National Statistics, Northern Ireland. Department of Enterprise, Trade, and Investment (2013). UK innovation Survey, 1994–2010: Secure Access. [DATA COLLECTION] 3rd EDITION. UK Data Service. SN 66,909. DOI https://doi.org/10.5255/UKDA-SN-6699-3.
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Declarations

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References

Acs, Z., Anselin, L., & Varga, A. (2002). Patents and innovation count as measures of regional production of new knowledge. *Research Policy*, *31*, 1069–1085.
Adner, R. (2006). Match your innovation strategy to your innovation ecosystem. *Harvard Business Review*, *84*(4), 98–107.
Aldieri, L., Sena, V., & Vinci, C. P. (2022). High growth episodes among R&D intensive firms. Evidence for Europe, US and Japan. *International Small Business Journal*, 02662426211070943.
Archibugi, D., Filippetti, A., & Frenz, M. (2013). The impact of the Economic Crisis on Innovation: evidence from Europe. *Technological Forecasting and Social Change*, *80*(7), 1247–1260.
Archibugi, D., & Iammarino, S. (1999). The policy implications of the globalisation of innovation. *Research Policy*, *28*, 317–336.
Audretsch, D. B., & Belitski, M. (2020a). The limits to collaboration across four of the most innovative UK industries. *British Journal of Management*, *31*(4), 830–855.
Audretsch, D. B., & Belitski, M. (2020b). The role of R&D and knowledge spillovers in innovation and productivity. *European Economic Review*, *123*, 1–24.

Audretsch, D. B., & Feldman, M. P. (1996). R&D spillovers and the geography of innovation and production. *American Economic Review*, *86*(3), 630–640.
Bartelsman, E. J., Caballero, R. J., & Lyons, R. K. (1994). Customer and supplier driven externalities. *American Economic Review*, *84*(4), 1075–1084.
Breschi, S., Malerba, F., & Orsenigo, L. (2000). Technological regimes and schumpeterian patterns of innovation. *Economic Journal*, *110*, 388–410.
Brynjolfsson, E., & Hitt, L. M. (1995). Information Technology as a factor of production: the role of differences among firms. *Economics of Innovation and New Technology*, *3*(3), 183–200.
Cassiman, B., & Veugelers, R. (2002). R&D cooperation and spillovers: some empirical evidence from Belgium. *American Economic Review*, *92*(4), 1169–1184.
Cohen, W. M., & Levinthal, D. A. (1989). Innovation and learning: two faces of R&D. *Economic Journal*, *99*(397), 569–596.
Corrado, C. A., Hulten, C. R., & Sichel, D. E. (2005). Measuring Capital and Technology: an expanded Framework. *Measuring capital in the New Economy*. Chicago. The University of Chicago Press.
Cournot, A. (1838). *Recherches sur les principes mathématiques de la théorie des richesses*. Paris: L. Hachette.
Crépon, B., Duguet, E., & Mairesse, J. (1998). Research, Innovation and Productivity: An Econometric Analysis at the firm level. *Economics of Innovation and New Technology*, *7*(2), 115–158.
Crescenzi, R., & Rodrıguez-Pose, A. (2012). An 'Integrated' Framework for the comparative analysis of the Territorial Innovation Dynamics of developed and emerging countries. *Journal of Economic Surveys*, *26*(3), 517–533.
Czernich, N., Falck, O., Kretschmer, T., & Woessmann, L. (2011). Broadband infrastructure and economic growth. *Economic Journal*, *121*(552), 505–532.
De Propris, L. (2002). Types of innovation and inter-firm cooperation. *Entrepreneurship & Regional Development*, *144*, 337–353.
Department of Business Innovation and Skills. (2014). *Private and external benefits from investment in Intangible Assets*. London: Research Paper No. 203.
Department of Business Innovation and Skills, Office for National Statistics, Northern Ireland. Department of Enterprise, Trade, and Investment, 2013. UK innovation Survey, 1994–2010: Secure Access. [DATA COLLECTION] 3rd EDITION. UK Data Service. SN 66909. DOI https://doi.org/10.5255/UKDA-SN-6699-3
Dosi, G., Piva, M., Virgillito, M. E., & Vivarelli, M. (2021). Embodied and disembodied Technological Change: the sectoral patterns of job-creation and job-destruction. *Research Policy*, *50*(4), 104199.
Enkel, H., Gassman, O., & Chesbrough, H. (2009). Open R&D and open innovation: exploring the phenomenon. *R&D Management*, *39*(4), 311–316.
Freel, M. S., & Harrison, R. T. (2006). Innovation and cooperation in the small firm sector: evidence from 'Northern Britain'. *Regional Studies*, *404*, 289–305.
Freire, J. A. F., & Gonçalves, E. (2021). Cooperation in Innovative Efforts: a Systematic Literature Review. Journal of the Knowledge Economy,1–37.
Fritsch, M., & Franke, G. (2004). Innovation, regional knowledge spillovers and R&D cooperation. *Research Policy*, *33*, 245–255.
Gassmann, O., Enkel, E., & Chesbrough, H. (2010). The future of Open Innovation. *R&D Management*, *40*(3), 213–221.
Giovannetti, E. (2013). Catching up, leapfrogging or forging ahead? Exploring the Effects of Integration and history on spatial Technological Adoptions. *Environment and Planning A*, *45*(4), 930–946.
Giovannetti, E., & Piga, C. A. (2017). The contrasting effects of active and passive cooperation on innovation and productivity: evidence from british local innovation networks. *International Journal of Production Economics*, *187*, 102–112.
Gkypali, A., Filiou, D., & Tsekouras, K. (2017). R&D collaborations: is diversity enhancing innovation performance? *Technological Forecasting and Social Change*, *118*, 143–152.
Griffith, R., Huergo, E., Mairesse, J., & Peters, B. (2006). Innovation and productivity across four european countries. *Oxford Review of Economic Policy*, *22*, 483–498.
Griliches, Z. (1979). Issues in assessing the contribution of Research and Development to Productivity Growth. *Bell Journal of Economics*, *10*(1), 92–116.
Hall, B., Lotti, F., & Mairesse, J. (2012). Evidence on the Impact of R&D and ICT Investment on Innovation and Productivity in Italian Firms. NBER Working Paper, No. 18053.
Hempell, T. (2005). What's spurious, what's real? Measuring the Productivity Impacts of ICT at the firm level. *Empirical Economics*, *30*(2), 427–464.

Higón, D. A. (2012). The impact of ICT on innovation activities: evidence for UK SMEs. *International Small Business Journal*, *30*(6), 684–699.

Huggins, R., Izushi, H., & Prokop, D. T. P. (2015). Network evolution and the spatiotemporal dynamics of knowledge sourcing. *Entrepreneurship & Regional Development*, *27*(7–8), 474–499.

Huggins, R., Johnston, A., & Thompson (2012). Network Capital, Social Capital and Knowledge Flow: how the nature of inter-organizational networks impacts on Innovation. *Industry and Innovation*, *19*(3), 203–232.

Iammarino, S., Piva, M., Vivarelli, M., & Von Tunzelmann, N. (2012). Technological capabilities and patterns of innovative Cooperation of Firms in the UK Regions. *Regional Studies*, *46*(10), 1283–1301.

Insiti, M., & Levien, R. (2004). *The keystone advantage: what the New Dynamics of Business Ecosystems Mean for Strategy, Innovation, and sustainability*. Cambridge, MA: Harvard Business School Press.

Jaffe, A. B. (1989). Real effect of academic research. *American Economic Review*, *79*, 957–970.

Jensen, M. B., Johnson, B., Lorenz, E., & Lundvall, B. A. (2007). Forms of knowledge and modes of Innovation. *Research Policy*, *36*(5), 680–693.

Katz, M. L., Ordover, J., & Fisher, F.R., S (1990). *R&D Cooperation and Competition. Brookings Papers on Economic Activity* (pp. 137–203). Microeconomics.

Keller, W. (2002). Trade and the transmission of technology. *Journal of Economic Growth*, *7*, 5–24.

Knoben, J., & Oerlemans, L. A. G. (2006). Proximity and inter-organisational collaboration: a Literature Review. *International Journal of Management Reviews*, *8*(2), 71–89.

Lam, A. (2000). Tacit Knowledge, Organizational Learning and Societal Institutions: an Integrated Framework. *Organisation Studies*, *21*(3), 487–451.

Los, B., & Verspagen, B. (2000). R&D spillovers and productivity: evidence from US manufacturing microdata. *Empirical Economics*, *25*(1), 127–148.

Marshall, A., 1890. Principles of Economics. London:Macmillan.

Medda, G., & Piga, C. A. (2012). Technological spillovers and productivity in italian manufacturing firms. *Journal of Productivity Analysis*, *41*, 419–434.

Moncada-Paternò-Castello, P. (2022). Top R&D Investors, Structural Change and the R&D growth performance of Young and Old Firms. *Eurasian Business Review*, *12*(1), 1–33.

Moore, J. (1993). Predators and prey: a new ecology of competition. *Harvard Business Review*, *7*(3), 75–86.

Nadiri, I. M. (1993). Innovations and technological spillovers. NBER Working Paper, Issue 4423.

Office for National Statistics, & Annual Respondent, D. (2012). 1973–2008: Secure Access. [DATA COLLECTION] 3rd EDITION. UK Data Service. SN 6644. DOI https://doi.org/10.5255/UKDA-SN-6644-5

Office for National Statistics (2013). Businesses Expenditure on Research and Development, 1995–2011: Secure Access. [DATA COLLECTION] 2nd EDITION. UK Data Service. SN 6690 BERD. DOI https://doi.org/10.5255/UKDA-SN-6690-2

Office for National Statistics (2011). Travel to Work Areas UK 2011 map V2. [Online] Available at: https://geoportal.statistics.gov.uk/Docs/Maps/Travel_to_Work_Areas_UK_2011_map_V2.pdf

Office for National Statistics (2011). Input-output supply and use tables. [Online] Available at: https://webarchive.nationalarchives.gov.uk/ukgwa/20120108114604/http://www.ons.gov.uk/ons/publications/re-reference-tables.html?edition=tcm%3A77-240418&format=contrast

Pakes, A., & Griliches, Z. (1984). Patents and R and D at the firm level: a first look. In Z. Griliches (Ed.), *R&D Patents & Productivity* (pp. 55–72). Chicago: University of Chicago Press.

Park, B., & – Lee, C. Y. (2022). Does R&D Cooperation with Competitors Cause Firms to Invest in R&D More Intensively? Evidence from Korean Manufacturing Firms.Journal of Technology Transfer.1–32

Parker, S. (2008). The economics of formal business networks. *Journal of Business Venturing*, *23*, 627–640.

Pellegrino, G., & - Piva, M. (2020). Innovation, Industry and Firm Age: are there New Knowledge Production Functions? *Eurasian Business Review*, *10*(1), 65–95.

Piening, E. P., & Salge, T. O. (2015). Understanding the antecedents, contingencies, and performance implications of process innovation: a dynamic capabilities perspective. *Journal of Product Innovation Management*, *32*(1), 80–97.

Piga, C. A., & Vivarelli, M. (2004). Internal and external R&D: a sample selection approach. *Oxford Bulletin of Economics and Statistics*, *66*, 457–482.

Polanyi, M. (1958). *Personal knowledge: towards a post-critical philosophy*. Chicago: University of Chicago Press.

Rohrbeck, R., Hölzle, K., & Gemünden, H. G. (2009). Opening up for competitive advantage – how Deutsche Telekom creates an open innovation ecosystem. *R & D Management*, *39*(4), 420–430.

Röller, L., & Waverman, L. (2001). Telecommunications infrastructure and Economic Development: A Simultaneous Approach. *American Economic Review*, *91*(4), 909–923.

Schumpeter, J. (1911). *The theory of Economic Development*. Cambridge, MA: Harvard University Press.

Tether, B. (2002). Who cooperates for innovation, and why: an empirical analysis. *Research Policy*, *31*, 947–967.

Von Hippel, E. A. (1988). *The sources of innovations*. Oxford: Oxford University Press.

Zoia, M. G., - Barbieri, L., - Cortelezzi, F., & - Marseguerra, G. (2018). The determinants of italian firms' Technological Competencies and Capabilities. *Eurasian Business Review*, *8*(4), 453–476.