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The Limits to Collaboration Across Four of the Most Innovative UK Industries [1]

Abstract

This study demonstrates the importance and limits to external knowledge collaboration across different geographical dimensions and the most innovative UK industries (knowledge intensive business services (KIBS); high-tech manufacturing; Information and Communication Technologies (ICT); creative industries). Traditionally this issue has presented a challenge for the geography of innovation, external knowledge sourcing and open innovation literatures, in terms of firstly identifying the phenomenon and secondly in measuring it.

We propose and estimate a structural model that estimates the knowledge production function with innovation inputs and outputs at the firm level. Our sample includes 19,510 observations and 17,859 firms mainly from the UK Innovation survey and Business registry. We demonstrate that external collaboration may bestow a significant advantage for innovation developed by the firm and in collaboration with other businesses, but there are limits to collaboration. They are likely to be better offset by firms in knowledge intense sectors (KIS), while they remain consistent across collaboration with partners across four geographical regions. Our findings call for further research on innovation and revision of national and regional innovation policies.

Introduction

The innovation process involves a resource intensive search to find new combinations of commercially exploitable new technology and knowledge (Nelson and Winter, 1982; Stuart and Podolny, 1996; Hargadon and Sutton, 1997; Colombo et al., 2016; Laursen and Salter, 2006; Laursen, 2012). This requires organizations to create knowledge within a firm as well as source knowledge from external collaborators (Shan et al., 1994; Rosenkopf and Nerkar, 2001; Colombo et al., 2011). The joint use of the internal and external knowledge to accelerate firm's innovation has become a major foundation of "open innovation" concept (Chesbrough, 2006).

While the traditional innovation collaboration models are becoming more open (von Hippel, 2005; Chesbrough et al., 2006; Aldieri and Cincera, 2009; Borgers, 2011; West and Borgers, 2014; Choi and Contractor, 2017), the theoretical and empirical emphasis has increasingly moved towards the assumption on both the benefits and costs of external collaboration (Teece, 1986, 2000; Grindley and Teece, 1997; Veugelers, 1997, 1998; Cassiman

[1] The use of these data does not imply the endorsement of the data owner or the UK Data Service at the UK Data Archive in relation to the interpretation or analysis of the data. This work uses research datasets which may not exactly reproduce National Statistics aggregates.

and Veugelers, 2002; Driffield et al., 2010, 2014; Colombo et al., 2016). Although external collaborations can help partners to co-create new products, managing external collaborations, facilitating knowledge transfer and offsetting potential costs of collaboration is not simple, as a firm may have to adopt a variety of external collaboration practices (Heiman and Nickerson, 2004). This includes the enhancement of internal knowledge base (e.g. investment in research and development (R&D), hiring highly-skilled employees, training, etc.) which increase firm's competitive advantage by accumulating and integrating both internal and external knowledge (Helfat and Martin, 2015). An increase in economically valuable knowledge will challenge firm's appropriation and legal protection mechanisms, may result in an increase transaction costs and risk of uncontrolled knowledge flows to third parties (Ceccagnoli, 2009; Veugelers and Schneider, 2018). This suggests that investment in internal knowledge base along with an enhancement of external collaboration intensity may become a fundamental dilemma in the innovation management (von Hippel, 1994; Faems et al. 2005).

The rationale is as follows. Getting the knowledge from the external collaborators is only half the challenge, the other half is to exploit knowledge inflows and leverage knowledge outflows (West and Bogers, 2014), where the proprietary model frequently broke down (Chesbrough and Rosenbloom, 2002).

Despite the theoretical underpinning and importance of external collaboration in open innovation management literatures (Heiman and Nickerson, 2004; West and Bogers, 2014; West et al. 2014), relatively little theoretical and empirical research is available on the relationship between external knowledge collaboration and new product development, which is either developed within a firm (enterprise group) or co-created with other business partners.

Building on the extent literature on open innovation (Cassiman and Veugelers, 2002; Colombo et al. 2016), knowledge spillovers (Marshall, 1920; Audretsch and Feldman, 1996), innovation collaboration (Faems et al. 2005; Laursen and Salter, 2014; Beck and Schenker-

Wicki, 2014) we discuss the potential limits to external collaboration and evaluate the direct and indirect effect of knowledge collaboration on firm's innovation developed by the firm and in collaboration with other businesses.

By employing both industrial and geographical perspectives (Boschma and Frenken, 2010; Kang and Park, 2012; Rodríguez et al., 2018) to external knowledge collaboration, this study estimates a knowledge production function (Pakes and Griliches, 1984; Crépon et al. 1998) for a sample of 17,859 firms (19,510 obs.) across the most innovative UK sectors (KIBS, high-tech manufacturing, ICT, creative sector) and across four geographical dimensions of collaboration (regionally, nationally, Europe and other world). In addition we control for selection bias (Dustmann and Rochina-Barrachina, 2007) and develop a model, which distinguishes between the benefits and costs of external knowledge collaboration for firm's innovation.

In doing so we aim to advance the theory and practice of external knowledge sourcing and open innovation (Dahlander and Gann, 2010) on how best to manage the firm's openness and enhance the internal knowledge base to the extent to which firm's innovation is facilitated. We also extend prior literature, which focused on knowledge sharing and expropriation in external innovation collaborations (Cassiman and Veugelers, 2002; Heiman and Nickerson, 2004) as well as on the dynamics of breadth in external innovation collaboration (Love et al. 2014; Chapman et al. 2018).

There are several important findings in this paper. Firstly, firms which develop innovation internally and in collaboration with other businesses will benefit from external knowledge collaboration. Secondly, a joint increase in external collaboration intensity and firm's internal knowledge base leads to a diminishing returns to knowledge collaboration also known as "the limits to collaboration". Thirdly, firms in knowledge intense sectors (KIS) are likely to be better integrate the external and internal knowledge into innovation activities, offsetting the limits to collaboration. Finally, our results highlight that limits to collaboration are consistent across four geographical dimensions of collaboration (regional, national, Europe, world). This study informs policymakers who are interested in stimulating firm's knowledge collaboration on a more comprehensive understanding of collaboration costs and benefits. This may lead to possible revisions in innovation and industrial policies as well as to revision in legal R&D agreements between collaborators nationally and internationally.

Our findings call for more selectivity over the R&D collaboration support for innovative firms (Beck and Schenker-Wicki, 2014; Hottenrott et al., 2017) as this may increase the pressure on firms to integrate internal and external resources at a high pace, increasing adjustment and valuation costs.

The next section sets out the hypotheses. Section 3 introduces the data and sample, while Section 4 introduces the methodology. Section 5 presents the results, while Section 6 discusses robustness checks. Section 7 concludes with major contributions, limitations, policy implications and future research.

2. Theoretical framework

The extent literature on knowledge collaboration and open innovation (Chesbrough, 2003, 2006; Laursen and Salter, 2014; Cassiman and Valentini, 2016) suggests that firms use external partners to exploit market opportunities, co-create new knowledge and commercialise it (Dyer and Singh, 1998; Ahuja, 2000; Belderbos et al., 2004; Cassiman and Veugelers, 2006).

Theoretically, external knowledge sourcing is grounded in a knowledge-based view (KBV) of the firm (Kogut and Zander, 1992; Grant, 1996), where knowledge becomes the key competitive resource (Penrose, 1959). Firms treat knowledge as the principal strategic resource, which is difficult to acquire freely in markets (Barney et al. 2001), rather than through inter-organisational (Fleming and Sorenson, 2004; Faems et al. 2005; Colombo et al. 2011) and R&D collaborations (Bogers, 2011; Chapman et al. 2018).

The benefit from external collaboration for firm's innovation has been illustrated by empirical and theoretical works (Hagedoorn, 1993; Powell et al. 1996; Beers and Zand, 2014).

First, external knowledge collaboration allows for the inflow of resources required to exploit the market opportunities which may not exist within the firm, but across numerous collaboration partners (Laursen, 2012; Lakhani et al. 2013). Regarding knowledge inflows, we assume that a firm treats knowledge inflows positively.

Second, it enables access to inter-organisational knowledge (Faems et al. 2005) to facilitate their innovation search and performance (Beck and Schenker-Wicki, 2014; Roper et al., 2017).

Third, it helps to distribute the costs of innovation between partners (Veugelers, 1997, 1998) and to reduce the product development stage (Hagedoorn, 1993)

Fourth, according to the technology-based view, external knowledge collaboration is a core strategy for exploiting a firm's technology base as firms have to externalize their technology sourcing (Granstrand, 2000). The locus of firm's competitiveness shifts from firms to collaborators (Huang et al. 2015).

Fifth, firms collaborate when they cannot appropriate spillovers of their research (Ouchi and Bolton, 1988) or in markets that are uncertain and risky for a firm to go alone (West and Gallagher, 2006).

Finally, it is the increasing complexity of knowledge, customers and markets, which demands more and different kinds of collaboration (Brandenburger and Nalebuff, 1996; Bogers, 2011) to innovate in different markets (Teece, 1998; 2000; Narula and Duysters, 2004). We hypothesize:

H1: External knowledge collaboration positively affects firm's innovation.

Prior research on open innovation assumes that external innovation collaboration increases the likelihood of complementarities between in-house knowledge creation and external knowledge embedded in partners (Cassiman and Veugelers, 2006; Beers and Zand, 2014). Complementarities and successful absorption of knowledge from external sources is likely to facilitate firm productivity and innovation (Nelson and Winter, 1982; Cohen and Levinthal, 1989; Cassiman and Valentini, 2016).

The resource-based view of a firm also suggests, that knowledge collaborations are established to develop a firm's dynamic capabilities and thus enhance its competitive advantage by accumulating and exploiting both internal and external resources (Teece, 1986) to successfully generate innovations (Lee and Wong, 2009; Santamaria et al. 2009; Escribano, Fosfuri and Tribó, 2009).

Although, investment in internal knowledge, while enhancing and diversifying external collaboration will add to cognitive, organizational and transaction costs (Cassiman and Valentini, 2016), prior research demonstrated, that firms gain from complementary knowledge, for example when co-location in industrial clusters to exploit knowledge collaboration and spillovers (Marshall, 1920; Audretsch and Feldman, 1996). External collaboration prevents firms from the "lock-in" risks and homogeneous knowledge (Balland et al. 2015). Investing in internal innovation and collaborating on "*both* sides of the R&D market" (Chesbrough and Euchner, 2011: 14) is crucial and firms should be both active sellers and buyers of knowledge. In a dynamic organizational setting, then, one can expect as a firm increases collaboration in one relation (product), but it may look for ways to decrease collaboration in other relations (products) , e.g. by establishing completely new collaboration to bestow knowledge commercialization (Cassiman and Veugelers, 2002), In practice, open innovation literature also demonstrated that the integration of internal and external resources entails five challenges, which increase the cost of collaboration and may limit marginal returns from collaboration, creating a certain limit.

Firstly, firms need a wide range of approaches to maximize the returns to external collaboration and simultaneous investment in R&D, skills and competences, including intellectual property (IP) (maximization challenge). With a joint increase in knowledge investment in-house and collaboration intensity it is likely that knowledge appropriation issues arise to prevent the dispersion of R&D efforts across various collaborators, adding to innovation costs (Cassiman and Veugelers, 2002; West, 2003).

Secondly, firm should be able to integrate external and internal knowledge as well as continuously incorporate the relevant external knowledge into firm's innovation activities. This requires investment in absorptive capacity (Jansen et al. 2005), highly-skilled labour, new methods and ways to organize external collaboration to incorporate external knowledge (incorporation challenge). External knowledge often felt by firm's scientists as an implicit "indictment" of its own knowledge (Veugelers, 1997).

Thirdly, before incorporation into firm's innovation, valuation of external knowledge is an important issue (Granstrand, 2000) which may increase transaction costs, because of the difficult negotiations between collaborators (West and Gallagher, 2006). Partners are often reluctant to disclose sensitive tacit information about products and services (Arrow, 1962) (valuation challenge). Knowledge disclosure becomes an important issue when collaboration intensity grows. The challenge increases when a collaboration portfolio includes many partners (Choi and Contractor, 2017).

Fourthly, the cost of external collaboration (Gans and Stern, 2003; Chesbrough, 2006) includes the possible unintended knowledge outflows to rivals (Grindley and Teece, 1997; Cassiman and Veugelers, 2002, 2006; Iammarino and McCann, 2006; Laursen and Salter,

2014) (knowledge appropriation challenge). Preventing it would require a cost of monitoring which leads to challenges in profit maximization and appropriability (Grindley and Teece, 1997; Laursen and Salter, 2005, 2014). The evidence was found in industries where knowledge creation is central activity (Hagedoorn, 1993; Powell et al. 1996; Almeida and Kogut, 1999; Kang and Park, 2012). Thus, a firm should be prepared and motivated to invest in internal R&D as well as develop appropriation mechanisms to manage knowledge flows between collaborators (motivation challenge) (West et al., 2014; Hottenrott and Lopes-Bento, 2014). Above challenges are at the heart of the open innovation 'paradox', which means that internal innovation and external collaboration may function as two substitutive innovation choices (Faems et al. 2005; West and Gallangher, 2006).

We hypothesize:

H2: A joint increase in internal knowledge base and external collaboration intensity limits firm's innovation (the limits to collaboration).

Although investment in internal innovation and its integration with external knowledge increases risks and costs for a firm compared to others who do not invest in knowledge collaboration and integration, this does not mean that internal innovation and co-creation of products in collaboration is a dichotomous choice. In particular, most competitive firms in KIS will pursue internal innovation and collaboration as a form of competitive advantage. Although internal innovation and collaboration may be two substitute choices (Faems et al. 2005; Cassiman and Valentini, 2016), afterall internal innovation may increase returns to external innovation though absorptive capacity and vice versa, increasing commercialization of new products. This bring us to the next question. Will all industries be equally affected by the limits to collaboration ? Not necessarily. In the KIS, external collaboration is strongly related to R&D partnering with benefits of new product development accruing to both parties, whereas in sectors with a paucity of knowledge (e.g. medium and low-tech sectors) a dominant feature of partnering is market access (Hagedoorn, 1993). Due to the considerable strategic interdependence of firms in KIS and the complexity of product development, external innovation collaboration is more likely to occur, while also the risks of such collaboration are higher (Hagedoorn, 1993). Firms in KIS are aware of it and will undertake strategic (Hall et al. 2013, 2014) and legal knowledge protection measures, including sharing the IP rights, licencing and other form of IP collaboration, contracts (Megantz, 1996; Bogers, 2011; Hottenrott et al. 2017) to minimize those risks.

In particular, KIS firms will aim to enforce appropriability mechanisms, including patents, registration of designs, secrecy, package complexity to offset the potential limits to external collaboration. We hypothesize:

H3: Firms in the knowledge-intense sectors (KIBS, ICT, high-tech manufacturing and creative) will offset the limits to collaboration for firm's innovation.

The innovation collaboration literature (Baum et al., 2000; Rogers, 2004; Heiman and Nickerson, 2004; Love et al. 2014), often describes the knowledge transfer between partners as the adoption of practices, routines and culture, such as co-location, that facilitate knowledge collaboration (von Hippel, 1994) and knowledge spillovers (Marshall, 1920; Audretsch and Feldman, 1996). The empirical evidence is mainly based in the knowledge spillovers literature (Feldman and Audretsch, 1999; Audretsch et al. 2015).

Despite the benefits of co-location and knowledge localisation (Maskell, 2001), the extent of regional collaboration is likely to be limited because the knowledge may suffer from "the lock-in effect" (Boschma, 2005), with very little novel knowledge to offer to partners. In order to find new combinations of commercially exploitable knowledge (Stuart and Podolny, 1996; Hargadon and Sutton, 1997; Rosenkopf and Nerkar, 2001; Laursen, 2012) firms will collaborate across regions and national borders (Lahiri, 2010; Hottenrott and Lopes-Bento, 2014; Delgado-Márquez et al. 2017).

Although such outcomes are likely to be most diverse internationally, this form of collaboration requires more effective protection of knowledge such as IP, licensing, knowledge pooling when entering markets, enforcing contracts and other (maximization challenge). While explicit knowledge may be legally protected, much of tacit knowledge remains unprotected and thus is subject to potential exploitation by partners (Hall et al. 2014). It is plausible to assume that legal protection channels which could minimize the risks of collaboration, including unintended knowledge outflows, information disclosure and market risks and uncertainty (West and Gallagher, 2006) are limited once partners go international and deal with different institutional and cultural contexts (Autio et al. 2014, 2017).

Firms that collaborate internationally will need to invest more in absorptive capacity to integrate external collaboration knowledge (incorporation challenge). Unlike collaboration with international partners, regional and national boundaries offers R&D collaboration agreements, which can be easily enforced and monitored. The higher benefits of collaboration with international partners could be easily dissipated if collaborative trust between partners is not established and disclosure of tacit knowledge cannot be prevented (Laursen and Salter, 2005).

There is a significant motivation challenge that increases external collaboration costs internationally. Firstly, on the supply side these are significant institutional differences between countries (Autio et al. 2014; Audretsch et al., 2018; Cumming et al., 2018), including rules enforcement, procedures and costs of registering a firm, market entry, taxes, tracking information flows. Secondly, on the demand side there is higher uncertainty and lower transparency in market operations between external partners and their customers, when collaborating internationally.

Finally, firms may face liabilities from increased coordination and management costs internationally due to international diversity of regulations, cultures and mode of market entry (Zahra et al. 2000; Autio et al. 2014). Liabilities are also related to the newness of regulations and products, as well as the establishment of expensive internal management systems and networks, increasing collaboration costs (Lu and Beamish, 2004). We hypothesize:

H4: Firms that engage in collaboration with international partners will experience higher limits to collaboration for firm's innovation.

3. Methodology and data

3.1. Data

We test our hypotheses using three datasets (Business Registry, BSD), Business Expenditure in Research and Development (BERD), the UK Innovation Survey (UKIS) and six cross-sectional surveys with a panel element over 2002-2014. First, we collected and matched six consecutive UKIS waves: UKIS 4 2002-04, UKIS 5 2004-06, UKIS 6 2006-08, UKIS 7 2008-10, UKIS 8 2010-12 and UKIS 9 2012-14. Each wave was conducted every second year by the Office of National Statistics (ONS) in the UK.

Second, we used BSD and BERD data for the years 2002, 2004, 2006, 2008, 2010 and 2012. The data were matched to a correspondent UKIS survey wave for the initial year of the UKIS period. Firm age and ownership, employment, industry and firm size were matched from BSD. BERD collects data for in-house and bought-out R&D, as well as the number of researchers with university degrees and above employed by the firm. The UKIS includes direct measures of innovation inputs and outputs, influencing barriers to innovation, measurements on human capital, partner types, training activity, partner locations, collaboration networks and other information related to our hypotheses.

Although there are six surveys covering 10 years, we work with a sample of 19,510 observations with 17,859 firms available with non-missing values for innovation outputs and our main explanatory and control variable. There is a small panel element of 1,651 firms in a sample which was observed at least twice over 2002-2014. To be included in a sample, all questions related to the variables of interest needed to be completed with no missing values. For the list of variables included in this study and a sample size, please refer to Table 1 and their correlations (Table 2).

TABLE 1 ABOUT HERE

TABLE 2 ABOUT HERE

3.2. Sample description

Our sample includes four major innovative industries: high-tech manufacturing, ICT, KIBS, creative and the rest (other industries). The creative sector constitutes only of 4.4% of the sample, followed by ICT (7.3%) and KIBS (10.5%). High-tech manufacturing accounts for the highest share, with 11.6% of the observations (Table 3A). Other sectors represent 66.3% of the sample.

The left side of Tables 3A-3C shows the distribution of firms in the estimated sample, while the right side indicates the distribution of firms by industry, region and size across the population sample (this sample is original, and includes missing values on the variables of interest). The distribution of firms across estimated and population samples with regards to industries, regions and size remains stable over 2002-2014 (Tables 3A-3C). This is important as it enables us to generalize the results of our estimates to a larger sample. We observe a significant increase in non-reporting on questions of product and process innovation starting from UKIS 2010-2012 as compared to previous years.

TABLE 3 ABOUT HERE

Table 4 shows the degree of collaboration with external partners across different geographic boundaries for firms in four major sectors (high-tech manufacturing, ICT, KIBS and the creative sector).

TABLE 4 ABOUT HERE

3.3. Variables.

We use three different dependent variables to measure firm's innovation, which is to the best of our knowledge are novel to external collaboration and firm's innovation research literature. Our first dependent variable equals to one if new to market goods and services were developed mainly by the business or enterprise group, zero otherwise. Our second dependent variable equals to one if new to market goods and services were developed mainly in collaboration with other businesses Our third dependent variable which was used for robustness check is the total sales of new-to-market products (in thousand pound sterling) taken in logarithms. It is calculated by multiplying total sales by the share of sales associated with new to market products. All three measures of firm innovation performance were taken from UKIS and their use is consistent with previous studies analysing firm innovation (Santamaría et al. 2009; Leiponen, 2005; Roper et al., 2008; Leiponen and Helfat, 2010), and within the UK Innovation surveys (Laursen and Salter, 2006, 2014; Frenz and Ietto-Gillies, 2009; Giovannetti and Piga, 2017).

We use two groups of observed explanatory variables. First group includes four variables describing knowledge collaboration with regional, national, European and international partners. These are continuous variable bounded between zero (if firm has zero collaboration partners within a specific region) to a maximum of six types of external collaboration partners (suppliers, customers, competitors, consultants and commercial labs, universities, governments) within each geographical dimension (Cassiman and Veugelers, 2002; Faems et al. 2005; Boschma and Frenken, 2010; Love et al. 2014). Second group includes R&D intensity (R&D expenditure to total sales) and the proportion of employees that hold a BA/BSc degree or higher qualification in science and engineering (scientists) (Cohen and Levinthal, 1989; Veugelers, 1997, 1998; Veugelers and Schneider, 2018). Both R&D intensity and share of scientists were used to measure the investment in internal knowledge base as well as to illustrate firm's readiness to collaborate with external partners (Grant, 1996; West and Gallagher, 2006).

4. Methodology

4.1. Sample selection

In many problems of applied econometrics and management, the equation of interest is only defined for a subset of firms from the overall population, while the parameters of interest refer to the whole population (Dustmann and Rochina-Barrachina, 2007). In our sample the dependent variable can only be measured when the firm innovates. Out of 89,518 observations collected by the UKIS during 2002-2014, only 49.0 percent of observations are available for product innovation created in-house, 47.7 percent of observations – for innovation with other businesses and 37.9 percent of new to market product sales. Each round of UKIS is collected as a stratified sample (ONS, 2017), of a pull of firms by industry, region and size. A straightforward regression analysis may lead to inconsistent parameter estimates. This problem is well known as sample selection bias, while a Heckman estimator is available to correct for this (Heckman, 1979). If the selection process is time constant, panel estimators are able to resolve this problem, however in the unbalanced panel as ours this may not be the case. We apply the selection correction of the data on UK innovation survey 2002-2014.

Heckman (1979) procedure is used to test for the existence of selection bias using all available n observations, estimate the probit model of S_i on Z_i and obtain the estimates $\widehat{\gamma_h}$. S_i is a selection indicator for each firm i by S_i we observe (y_i, x_i), S_i =0 otherwise. S_i indicates we will use the observation in our analysis; S_i =0 means the observation will not be used. Given missing and unreported values of innovation outputs we use less than n in our sample, say n_i. In the selection equation of the Heckman (1979) procedure, our dependent variables y_i are binary, equal one if innovation was reported by a firm (i) (in-house, co-creation or new product to market sales), zero otherwise. We compute the inverse Mill's ratio $\widehat{\lambda_i} = \lambda(z, \hat{\gamma})$ for each i. Using the selected sample, that is, the observations for which S_i =1 we run the regression of

$$y_i \text{ on } x_i \text{ and } \hat{\lambda}_i \qquad (1)$$

The equation provides a simple test of selection bias. We use the usual t-statistics on $\hat{\lambda}_i$ as a test of null hypothesis: ρ=0. Under null hypothesis, there is no sample selection problem (Wooldridge, 2009: 610). In addition to x_i , we used three variables in the selection equation such as number of active plant units, in logs, factors constraining innovation (finance availability) and regulatory requirements (see Table 1). These variables are associated with propensity to innovate. Table A2 contains the results from the Probit (Tobit) and Heckman regressions for three innovation outputs. Standard errors reported for the Heckman results are Probit standard errors from regression (1). There is no evidence of a sample selection problem in estimating the innovation output function. The coefficient $\hat{\lambda}_i$has a very small t-statistics (1.23), so we fail to reject the null: ρ=0. Just as importantly, there are no practically large differences in the estimated slope coefficients in Table A2. If there is no evidence of a sample selection, there is no reason to continue with correction for selection bias.

4.2. Model specification: a two-stage knowledge production function

First stage estimation

Firms decide whether to source knowledge strategically, and firms with high levels of innovation performance may be more likely to source knowledge externally. This raises a possible endogeneity issue. In order to analyse the relationship between external knowledge collaboration and innovation performance at the firm level, we estimate a knowledge production function (Pakes and Griliches, 1984; Crépon et al. 1998) and correct for potential endogeneity. The IV estimator is obtained in two stages. The first stage concerns external innovation collaboration (collaboration intensity) (Leiponen and Helfat, 2010) when firms decide if or not to collaborate and how many types of collaborative partners to choose (Santamaria et al. 2009; Frenz and Ietto-Gillies, 2009). External collaboration intensity is correlated with the error. To estimate the knowledge production function we consider a standard linear model with a dependent variable y_i (firm's innovation) and an endogenous variable φ_i (collaboration intensity):

$$y_i = \beta_0 + \beta_i x_i + \omega_i \varphi_i + u_i \qquad (2)$$

We can also call it structural equation to emphasize that we are interested in β_i and that the equation to be measured as causal. Variables x_i and φ_i are explanatory variables of firm's innovation and u_i is an error term. x_i is exogenous and not correlated with u_i, while φ_i is likely to be correlated with u_i (Wooldridge, 2009: 517). φ_i is external collaboration intensity measured as the number of partner types (collaboration portfolio) with whom firm collaborates on innovation (suppliers, clients, competitors, consultants, universities, government (0– no collaborators , max. 6) (Beers and Zand, 2014; Choi and Contractor, 2017).

We will instrument φ_i with two exogenous variables with an assumption ϱ_1 (business belongs to an enterprise group (alliance) which includes at least 2 independent business units) and ϱ_2 (business made major changes in introducing new methods of organizing external relationships with other external firms and public institutions), that do not appear in (2) and are uncorrelated with the error u_i are known as exclusion restrictions. In the reduced form of equation φ_i is estimated as:

$$\varphi_i = \pi_0 + \beta_i x_i + \pi_1 \varrho_1 + \pi_2 \varrho_2 + v_i \qquad (3)$$

where $E(v_i) = 0$, $cov(\varrho_1, v_i) = 0$, $cov(\varrho_2, v_i) = 0$. For this IV not to be perfectly correlated with ϱ_1 we need $\pi_2 \neq 0$ and not to be perfectly correlated with ϱ_2 we need $\pi_1 \neq 0$. The identification requires that $\pi_1 \neq 0$ and $\pi_2 \neq 0$ or both (Wooldridge, 2009: 523).

Using panel data element and, due to the nature of the dependent variables from the UKIS we used four multivariate Tobit models to predict the collaboration intensity ($\hat{\varphi}_i$). The reason of utilising Tobit estimation is that a significant number of firms. which report no collaboration partner (Table 4), results of collaboration intensity variable to be double censored. In addition to ϱ_1, ϱ_2 which are exclusion restrictions, other explanatory exogenous variables x_i are included as well as a set of time and legal status fixed effects. Regional dummies were not used, because our dependent variable $\varphi_i$in model (3) is regional and national collaboration intensity, which is a linear combination of regional dummies. The results of the first stage IV estimation across four geographical dimensions are reported in Table A1 in the Appendix, including the post-estimation test (chi2) of a joint significance of chosen instruments. Table A1 (specifications 1-4) in the Appendix illustrates the evidence for the first condition being satisfied with the coefficients of the chosen instruments and significant and positively associated with endogenous variable φ_i, ceteris paribus. Firms that belong to an enterprise group (ϱ_1) (β=0.13-0.20, $p<0.05$) and firms that introduce new methods of organizing external relationships with other firms ϱ_2 (β=1.06-1.61, $p<0.001$) will experience higher collaboration intensity φ_i.

Second stage estimation

IV Probit (IV Tobit) first "purges" φ_i of its correlation with u_i before doing the Probit (Tobit) regression in (2). Table 5 and 6 report the second-stage IV estimation with $\widehat{\varphi_i}$ and $x_i$as explanatory variables.

We estimated equation (2) using IV Probit model when a dependent variable is binary and IV Tobit model (Amemiya, 1984) when a dependent variable is new to market sales which is double censored, as firms can have none or all sales from new to the market products (Faems et al., 2005; Laursen and Salter, 2006).

We save u_i to provide the evidence of the second condition for IV to hold: ϱ_1 and ϱ_2 to be uncorrelated with u_i corr(ϱ_i,u_i) = 0, any linear combination is also uncorrelated with u_i (Wooldridge, 2009). We estimate equation (4), where the dependent variable is u_i from equation (2) regressed on the chosen instruments (ϱ_1, ϱ_2) . Table A3 has three models with three dependent variables u_i : product innovation in-house residuals (specifications 1-4), product innovation external residual (specifications 5-8), innovative sales , in logs residual (specification 9-12).

$$u_i = \beta_0 + \beta_i z_i + \rho_1 \varrho_1 + \rho_2 \varrho_2 + \epsilon_i \quad (4)$$

where u_i is error from equation (2). Variables z_i are control variables such as regional, year and industry 2 digit SIC fixed effects, firm ownership status variable and ϵ_i is an error term. Coefficients ρ_1 and ρ_2 (Table A3) are not statistically significant and we conclude that across two innovation models and four geographical dimensions corr(ϱ_i,u_i) = 0, thus ρ_1 and ρ_2 are valid instruments for φ_i.

5. Results

5.1. External collaboration and innovation in firms

We start by estimating equation (2) using IV probit across four KIS, other sectors and the overall estimation. Results are reported in Table 5 and illustrate the direct effect of knowledge collaboration on firm's own innovation (in-house).

TABLE 5 ABOUT HERE

Although the benefits from external collaboration are different across four KISs and other sectors, the coefficients of regional, national and European external collaboration intensity are consistently positive and significant. Firms in the high-tech manufacturing have almost no benefits from external knowledge collaboration, while the factors which drive firm's innovation are R&D intensity (β=0.20, p<0.01), exploration activity in new markets and products (β=0.44, p<0.01), investment in human capital (β=0.15, p<0.001) and export orientation (β=0.88, p<0.01). Amongst KIS, firms in the ICT and KIBS sectors benefit most from external collaboration with major effect of collaboration with regional and national partners. Other factors which facilitate innovation in ICT are R&D intensity (β=0.23, p<0.001), exploration activity (β=0.25, p<0.001), investment in human capital (β=0.14, p<0.001), and export orientation (β=0.39, p<0.001). For KIBS the most influential factors remain, R&D intensity (β=0.31, p<0.001), exploration activity (β=0.39, p<0.001), investment in human capital (β=0.10, p<0.001), export orientation (β=0.45, p<0.001), firm age (β=-0.08, p<0.001) and firm size (β=0.28, p<0.001). Creative sector benefits from collaboration with national partners most as well as investment in innovation are R&D intensity (β=0.06, p<0.01), exploration activity (β=0.53, p<0.01), human capital (β=0.07, p<0.001) and export (β=0.42, p<0.01).

Factors which impede innovation are lack of market knowledge and other factors equally negatively affected all KIS and non-KIS (other sectors). Interestingly, the "other sectors" (non-KIS), characterized by the paucity of knowledge have strong positive benefits from external knowledge collaboration in particular within national and regional partners. Firms in non-KIS are less likely to invest in internal knowledge find it economically viable to source knowledge from external partners. Our finding supports H1 (Chesbrough, 2006; Laursen and Salter, 2014).

5.2. External collaboration and firm's innovation

The results of IV probit estimation are in (Table 6, columns 1-8), while the results of IV Tobit are in (Table 6, columns 9-12).Table 6 (columns 1-4 and 9-12) illustrates the direct and indirect effects (interaction analysis) of external collaboration on firm's innovation developed by a firm, while Table 6 (columns 5-8) illustrates the direct and indirect effects (interaction analysis) for firm's innovation co-created with other businesses. Results overwhelmingly support H1 on the positive impact of external collaboration for new product creation by the firm and in collaboration with external partners. External collaboration facilitates new to market product sales. Collaboration with regional and national partners has higher impact on firm's innovation that external collaboration with Europeans and international partners (Table 6). von Hippel (1994) and Iammarino and McCann (2006) explain this phenomenon as a 'sticky' innovation process within particular regions. Although both the KISs and other sectors have positive returns to external collaboration on firm's innovation and across different geographical dimensions, non-KIS are likely to benefit more by collaboration (Figure 1).

FIGURE 1 ABOUT HERE

5.3. The limits to collaboration

To test our H2 we investigate the sign of the two-way interaction between internal knowledge investment (R&D intensity and share of scientists) and external collaboration intensity across three equations. Although the direct effect of R&D and scientists (standardized) is positive and statistically significant (Chesbrough et al. 2006; Escribano et al.

2009; Beers and Zand, 2014), the interaction (indirect) effect of R&D intensity and collaboration intensity as well as share of scientists and collaboration intensity is negative (Veugelers et al. 1997; Cassiman and Veugelers, 2002). Although the coefficient is small, it is significant pointing on the existence of negative externalities of collaboration such as maximization challenges and transaction costs (Bogers et al. 2017). The results are consistent across three models. The negative sign of the interaction term demonstrates a decreasing pattern of returns to external collaboration. For example, an increase in one standard deviation of R&D intensity along with an increase in collaboration intensity by one unit (partner) is likely to decrease the likelihood of firm's innovation in-house on average by (β=-0.03, $p<0.05$) when collaborating with regional partners, (β=-0.05, $p<0.01$) when collaborating with national partners, (β=-0.04, $p<0.01$) when collaborating with European partners and (β=-0.06, $p<0.01$) when collaborating with international partners (Table 6, spec. 1-4). For firms who co-create products with other businesses, an increase in one standard deviation of R&D intensity along with increase in collaboration intensity by one unit (partner) is likely to decrease returns to co-creation between by 0.02 for European and international partners and 0.04 for national partners (Table 6, spec. 5-8). A decrease in firm's innovation when a firm jointly increases internal knowledge base and external collaboration intensity is termed "the limits to collaboration". Our robustness check of the limits to collaboration using IV Tobit estimation for new product sales supports H2 (Table 6, spec. 9-12).

The interaction results also support H2 (Table 6, spec. 1-8). An increase in one standard deviation of "scientists" along with an increase in collaboration intensity by one unit (partner) is likely to decrease the likelihood of firm's innovation in-house between 0.01 and 0.05 ($p<0.01$). No factors constraining collaboration with European and international external partners were found for in-house innovation (Table 6, spec. 1-4). It is likely that firms collaborate to a lesser extent with international partners while developing new products in-house or firms who collaborate internationally are better prepared to monitor the knowledge transfer (or both) (Veugelers et al. 1997)

Firms which co-create new product with other businesses are more likely to experience the limits to collaboration as we observe decreasing returns to knowledge collaboration by (β=-0.04, p<0.001) when collaborating with regional and European partners, by (β=-0.06, p<0.001) when collaborating with regional partners, by (β=-0.05, p<0.001) when collaborating with European partners and by (β=-0.04, p<0.001) when collaborating with national and international partners (Table 6, spec. 5-8). Robustness check for the "limits to collaboration" applied to new product to market sales (Table 6, spec. 9-12) also supports H2. Table 6 (spec. 9-12) illustrates a joint increase in one standard deviation of scientists' share and one collaboration partner decreases returns to regional collaboration for new product sales by 0.31 percent for regional collaboration, 0.17 percent for national collaboration, 0.21 percent for European and 0.25 percent for international collaborators supporting prior findings on knowledge integration (West and Gallagher, 2006; Bogers et al. 2017).

The fact that the limits to collaboration are consistent across external collaborations within all four geographical dimensions does not support H4. This is an interesting finding, as we evidence that co-location increases the likelihood of new product creation, while the distance to partner is not a boundary condition limiting collaboration.

5.4. Internal innovation and external collaboration: substitutes or compliments?

The essential premise of the limits to collaboration appears to be that combining internal and external sources of knowledge is costly and risky. This brings us to consideration that external sources and internal innovation may be substitutes and it needs to be unpicked further. Although both internal and external innovation is likely to facilitate the development and commercialization of new products (Chesbrough, 2003, 2006; West et al. 2014), their joint development is costly and when resources are limited, managers are likely to choose either of two strategies. Firms may rely on absorptive capacity to facilitate innovation.

In order to test this relationship we estimated equation (2) using internal collaboration (innovation was created in-house) and external collaboration (co-creation of innovation) as explanatory variables, interacting them with firm's absorptive capacity (Jansen et al. 2005) to demonstrate if afterall internal innovation may increase returns to external innovation though absorptive capacity and vice versa. Table A4 (spec. 1,4,7) in the Appendix reports the results of estimation with controls only. Table A4 (spec. 4-6) illustrates the effect of internal innovation on external collaboration and (Table A4, spec. 1-3) - the effect of external collaboration on internal innovation. We also examine the joint effect of external collaboration and internal innovation on new product sales interacting internal innovation and co-creation with absorptive capacity (proxied by scientists and R&D intensity). Our results are intriguing. Table A4 (spec. 1-3) demonstrated that co-creating innovation decreases the likelihood of internal innovation by 44.4%, while further investment in absorptive capacity accelerates the substitution effect (Cassiman and Valentini, 2016) both for scientists and R&D intensity. Similarly, firms that invest in internal innovation are 48% less likely to co-create innovation with partners, with investment in absorptive capacity increases the substitution effect, both for scientists and R&D intensity (Table A4, spec. 4-6). Although, the limits to collaboration will make a firm to choose between two strategies as the long-run cost of learning through absorptive capacity may be substantial (Cohen and Levinthal, 1989), internal innovation and co-creation of products positively affect new product sales (Table A4, spec. 7-9). We found that interaction coefficient of innovation and R&D is not statistically significant, while the interaction coefficient between innovation and share of scientists is positive. The result demonstrated that capabilities and skills embodied in scientists are crucial for both internal innovation and co-creation with external partners to commercialize new products as a form absorptive capacity (Cohen and Levinthal, 1989). R&D costs further limits assimilating and exploiting of innovation (in-house and co-creation). This is likely to be associated with the cost and maturity level of R&D expenditure (Enkel, Bell and Hogenkamp, 2011), while human capital can be rapidly applied and integrated in innovation strategies.

5.5. Industrial perspective to the limits to collaboration

To test our H3 we investigate the sign of the three-way interaction between internal knowledge investment (R&D intensity and share of scientists) and external collaboration intensity conditional on the industry where a firm is located ("KIS" vs. non-KIS sector). Our rationale comes from the a prior evidence that firms in KIS are likely to better monitor and appropriate intangible knowledge (Bogers, 2011; Bogers et al. 2017) than do firms in the other sectors. Results in Table 6 partially support H3 with KIS firms are able to offset the cost to collaboration associated with control over R&D expenditure, however not the limits of collaboration which are associated with human capital management (share of scientists). Results of the estimation across three dependent variables are different. For example, KIS firms are more likely to leverage the limits to collaboration when creating products in with other businesses (β=0.03-0.05, $p<0.01$) (Table 6, spec. 5-8), rather than doing it in-house (β=0.01, $p>0.10$) (Table 6, spec. 1-4). We also found that firms in KIS are able better offset a decrease in new product sales, while non-KIS are not (Table 6, spec. 9-12). The results of Tobit estimation can be interpreted directly with 0.27, 0.46, 0.47 and 0.38 percent offsetting sales-drop in KISs while investing in R&D and collaboration compared to non-KIS firms. The fact that firms in both KIS and non-KIS sectors who have higher share of scientists cannot offset the costs to collaboration is likely to be associated with more complex mechanisms and loopholes in labor market. Greater monitoring and instructing scientists employed by a firm, while those exploit various channels of collaboration and co-creation, knowledge transfer may be limited (Boardman and Ponomariov, 2009; Bradley et al. 2013) which may result in knowledge outflows.

Interesting finding relates to our control variables (Table 6). Firm size is an important predictor of innovation within a firm (enterprise group). Large firms and medium firms (are more likely than small firms to develop new products in-house, while both large and small firms with equal likelihood co-create new products (Baum et al. 2000). The exploration activity is positively associated with the likelihood of innovation and new product sales. Firms which report a high cost of innovation as an impediment are more likely to innovate in-house, than co-create new products. Firm age is negatively associated with new product developed by the firm and in collaboration with other businesses. More mature firms also experience lower new product sales, than do younger firms.

6. Further robustness checks

Firstly, the difficulties arise from the fact that the product innovation indicators and collaboration are defined over 3-year period. As a robustness check we estimated the equation (4) using lagged predicted values of collaboration for a small panel element of 1,651 firms observed at least twice over 2002-2014. Given the low volatility of external innovation collaboration over time, the results with signs and confidence intervals of the regression coefficients were similar to those reported in Tables 6.

Secondly, we included the associated longitudinal survey weights (ONS, 2017) in the estimation of (4) with the coefficients signs and significance remained unchanged.

Thirdly, we estimated (4) for each of three dependent variables, using a multilevel model, sometimes also called a hierarchical, random coefficient or mixed-effect model, as the data structure in the population is hierarchical (Goldstein, 2003; Gelman and Hill, 2006). Firms are hierarchically nested in a three-level model: six waves of the BSD-BERD-UKIS dataset; 12 UK regions and industris (Goldstein, 2003)[2]. The signs and the direction of the relationship and coefficients for explanatory variables reported in Table 6 were not statistically different.

7. Discussion and Conclusion

The measurement and management of the external knowledge collaboration for firm's innovation has long remained an open question in the external knowledge sourcing and open innovation literatures (Cassiman and Veugelers, 2002; Gans and Stern, 2003; West and Gallagher, 2006; Chesbrough, 2006; Bogers, 2011).

The purpose of this study was to understand and measure the effect of external collaboration as well as the limits to such collaboration for the most innovative UK firms. To accomplish this we applied both the industrial and geographical perspective within the evolving literature on open innovation (West, 2003; Chesbrough 2003, 2006; West and Gallagher, 2006; Colombo et al. 2011, 2016; Driffield et al., 2010, 2014; Love et al., 2014; Cassiman and Valentini, 2016).

We found strong evidence that the likelihood of firm's innovation developed by the firm and in collaboration with other businesses increases with external collaboration intensity. Firms who collaborate within close proximity will not experience higher innovation than firms collaborating with international partners, illustrating that limits to collaboration do not increase with the geographical proximity. . We also found that joint increase in collaboration intensity and absorptive capacity does not results in more benefits from external collaboration. On the contrary, there are limits to collaboration associated with maximization, incorporation, valuation and motivation challenges, preventing a continuous increase in innovation output.

[2] Estimates are available from authors upon request.

Interestingly, firms in KIS are more likely to offset the limits to collaboration via control over R&D intensity, rather than share of scientists they employ.

The geographical and industrial perspective to external collaboration enables us to distinguish three collaboration strategies, which could be applied by the most innovative firms to better offset the limits to collaboration. First, control and monitoring human capital when developing new to market product in-house (internal innovation). Second, prioritizing a certain type of collaboration partner to offset increase in transaction costs when a number of partners increases. Third, develop appropriation and coordination mechanisms to enhance the likelihood of new product creation (Choi and Contractor, 2017). This study makes the following contributions to the management of innovation, external knowledge sourcing and open innovation literature.

Firstly, we identify the industrial boundaries of the external knowledge collaboration, such as KISs in terms of their size and impact on firm innovation, when a new product is developed by the firm and in collaboration with other businesses. We emphasize the role of KIS firms who better offset the limits to collaboration compared to non-KIS firms.

Secondly, we identify the role of geographical dimension for external knowledge collaboration and demonstrate that returns to collaboration are consistent across different geographical dimensions.

In addition, the application of a structural model to innovation data on external knowledge collaboration may offer methodological cues for cross-sectional analysis with a small panel component as well as the issue of selection biases when dealing with innovation survey data.

Our results are in line with previous research (Chesbrough, 2003, 2006; Laursen and Salter, 2006; Leiponen and Helfat, 2010; Bogers, 2011; Bogers and Horst, 2014), suggesting that firms in the KIS and non-KIS need to be treated differently. .

Finally, this study makes several key points to firm managers and policy-makers. Firstly, despite the importance of innovation openness (Love et al. 2014), there are the limits to external collaboration (Teece, 1986; Veugelers, 1997). The assumption that UK firms can linearly increase their innovation outputs while increasing collaboration intensity (partner portfolio) and investing in the knowledge base internally was not supported.

Secondly, while firms are likely to choose either internal innovation or external collaboration, the simultaneous engagement in internal innovation and co-creation with external partners provides extra gains in new product commercialization, with human capital playing a crucial role in facilitating innovation.

Thirdly, we suggest that KIS firms may benefit from an increased positive externalities and knowledge spillovers (Audretsch and Feldman, 1996).

One of the limitations of this study is that data was gathered using a survey that was not specifically designed to tests the limits to external collaboration. In the UKIS, firms are asked about their collaboration decisions along with the collaboration partner portfolio and the degree of collaboration, rather than the number of collaboration partners within each type, the level of connectedness (frequency of communication, intensity) and the length of such collaboration contacts. Another limitation is a reduction in observations in the final three waves of UKIS (2008-2014). It is likely that the global financial crises had an impact on the innovation and external collaboration behaviour of firms.

This study calls for future research on knowledge sourcing from external partners within and between industries as well as across different geographical proximities. Special focus should be on capturing the intensity of contacts when collaboration takes place between firms (organizational level) as well as between leading managers and scientists (individual level). Further information should be obtained on collaborative R&D and other knowledge transfer agreements between the recipient and distributor of knowledge. Finally, research is needed on innovation collaboration costs (beyond R&D expenditure) in the most innovative sectors. Future research on "other sectors", including emerging sectors as well as comparative studies using firm–level data across various spatial, technological, institutional, temporal, cultural and other proximities (Boschma, 2005). Subsequent research will need to embrace other forms of firm's innovation performance, including process innovation, organizational and management innovation, exploration activity and innovation search.

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Table 1: Descriptive Statistics

Label		questions related to the variables and their derivatives	Mean	Std. Dev.	Min	Max
			Overall sample = 19,510 obs.			
Product innovation in-house (DV1)		New goods and services developed mainly by the business or enterprise group=1, zero otherwise	0.312	0.463	0.00	1.00
Product innovation external (DV2)		New goods and services developed mainly with other businesses =1, zero otherwise	0.124	0.330	0.00	1.00
Product innovation sales (DV3)		Sales of new to the market products, thousand GBP taken in logarithm	1.640	2.937	0.00	10.31
Independent variables (UKIS)	*Collaboration intensity regional*	# partner types firm cooperates on innovation regionally (suppliers, clients, competitors, consultants, universities, government (0– no collaborators , max. 6)	0.398	1.107	0.00	6.00
	Collaboration intensity national	# number partner types firm cooperates on innovation nationally(suppliers, clients, competitors, consultants, universities, government (0– no collaborators, max. 6)	0.590	1.351	0.00	6.00
	Collaboration intensity Europe	# partner types firm cooperates on innovation in Europe (suppliers, clients, competitors, consultants, universities, government (0– no collaborators , max. 6)	0.221	0.772	0.00	6.00
	Collaboration intensity world	# partner types firm cooperates on innovation in other world (suppliers, clients, competitors, consultants, universities, government (0– no collaborators , max. 6)	0.190	0.736	0.00	6.00
Five sectors of interest (BSD)	*High-tech Manufacturing*	Binary variable equal one if firms belongs to one of the following SIC 2007 (2 digit): 19-22, 26-27, 29, 32, 33.20, zero otherwise	0.112	0.317	0.00	1.00
	ICT	Binary variable equal one if firms belongs to one of the following SIC 2007 (2 digit): 58-63, zero otherwise	0.073	0.260	0.00	1.00
	KIBS	Binary variable equal one if firms belongs to one of knowledge intensive business services sectors SIC 2007 (2 digit): 64-66, 69-71, 74.20, 74.30 and 74.90, zero otherwise	0.105	0.306	0.00	1.00
	Creative	Binary variable equal one if firms belongs to one of SIC2007 (2 digit): 70.21, 71.11, 71.20, 73.11, 73.12, 74.10, 74.20, 85, zero otherwise	0.044	0.205	0.00	1.00
	Other sectors	Binary variable equal one if firms belongs to one of SIC2007 (2 digit) sectors except high-tech manufacturing, ICT, KIBS and creative, zero otherwise	0.665	0.472	0.00	1.00
	Knowledge intense sectors	Binary variable equal one if firms belongs to high-tech manufacturing, ICT, KIBS or creative sector, zero otherwise	0.335	0.472	0.00	1.00
R&D intensity (BERD and UKIS)		Internal Research and Development expenditure (£) to total sales (£) ratio	0.013	0.052	0.00	0.67
Firm size (BSD)	*Small*	Binary variable equal one if number of FTEs is <50, zero otherwise	0.446	0.497	0.00	1.00
	Medium	Binary variable equal one if number of FTEs is between 50and 249, zero otherwise	0.277	0.448	0.00	1.00
	Large	Binary variable equal one if number of FTEs is >=250, zero otherwise	0.275	0.447	0.00	1.00
Exploration (UKIS)	Exploration	Binary variable equals one if a firm states the importance of increasing range of goods or services and enter new markets is high, zero otherwise	0.408	0.492	0.00	1.00
Hampering factor (UKIS)	*Cost*	Binary variable equals one if firm states the factors has severely constrained innovation: excessive perceived economic risks, direct innovation costs too high, cost and availability of finance, zero otherwise	0.331	0.471	0.00	1.00
	Knowledge	lack of qualified personnel, lack of information on markets, lack of information on technology and markets, zero otherwise	0.137	0.344	0.00	1.00
	Other	market dominated by established businesses, uncertain demand for innovative goods or services, zero otherwise	0.173	0.379	0.00	1.00
Ownership Status (BSD)	*Company*	Binary variable=1 if firm's legal status is limited liability company, 0 otherwise	0.844	0.361	0.00	1.00
	Sole proprietor	Binary variable=1 if firm's legal status is Sole-proprietor, 0 otherwise	0.041	0.201	0.00	1.00
	Partnership	Binary variable=1 if firm's legal status is partnership, 0 otherwise	0.100	0.300	0.00	1.00
	Public corporation	Binary variable=1 if firm's legal status is *Public corporation*, 0 otherwise	0.001	0.027	0.00	1.00
	Non-for-profit body	Binary variable=1 if firm's legal status is *Non for profit*, 0 otherwise	0.013	0.113	0.00	1.00
Foreign (BSD)		Binary variable=1 if a firm has a headquarter in a foreign country, zero otherwise	0.468	0.499	0.00	1.00
Age of firm, logs (BSD)		Age of a firm (years since the establishment) in logarithm	2.620	0.808	0.00	3.98
Scientist, % of FTE (UKIS/BERD)		The proportion of employees that hold a degree or higher qualification in science and engineering at BA / BSc, MA / PhD, PGCE levels	7.673	17.537	0.00	100.0
Exporter (UKIS)		Binary variable=1 if a firm sells its products in foreign markets, 0 otherwise	0.397	0.489	0.00	1.00
Variables used as exclusion restrictions in the Two Stage IV estimation of knowledge production function						
Enterprise group		Business belongs to an enterprise group (alliance) which includes at least 2 independent business units.	0.309	0.462	0.00	1.00
External relations		Business made major changes in introducing new methods of organizing external relationships with other firms and public institutions (e.g. alliances, partnerships, outsourcing, sub-contracting, etc.)	0.276	0.447	0.00	1.00
Additional variables used for Heckman selection equation on all obs. available						
Hampering factor: finance availability		How important were the following factors in constraining innovation: availability of finance (0 – not at all; 3 – high constraint)	0.996	1.071	0.00	3.00

Number of active plant units	Number of active plant units (enterprise units with physical location), in logarithms	0.984	0.938	0.00	4.941
Market share	Importance for business to meet regulatory requirements (standards)(0 – not important – 3 very important)	1.409	1.219	0.00	3.00

Source: Department for Business, Innovation and Skills, Office for National Statistics, Northern Ireland. Department of Enterprise, Trade and Investment. (2018). *UK Innovation Survey, 1994-2016: Secure Access*. [data collection]. *6th Edition.* UK Data Service. SN: 6699, http://doi.org/10.5255/UKDA-SN-6699-6 hereinafter named UKIS – UK Innovation Survey (2002-2014).

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Table 2: Matrix Correlation

	Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	Product innovation in-house	1																
2	Product innovation external	0.11*	1															
3	Product innovation sales	0.55*	0.24*	1														
4	Collab intensity regional	0.13*	0.14*	0.18*	1													
5	Collab intensity national	0.24*	0.22*	0.34*	0.39*	1												
6	Collab intensity Europe	0.22*	0.16*	0.31*	0.33*	0.56*	1											
7	Collab intensity world	0.19*	0.12*	0.28*	0.25*	0.43*	0.59*	1										
8	R&D intensity	0.20*	0.05*	0.19*	0.09*	0.19*	0.21*	0.24*	1									
9	Medium	-0.02	-0.03	-0.04*	-0.03	-0.03*	-0.04*	-0.04*	0.00	1								
10	Large	0.10*	0.06*	0.16*	0.03*	0.13*	0.14*	0.11*	-0.03*	-0.37*	1							
11	Exploration	0.24*	0.16*	0.24*	0.07*	0.13*	0.11*	0.10*	0.10*	-0.00	0.04*	1						
12	Cost	0.09*	0.05*	0.11*	0.11*	0.12*	0.09*	0.08*	0.09*	-0.00	-0.03*	0.21*	1					
13	Knowledge	0.02*	0.01	0.04*	0.05*	0.05*	0.03*	0.04*	0.05*	-0.00	-0.06*	0.15*	0.35*	1				
14	Other	0.03*	0.01*	0.03*	0.05*	0.05*	0.04*	0.03*	0.04*	-0.00	-0.03*	0.15*	0.39*	0.44*	1			
15	Foreign	0.11*	0.06*	0.13*	0.00	0.09*	0.12*	0.09*	0.00	0.03*	0.46*	-0.07*	-0.08*	-0.09*	-0.06*	1		
16	Age	0.01	0.02*	0.02*	0.00	0.01*	0.02*	0.00	-0.08*	0.10*	0.19*	-0.02*	-0.03*	-0.02*	-0.01	0.23*	1	
17	Scientist	0.20*	0.06*	0.22*	0.08*	0.20*	0.21*	0.23*	0.39*	-0.03*	0.00	009*	0.08*	0.05*	0.04*	0.04*	-0.08*	1
18	Exporter	0.32*	0.15*	0.32*	0.07*	0.21*	0.27*	0.24*	0.17*	0.03*	0.16*	0.14*	0.06*	0.00	0.02*	0.20*	0.09*	0.24*

Note: Significance level: * p<0.05. Number of obs. = 19,510.
Source: BSD - Business Register (2002-2014) and UKIS - UK Innovation Survey (2002-2014).

Table 3A: Five aggregated sectors (by SIC 2007)

Description	Sample of the regressions (DV: Product innovation)							Population sample: (DV: Product innovation)						
	2005	2007	2009	2011	2013	2015	Total	2005	2007	2009	2011	2013	2015	Total
High-tech Manufacturing	1565	312	304	39	19	18	2257	1692	642	414	77	19	18	2862
ICT	896	171	195	86	28	43	1419	994	452	279	347	129	135	2336
KIBS	1514	149	151	168	28	31	2041	1732	524	231	823	155	175	3640
Creative	541	52	89	84	33	54	853	600	159	119	341	104	140	1463
Other sectors	9944	781	682	1181	176	176	12940	11435	2918	1208	5973	1008	1136	23668
Total							19,510							33,969

Note: The totals of rows, which could be used to calculate the number of enterprises in cells (<10) across sectors were suppressed for disclosure control.

Table 3B: Sample distribution by ONS 12 regions

Description	Sample of the regressions (DV: Product innovation)							Population sample: (DV: Product innovation)						
	2005	2007	2009	2011	2013	2015	Total	2005	2007	2009	2011	2013	2015	**Total**
North East	830	93	85	61	<20	17		950	298	135	262	61	76	
North West	1341	129	117	174	32	23		1498	380	198	767	139	130	
Yorkshire and The Humber	1,179	110	133	126	<20	17		1,348	363	203	640	116	125	
East Midlands	1178	145	121	121	<20	23		1329	397	189	570	112	128	
West Midlands	1,285	146	122	143	21	19		1,456	409	207	650	114	138	
Eastern	1,252	143	128	159	25	34		1,419	421	176	750	132	152	
London	1,401	104	111	170	36	32		1,615	495	196	1006	205	183	
South East	1543	162	157	203	48	45		1738	465	248	1,084	228	226	
South West	1,196	127	141	128	27	18		1,361	380	213	637	139	107	
Wales	975	106	97	74	<20	19		1,100	338	155	344	51	97	
Scotland	1,115	116	122	104	<20	38		1,270	360	176	583	78	167	
Northern Ireland	1215	84	90	73	<20	22		1359	389	155	268	40	75	
Total							19,510							33,969

Table 3C: Sample distribution by Size (Micro and Small, Medium and Large)

Description	Sample of the regressions (DV: Product innovation)							Population sample: (DV: Product innovation)						
	2005	2007	2009	2011	2013	2015	Total	2005	2007	2009	2011	2013	2015	Total
Micro and Small 1-49	6,380	513	558	912	184	178		6,970	1934	838	2166	356	389	
Medium 50-249	4,098	362	389	404	61	105		4,408	1034	579	1016	117	174	
Large >249	4,032	590	477	220	23	24		4,324	1452	779	524	58	46	
Total							19,510							33,969

Source: BSD - Business Register (2002-2014) and UKIS - UK Innovation Survey (2002-2014).

Table 4: Collaboration with external partners by geographic dimensions for four major UK sectors (N=19,510)

Number of firm in the sample

Regional

High Tech	*Collaboration* No	*Collaboration* Yes	Total	**ICT**	*Collaboration* No	*Collaboration* Yes	Total	**KIBS**	*Collaboration* No	*Collaboration* Yes		**Creative**	*Collaboration* No	*Collaboration* Yes	
No	83.6%	16.4%	**17305**	No	83.5%	16.5%	**18089**	No	83.3%	16.7%	**17463**	No	83.7%	16.3%	**18654**
Yes	80.3%	19.7%	**2205**	Yes	80.5%	19.5%	**1421**	Yes	83.1%	16.9%	**2047**	Yes	72.7%	27.3%	**856**
Total	**17422**	**2088**	**19510**	Total	**17422**	**2088**	**19510**	Total	**17422**	**2088**	**19510**	Total	**17422**	**2088**	**19510**

Nation

High Tech	*Collaboration* No	*Collaboration* Yes	Total	**ICT**	*Collaboration* No	*Collaboration* Yes	Total	**KIBS**	*Collaboration* No	*Collaboration* Yes		**Creative**	*Collaboration* No	*Collaboration* Yes	
No	79.2%	20.8%	**17305**	No	79.2%	20.8%	**18089**	No	78.4%	21.6%	**17463**	No	79.1%	20.9%	**18654**
Yes	70.7%	29.3%	**2205**	Yes	66.5%	33.5%	**1421**	Yes	76.6%	23.4%	**2047**	Yes	59.3%	40.7%	**856**
Total	**17422**	**2088**	**19510**	Total	**17422**	**2088**	**19510**	Total	**17422**	**2088**	**19510**	Total	**17422**	**2088**	**19510**

Europe

High Tech	*Collaboration* No	*Collaboration* Yes	Total	**ICT**	*Collaboration* No	*Collaboration* Yes	Total	**KIBS**	*Collaboration* No	*Collaboration* Yes		**Creative**	*Collaboration* No	*Collaboration* Yes	
No	90.3%	9.7%	**17305**	No	89.7%	10.3%	**18089**	No	89.0%	11.0%	**17463**	No	90.0%	10.0%	**18654**
Yes	81.1%	18.9%	**2205**	Yes	84.8%	15.2%	**1421**	Yes	92.0%	8.0%	**2047**	Yes	73.9%	26.1%	**856**
Total	**17422**	**2088**	**19510**	Total	**17422**	**2088**	**19510**	Total	**17422**	**2088**	**19510**	Total	**17422**	**2088**	**19510**

Europe

High Tech	*Collaboration* No	*Collaboration* Yes	Total	**ICT**	*Collaboration* No	*Collaboration* Yes	Total	**KIBS**	*Collaboration* No	*Collaboration* Yes		**Creative**	*Collaboration* No	*Collaboration* Yes	
No	91.9%	8.1%	17305	No	91.4%	8.6%	**18089**	No	90.7%	9.3%	**17463**	No	91.4%	8.6%	**18654**
Yes	82.1%	17.9%	2205	Yes	82.4%	17.6%	**1421**	Yes	91.8%	8.2%	**2047**	Yes	76.7%	23.3%	**856**
Total	**17711**	**1799**	**19510**	Total	**17711**	**1799**	**19510**	Total	**17711**	**1799**	**19510**	Total	**17711**	**1799**	**19510**

Source: BSD - Business Register (2002-2014) and UKIS - UK Innovation Survey (2002-2014).

Table 5. Knowledge production function (second-stage) across five UK industries

Specification	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable	**Product innovation in-house (new to market products/ services were developed mainly by business)**					
Sectors	High-tech manufacturing	ICT	KIBS	Creative	Other sectors	All sample
Method	IV probit	IV probit	IV probit	IV probit	IV probit	IV probit
Collab. intensity (region) $\hat{\varphi}_i$	0.03 (0.02)	0.13** (0.04)	0.08* (0.03)	0.01 (0.04)	0.09*** (0.01)	0.09*** (0.11)
Collab. intensity (national) $\hat{\varphi}_i$	0.03 (0.02)	0.07* (0.03)	0.08** (0.03)	0.06* (0.03)	0.09*** (0.01)	0.08*** (0.01)
Collab. intensity (Europe) $\hat{\varphi}_i$	0.01 (0.01)	0.08 (0.09)	0.08 (0.66)	0.04 (0.03)	0.04 (0.03)	0.01 (0.01)
Collab. intensity (world) $\hat{\varphi}_i$	0.02 (0.03)	0.01 (0.01)	0.02 (0.02)	0.01 (0.00)	0.01 (0.02)	0.01 (0.03)
Standardized R&D intensity	0.20*** (0.04)	0.23*** (0.03)	031*** (0.05)	0.06** (0.02)	0.31*** (0.03)	0.15*** (0.01)
Medium	0.12 (0.17)	0.16 (0.17)	0.14 (0.09)	-0.11 (0.12)	0.02 (0.03)	0.03 (0.03)
Large	0.16 (0.52)	-0.12 (0.42)	0.26** (0.09)	0.14 (0.15)	0.07** (0.03)	0.05 (0.02)
Exploration	0.44*** (0.06)	0.25*** (0.08)	0.39* (0.17)	0.53*** (0.10)	0.33*** (0.02)	0.36*** (0.02)
Hampering factor: cost of innovation	-0.09 (0.06)	0.03 (0.11)	0.08 (0.11)	0.07 (0.16)	0.05 (0.03)	0.04* (0.02)
Hampering factor: knowledge on market	-0.21** (0.08)	-0.55*** (0.09)	-0.48** (0.09)	-0.20* (0.10)	-0.35*** (0.04)	-0.35*** (0.03)
Hampering factor: other	-0.22** (0.07)	-0.23* (0.10)	-0.25** (0.10)	-0.24 (0.17)	-0.23*** (0.04)	-0.25*** (0.02)
Foreign	0.21 (0.53)	0.05 (0.08)	-0.29 (0.39)	-0.05 (0.11)	0.49 (0.25)	0.36 (0.22)
Age of firm	-0.02 (0.06)	-0.02 (0.05)	-0.08* (0.04)	-0.16 (0.10)	-0.06*** (0.01)	-0.05*** (0.01)
Standardized Scientist	0.15*** (0.04)	0.14*** (0.02)	0.10*** (0.02)	0.07*** (0.02)	0.13*** (0.01)	0.12*** (0.01)
Exporter	0.88*** (0.07)	0.39*** (0.07)	0.45*** (0.07)	0.42*** (0.11)	0.50** (0.03)	0.55*** (0.02)
Legal status dummies	Yes	Yes	Yes	Yes	Yes	Yes
Industry, survey wave and the UK region dummies	Yes	Yes	Yes	Yes	Yes	Yes
Constant	-1.08*** (0.16)	-0.89*** (0.22)	-1.32*** (0.22)	-0.63** (0.24)	-1.05*** (0.13)	-1.08*** (0.13)
Number of observations	2257	1419	2041	853	12940	19510
Chi2	704.90	351.93	519.41	238.24	3332.05	5590.10
Log-likelihood	-1355.90	-892.92	-1034.76	-483.36	-6959.60	-10952.20

Note: standard errors robust for hereroskedastisity are in parenthesis. Reference groups: small firm (10-49 FTEs); legal ownership (listed company); UK region (North East); survey wave (2002-2004). Industry (1 digit SIC), UK region and year fixed effects were suppressed to save space. Significance level: * p<0.05; ** p<0.01; *** p<0.001".
Source: BSD - Business Register (2002-2014) and UKIS - UK Innovation Survey (2002-2014).

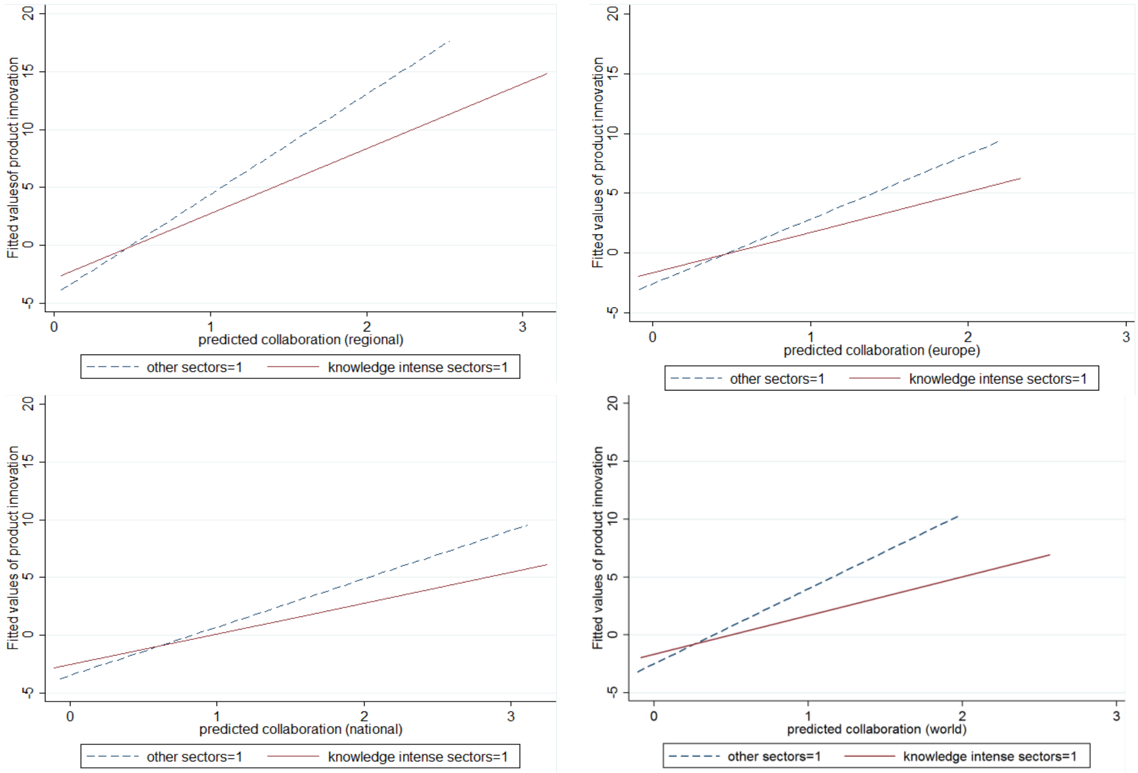
Table 6. Knowledge production function (second-stage): knowledge intense sectors vs. other sectors

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Method	Probit	Probit	Probit	Probit	Probit	Probit	Probit	Probit	Tobit	Tobit	Tobit	Tobit
Dependent variable	**New goods and services developed by business or / and enterprise group=1**				**New goods and services developed by business with other businesses =1**				**New product sales, (logs)**			
Collaboration region	regional	national	Europe	world	regional	national	Europe	world	regional	national	Europe	world
Knowledge intense sectors (KIS)	0.06* (0.03)	0.07* (0.02)	0.07* (0.03)	0.06* (0.03)	-0.09 (0.08)	-0.07 (0.06)	-0.11 (0.07)	-0.16* (0.07)	0.85*** (0.25)	0.79*** (0.23)	0.87*** (0.23)	0.80*** (0.23)
Collab. intensity (region) $\widehat{\varphi}_i$ (***H1***)	0.10*** (0.01)	0.08*** (0.01)	0.08*** (0.01)	0.09*** (0.01)	0.11*** (0.01)	0.12*** (0.01)	0.12*** (0.01)	0.12*** (0.01)	0.69*** (0.07)	0.62*** (0.06)	0.64*** (0.07)	0.65*** (0.06)
Collab. intensity (national) $\widehat{\varphi}_i$(***H1***)	0.07*** (0.00)	0.10*** (0.01)	0.07*** (0.00)	0.07*** (0.00)	0.14*** (0.01)	0.17*** (0.00)	0.14*** (0.00)	0.14*** (0.01)	0.92*** (0.05)	1.04*** (0.06)	0.91*** (0.05)	0.91*** (0.05)
Collab. intensity (Europe) $\widehat{\varphi}_i$ (***H1***)	0.02** (0.01)	0.02* (0.01)	0.06** (0.02)	0.01* (0.00)	0.02 (0.02)	0.02 (0.02)	0.02 (0.10)	0.01 (0.02)	0.03 (0.10)	0.04 (0.07)	0.30** (0.09)	0.05* (0.02)
Collab. intensity (world) $\widehat{\varphi}_i$ (***H1***)	0.97 (0.99)	0.99 (0.98)	0.95 (0.99)	0.96 (0.80)	0.75 (1.11)	0.95 (1.21)	0.74 (1.12)	0.72 (1.16)	9.93 (4.61)	9.95 (4.76)	9.81 (4.61)	9.98 (4.84)
KIS x collab. intensity by region	0.04* (0.01)	0.02* (0.01)	0.02* (0.01)	0.02* (0.01)	-0.02* (0.01)	-0.02* (0.01)	-0.02* (0.01)	-0.03* (0.01)	0.78*** (0.23)	0.76*** (0.22)	0.77*** (0.23)	0.71*** (0.35)
Standardized R&D intensity	0.33*** (0.03)	0.35*** (0.03)	0.34*** (0.04)	0.34*** (0.04)	0.07* (0.03)	0.11** (0.04)	0.08* (0.04)	0.07* (0.03)	1.58*** (0.18)	1.85*** (0.19)	1.67*** (0.19)	1.52*** (0.20)
KIS x Standardized R&D intensity	-0.18*** (0.03)	-0.17*** (0.03)	-0.17*** (0.03)	-0.16*** (0.04)	-0.10*** (0.03)	-0.16*** (0.04)	-0.11*** (0.03)	-0.11*** (0.03)	-1.13*** (0.23)	-1.30*** (0.22)	-1.21*** (0.21)	-1.04*** (0.22)
Collab. intensity x Standardized R&D intensity (H2 & H4)	***-0.03* (0.02)***	***-0.05** (0.02)***	***-0.04** (0.02)***	***-0.06* (0.03)***	***-0.02* (0.01)***	***-0.04** (0.01)***	***-0.02* (0.01)***	***-0.02 (0.02)***	***-0.45*** (0.10)***	***-0.59*** (0.08)***	***-0.60*** (0.11)***	***-0.53*** (0.12)***
KIS x Collab. intensity x Standardized R&D intensity (H3)	***0.02 (0.01)***	***0.01 (0.01)***	***0.01 (0.01)***	***0.01 (0.01)***	***0.03** (0.01)***	***0.05*** (0.01)***	***0.03* (0.01)***	***0.03 (0.02)***	***0.27** (0.12)***	***0.46*** (0.09)***	***0.47*** (0.12)***	***0.38** (0.12)***
Standardized Scientist	0.16*** (0.02)	0.16*** (0.02)	0.15*** (0.03)	0.15*** (0.02)	0.07** (0.02)	0.07*** (0.02)	0.08*** (0.02)	0.08*** (0.02)	1.25*** (0.13)	1.23*** (0.13)	1.20*** (0.13)	1.25*** (0.13)
KIS x Standardized Scientist	-0.03 (0.06)	-0.01 (0.03)	-0.04 (0.04)	-0.03 (0.03)	-0.08** (0.03)	-0.06** (0.02)	-0.09** (0.03)	-0.08** (0.02)	-0.47*** (0.15)	-0.39*** (0.16)	-0.39*** (0.15)	-0.46*** (0.15)
Collab. intensity x Standardized Scientist (H2 & H4)	***-0.05** (0.01)***	***-0.01* (0.00)***	***-0.01 (0.01)***	***-0.01 (0.02)***	***-0.06*** (0.01)***	***-0.04*** (0.01)***	***-0.05*** (0.02)***	***-0.04*** (0.01)***	***-0.31*** (0.09)***	***-0.17** (0.06)***	***-0.21** (0.09)***	***-0.25** (0.09)***
KIS x Collab. intensity x Standardized Scientist (H3)	***-0.01 (0.01)***	***-0.01 (0.00)***	***-0.01 (0.01)***	***-0.01 (0.01)***	***0.03 (0.02)***	***0.02 (0.01)***	***0.02 (0.01)***	***0.02 (0.01)***	***0.14 (0.11)***	***0.01 (0.06)***	***0.04 (0.11)***	***-0.08 (0.12)***
Medium	0.21*** (0.05)	0.20*** (0.05)	0.21*** (0.05)	0.21*** (0.05)	0.01 (0.06)	0.02 (0.06)	0.01 (0.06)	0.01 (0.06)	0.61 (0.33)	0.66** (0.30)	0.69* (0.33)	0.66* (0.33)
Large	0.26** (0.09)	0.24*** (0.05)	0.21** (0.09)	0.22** (0.08)	0.01 (0.15)	0.01 (0.09)	0.01 (0.15)	0.01 (0.15)	3.36*** (0.83)	3.22*** (0.83)	3.01*** (0.83)	3.07*** (0.83)
Exploration	0.36*** (0.02)	0.36*** (0.02)	0.36*** (0.02)	0.36*** (0.02)	0.20*** (0.03)	0.19*** (0.03)	0.20*** (0.03)	0.20*** (0.03)	2.35*** (0.15)	2.38*** (0.15)	2.49*** (0.15)	2.51*** (0.15)
Hampering factor: cost of innovation	0.04* (0.02)	0.04* (0.02)	0.04* (0.02)	0.04* (0.02)	0.04 (0.04)	0.04 (0.04)	0.04 (0.04)	0.04 (0.04)	0.71*** (0.15)	0.70*** (0.15)	0.73*** (0.15)	0.71*** (0.15)
Hampering factor: knowledge on market	-0.35*** (0.03)	-0.35*** (0.03)	-0.35*** (0.03)	-0.35*** (0.03)	-0.36*** (0.04)	-0.36*** (0.04)	-0.36*** (0.04)	-0.36*** (0.04)	-1.57*** (0.22)	-1.57*** (0.22)	-1.57*** (0.22)	-1.57*** (0.22)
Hampering factor: other	-0.24*** (0.03)	-0.24*** (0.03)	-0.25*** (0.03)	-0.24*** (0.03)	-0.19*** (0.04)	-0.19*** (0.04)	-0.19*** (0.05)	-0.19*** (0.04)	-1.16*** (0.26)	-1.16*** (0.26)	-1.12*** (0.26)	-1.11*** (0.26)

Foreign	0.01 (0.02)	0.01 (0.02)	0.01 (0.02)	0.01 (0.02)	0.03 (0.03)	0.03 (0.03)	0.03 (0.03)	0.03 (0.03)	0.08 (0.16)	0.08 (0.16)	0.08 (0.16)	0.04 (0.16)
Age of firm	-0.08* (0.01)	-0.08* (0.01)	-0.08* (0.01)	-0.08* (0.01)	-0.05** (0.01)	-0.06** (0.02)	-0.05** (0.01)	-0.06** (0.02)	-0.86*** (0.09)	-0.85*** (0.09)	-0.81*** (0.09)	-0.89*** (0.10)
Exporter	0.53*** (0.02)	0.53*** (0.02)	0.53*** (0.02)	0.53*** (0.02)	0.24*** (0.02)	0.24*** (0.02)	0.24*** (0.02)	0.24*** (0.04)	3.50*** (0.15)	3.42*** (0.15)	3.43*** (0.15)	3.45*** (0.15)
Legal status dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry, survey wave and the UK region dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	-1.05*** (0.13)	-1.05*** (0.13)	-1.05*** (0.13)	-1.05*** (0.13)	-1.73*** (0.17)	-1.73*** (0.17)	-1.73*** (0.17)	-1.73*** (0.17)	-14.09*** (1.61)	-15.66*** (1.71)	-16.01*** (1.71)	-15.60*** (1.79)
Sigma (e)									47.70*** (1.07)	47.70*** (1.07)	47.70*** (1.07)	47.70*** (1.07)
chi2	9134.45	4343.05	9117.82	4350.22	9076.55	4353.44	9086.66	4357.09	7129.02	7136.33	7092.09	7190.66
Preudo R2	0.32	0.23	0.31	0.24	0.30	0.24	0.31	0.25	0.14	0.16	0.15	0.14

Note: standard errors robust for hereroskedastisity are in parenthesis. Reference groups: small firm (10-49 FTEs); legal ownership (listed company); UK region (North East); survey wave (2002-2004). Industry (1 digit SIC), UK region and year fixed effects were suppressed to save space. Significance level: * p<0.05; ** p<0.01; *** p<0.001".
Number of observations 19510. Uncensored observations for Tobit estimation (new product sales>0) = 4960.
Source: BSD - Business Register (2002-2014) and UKIS - UK Innovation Survey (2002-2014).

Figure 1: Predicted values of new product development by the firm (vertical axis) for external knowledge collaboration with multiple partner types (horizontal axis) and across four geographical dimensions (KIS vs. non-KIS).



Note: Estimation method: IV Probit with the predicted values of collaboration in the first stage IV regression. Geographical dimensions from top left: regional, national, Europe and international collaboration partners.
Note: Calculation based on Table 6 (columns 1-4). Number of obs. =19510.
Source: BSD - Business Register (2002-2014) and UKIS - UK Innovation Survey (2002-2014).

Appendix

Table A1: Knowledge production function (first-stage): Tobit estimation

Specification	(2)	(4)	(6)	(8)
Dependent variable	Collaboration intensity regional	Collaboration intensity national	Collaboration intensity Europe	Collaboration intensity World
Method	Tobit	Tobit	Tobit	Tobit
Exclusion restrictions				
Enterprise group π_1	***0.13**** ***(0.07)***	***0.16***** ***(0.07)***	***0.14**** ***(0.08)***	***0.20**** ***(0.10)***
External relations π_2	***1.53****** ***(0.07)***	***1.61****** ***(0.06)***	***1.06****** ***(0.07)***	***1.06****** ***(0.08)***
Other controls				
R&D intensity	3.41*** (0.57)	4.30*** (0.50)	4.86*** (0.47)	5.43 *** (0.51)
Medium	0.06 (0.09)	0.13* (0.07)	-0.13 (0.10)	-0.13 (0.11)
Large	0.20* (0.10)	0.73*** (0.10)	0.71*** (0.11)	0.83*** (0.13)
Exploration	-0.09 (0.08)	0.03 (0.07)	0.34*** (0.07)	0.25** (0.09)
Hampering factor: cost of innovation	0.92*** (0.08)	0.75*** (0.07)	0.58*** (0.07)	0.44*** (0.08)
Hampering factor: knowledge on market	0.12 (0.10)	0.22** (0.09)	0.03 (0.10)	0.16 (0.11)
Hampering factor: other	0.11 (0.09)	-0.12 (0.08)	0.09 (0.09)	0.04 (0.10)
Foreign	-0.08 (0.09)	0.41*** (0.08)	0.52*** (0.09)	0.51*** (0.10)
Age of firm	-011** (0.04)	-0.09** (0.04)	-0.04 (0.05)	-0.11* (0.05)
Scientist	0.01*** (0.00)	0.02** (0.00)	0.02*** (0.00)	0.03*** (0.00)
Exporter	0.47*** (0.08)	1.11*** (0.07)	2.51*** (0.09)	2.55*** (0.10)
Legal status dummies	Yes	Yes	Yes	Yes
Industry and time dummies	Yes	Yes	Yes	Yes
Constant	-6.51*** (0.51)	-6.20*** (0.43)	-7.91*** (0.51)	-9.04*** (0.63)
Left censored obs.	16190	15207	17359	17648
Number of observations	19510	19510	19510	19510
Log-likelihood	-19058.09	-22753.00	-11149.03	-9977.17
Chi2	1887.34	3862.75	2228.24	1945.11
$\pi_{1=}\pi_2 = 0$ **(Chi2, p-value)**	445.21 (p<0.001)	630.80 (p<0.001)	253.72 (p<0.001)	201.20 (p<0.001)
Rho (fraction of variance of the overall error ui).	0.32	0.29	0.37	0.38

Note: RE – random effects panel data estimation; standard errors robust for hereroskedastisity are in parenthesis.
Reference groups: small firm (10-49 FTEs); legal ownership (listed company); survey wave (2002-2004). Industry (1 digit SIC) and year fixed effects as well as legal ownership status dummies are suppressed to save space. Significance level: * p<0.05; ** p<0.01; *** p<0.001"
Source: BSD - Business Register (2002-2014) and UKIS - UK Innovation Survey (2002-2014).

Table A2. Sample selection correction bias: outcome equations for each dependent variable.

Specification	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable	**Product innovation in-house**		**Product innovation co-creation**		**Product innovation sales (in logs) external**	
Method	Probit	Heckman	Probit	Heckman	Tobit	Heckman
R&D intensity	3.06*** (0.36)	0.81*** (0.05)	0.02 (0.24)	0.02 (0.04)	8.84*** (1.30)	3.02*** (0.40)
Medium	0.01 (0.02)	0.02 (0.02)	0.02 (0.03)	0.02 (0.03)	0.06 (0.16)	0.06 (0.16)
Large	0.08*** (0.03)	0.03** (0.00)	0.04 (0.03)	0.07 (0.03)	1.10*** (0.18)	0.69*** (0.04)
Exploration	0.37*** (0.02)	0.12*** (0.00)	0.20*** (0.02)	0.04** (0.00)	2.67*** (0.17)	0.76*** (0.03)
Hampering factor: cost of innovation	0.07*** (0.02)	0.04*** (0.00)	0.07*** (0.03)	0.04*** (0.00)	1.07*** (0.16)	0.30*** (0.03)
Hampering factor: knowledge on market	-0.37*** (0.03)	-0.02*** (0.00)	-0.36*** (0.01)	-0.01** (0.00)	-1.72** (0.16)	-0.30*** (0.03)
Hampering factor: other	0.04 (0.03)	0.04 (0.03)	0.03 (0.03)	0.03 (0.03)	-0.06 (0.18)	-0.04 (0.18)
Foreign	0.01 (0.02)	-0.01 (0.01)	0.05* (0.02)	0.01** (0.00)	0.23** (0.10)	0.13** (0.04)
Age of firm	-0.05*** (0.01)	-0.01*** (0.00)	-0.04** (0.01)	-0.01** (0.00)	-0.38*** (0.08)	-0.05*** (0.00)
Scientist	0.01*** (0.00)	0.01*** (0.00)	-0.01 (0.01)	-0.01 (0.01)	0.05*** (0.00)	0.02*** (0.00)
Exporter	0.58*** (0.02)	0.12*** (0.01)	0.01 (0.00)	0.01 (0.00)	0.05*** (0.00)	0.02*** (0.01)
Inverse Mill's ratio from selection equation (λ)		0.35 (0.21)		0.24 (0.22)		1.76 (1.25)
Constant	-1.16*** (0.12)	-0.06** (0.03)	-1.79*** (0.15)	-0.01 (0.02)	-10.10*** (0.87)	-0.10 (0.07)
Legal status dummies	Yes	Yes	Yes	Yes	Yes	Yes
Industry, survey wave and the UK region dummies	Yes	Yes	Yes	Yes	Yes	Yes
Wald chi2 (F-stat)	5601.01	5594.34	3222.32	1906.04	256.11	3892.64
Number of observations		22073		22073		21770
Number of observations (selected for Heckman)	19510	(19510)	19510	(19510)	19510	(19510)
Rho		0.81		0.78		0.69

Note: standard errors robust for hereroskedastisity are in parenthesis. Reference groups: small firm (10-49 FTEs); legal ownership (listed company); UK region (North East); survey wave (2002-2004). Industry (1 digit SIC), UK region and year fixed effects were suppressed to save space. Significance level: * p<0.05; ** p<0.01; *** p<0.001".

Variables for selection equation in Heckman: Number of active plant units, in logs, Impediment to innovation - finance availability, regulatory requirements.

Endogenous variables of collaboration are not included in the sample selection test to avoid endogeneity in the model.

Number of observations 19510. Uncensored observations for Tobit estimation (column 5 and 6) (new product sales>0) = 4960.

Source: BSD - Business Register (2002-2014) and UKIS - UK Innovation Survey (2002-2014).

Table A3. Two stage post-estimation analysis: random effect (RE) estimation of model (4) using predicted residuals of product innovation in-house, product innovation external and innovation sales from second stage estimation (model 2).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Dependent variable	**Product innovation in-house residual $y_i - \hat{y}_i$ across four partner regions**				**Product innovation external residual $y_i - \hat{y}_i$ across four partner regions**				**New product sales residual $y_i - \hat{y}_i$ across four partner regions**			
Equation with the dimension of collaboration used to predict $\hat{y}_i$	regional	national	Europe	world	regional	national	Europe	world	regional	national	Europe	world
Enterprise group ρ_1	0.01 (0.02)	0.01 (0.01)	0.01 (0.01)	0.02 (0.02)	0.03 (0.03)	0.03 (0.04)	0.03 (0.02)	0.03 (0.05)	0.05 (0.12)	0.05 (0.11)	0.05 (0.13)	0.04 (0.13)
External relations ρ_2	0.38 (0.21)	0.38 (0.22)	0.36 (0.22)	0.39 (0.22)	0.27 (0.15)	0.26 (0.15)	0.27 (0.17)	0.29 (0.21)	2.69 (1.37)	2.62 (1.26)	2.78* (1.17)	2.79* (1.19)
Control variables												
Legal status controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry, and wave controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	1.35*** (0.36)	1.33*** (0.33)	1.31*** (0.32)	1.27*** (0.26)	1.84*** (0.27)	1.86*** (0.27)	1.89*** (0.37)	1.85*** (0.34)	9.85*** (2.61)	9.80*** (3.01)	9.72*** (2.71)	9.91*** (2.70)
Chi2	40,177	40,320	40,980	41,452	46,013	45,822	46187	45,738	24,392	24,120	24,104	23,945

Note: standard errors robust for hereroskedastisity are in parenthesis. Reference groups: Legal status (listed company); UK region (North East); survey wave (2002-2004). Industry (1 digit SIC), UK region and year fixed effects were suppressed to save space. Significance level: * p<0.05; ** p<0.01; *** p<0.001".

Coefficients ρ_2 (new methods of collaboration) are weakly significant (p<0.10) in model 3 when innovation sales residuals is used as dependent variable. Number of observations 19510.

Source: BSD - Business Register (2002-2014) and UKIS - UK Innovation Survey (2002-2014).

Table A4. Knowledge production function

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Dependent variable	**Product innovation in-house**			**Product innovation co-creation**			**Product innovation sales (in logs) external**		
Method	Probit			Probit			Tobit		
Product innovation co-creation		-0.44*** (0.03)	-0.41*** (0.03)					1.23*** (0.04)	1.24*** (0.05)
Product innovation co-creation X Standardized R&D intensity			-0.20*** (0.03)						0.10 (0.06)
Product innovation co-creation X Standardized Scientists			-0.08*** (0.02)						0.05* (0.02)
Product innovation in-house					-0.48*** (0.03)	-0.44*** (0.03)		2.61*** (0.04)	2.58*** (0.03)
Product innovation in-house X Standardized R&D intensity						-0.16*** (0.03)			0.19 (0.09)
Product innovation in-house X Standardized Scientists						-0.14*** (0.02)			0.20*** (0.03)
Knowledge intense sectors (KIS)	0.07* (0.03)	0.07* (0.02)	0.07* (0.03)	0.04 (0.03)	0.03 (0.03)	0.03 (0.03)	0.11* (0.05)	0.05 (0.04)	0.05 (0.04)
Standardized R&D intensity	0.17*** (0.01)	0.18*** (0.01)	0.22*** (0.02)	0.01 (0.02)	0.02 (0.02)	0.12*** (0.02)	0.19*** (0.02)	0.07*** (0.01)	0.20*** (0.03)
Standardized Scientist	0.13*** (0.01)	0.14*** (0.01)	0.15*** (0.01)	0.01 (0.02)	0.03 (0.01)	0.10*** (0.02)	0.32*** (0.02)	0.18*** (0.01)	0.10*** (0.02)
Medium	0.02 (0.02)	0.02 (0.02)	0.01 (0.02)	0.01 (0.02)	0.01 (0.03)	0.01 (0.03)	0.06 (0.03)	0.05 (0.03)	0.05 (0.03)
Large	0.08*** (0.02)	0.08*** (0.03)	0.08** (0.02)	0.02 (0.03)	0.02 (0.03)	0.01 (0.03)	0.57*** (0.04)	0.52*** (0.04)	0.52*** (0.05)
Exploration	0.37*** (0.02)	0.38*** (0.02)	0.39*** (0.02)	0.20*** (0.02)	0.24*** (0.03)	0.24*** (0.03)	0.61*** (0.03)	0.34*** (0.03)	0.34*** (0.03)
Hampering factor: cost of innovation	0.07*** (0.02)	0.07*** (0.02)	0.07** (0.03)	0.07*** (0.02)	0.07*** (0.02)	0.07** (0.03)	0.23*** (0.03)	0.13*** (0.03)	0.13*** (0.03)
Hampering factor: knowledge on market	-0.37*** (0.03)	-0.42*** (0.03)	-0.42*** (0.03)	-0.37*** (0.03)	-0.45*** (0.03)	-0.44*** (0.03)	-0.48*** (0.04)	-0.13** (0.04)	-0.14** (0.04)
Hampering factor: other	-0.25*** (0.03)	-0.28*** (0.03)	-0.27*** (0.03)	-0.21*** (0.03)	-0.26*** (0.04)	-0.25*** (0.03)	-0.43*** (0.04)	-0.20*** (0.04)	-0.21*** (0.04)
Foreign	0.01 (0.02)	0.01 (0.02)	0.00 (0.01)	0.05 (0.02)	0.06* (0.02)	0.05** (0.01)	0.10** (0.03)	0.07* (0.03)	0.07* (0.03)
Age of firm	-0.05* (0.01)	-0.06* (0.01)	-0.06* (0.01)	-0.04* (0.01)	-0.05** (0.01)	-0.05** (0.01)	-0.07*** (0.02)	-0.03* (0.01)	-0.04** (0.01)
Exporter	0.57*** (0.02)	0.60*** (0.02)	0.60*** (0.02)	0.31*** (0.02)	0.39*** (0.02)	0.38*** (0.02)	1.03*** (0.03)	0.52*** (0.03)	0.52*** (0.02)
Legal status dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry, survey wave and the UK region dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	-1.06*** (0.13)	-1.06*** (0.13)	-1.04*** (0.13)	-1.70*** (0.16)	-1.62*** (0.15)	-1.60*** (0.16)	-11.09*** (1.81)	-11.65*** (1.31)	-11.77*** (1.39)
Sigma (e)							5.39*** (0.05)	4.32*** (0.03)	4.31*** (0.03)
chi2	8028.15	8231.45	8315.55	3614.12	3866.05	4002.04	7925.06	12629.01	12685.52

Note: standard errors robust for hereroskedastisity are in parenthesis. Reference groups: small firm (10-49 FTEs); legal ownership (listed company); UK region (North East); survey wave (2002-2004). Industry (1 digit SIC), UK region and year fixed effects were suppressed to save space. Significance level: * p<0.05; ** p<0.01; *** p<0.001".

Number of observations 19510. Uncensored observations for Tobit estimation (new product sales>0) = 4960.

Source: BSD - Business Register (2002-2014) and UKIS - UK Innovation Survey (2002-2014).