ETLA Working Papers
No. 25
6 August 2014

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Suggested citation: Koski, Heli & Svento, Rauli (6.8.2014). "Knowledge Complementarity of a Firm's Internal and External R&D Capabilities". ETLA Working Papers No 25. http://pub.etla.fi/ETLA-Working-Papers-25.pdf

ETLA ELINKEINOELÄMÄN TUTKIMUSLAITOS
THE RESEARCH INSTITUTE OF THE FINNISH ECONOMY

ISSN-L 2323–2420
ISSN 2323–2420 (print)
ISSN 2323–2439 (online)

Knowledge complementarity of a firm's internal and external R&D capabilities

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Abstract

We use data from over 1500 Finnish companies for the years 2006-2008 and 2008-2010 to explore complementarity of a firm's R&D strategy with its external knowledge acquisition and innovation collaboration strategies. We define *knowledge complementarity* (*tacit knowledge complementarity) of R&D capabilities* to exist when increase in investments in R&D also increases marginal returns from broader external knowledge search (deeper innovation collaboration with external partners). Our estimation results provide support for knowledge complementarity of external R&D. Instead, our data provide no evidence on tacit knowledge complementary of external R&D generally. However, our empirical results concerning the separate types of external R&D suggest that a firm's acquisition of new technology (i.e., advanced machinery, equipment or software) for innovation purposes appears to be tacit knowledge complementary.

Keywords: open innovation, external knowledge search, complementarity

JEL: D83, O3, L2

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INTRODUCTION

The literature focusing on open innovation has addressed the roles of breadth and depth of external knowledge search in firms' innovation performance (see, e.g, Laursen and Salter, 2006; Love et al., 2013). There is convincing empirical evidence on the positive relationship between the breadth and depth of a firm's knowledge search and innovation. The reported empirical study contributes to this stream of literature by addressing a question of knowledge complementarity of R&D capabilities. Our major argument is that the benefits a firm acquires from broader knowledge search and deeper inter-firm innovation collaboration depend fundamentally on the firm's (in-house) R&D strategy and particularly on its acquisition of external R&D capabilities.

Generally, innovation activities are defined to be complementary if an increase in one activity increases marginal returns from the other activity (Milgrom and Roberts, 1990). Complementary R&D capabilities for a firm are typically defined as those augmenting the firm's internal capability base (Lorenzoni and Lipparini, 1999). We take the discussion on complementarity to the open innovation framework by defining *knowledge complementarity of R&D capabilities* to exist when an increase in a firm's investments in R&D increases its marginal returns from broader external knowledge search, and vice versa. Furthermore, we define *tacit knowledge complementarity of R&D capabilities* to exist when an increase in a firm's investment in R&D increases its marginal return from deeper collaboration with external parties, and vice versa. The latter definition emphasizes the importance of tacit knowledge exchange; one of the primary aims of the inter-firm information collaboration is to facilitate the exchange of tacit knowledge.

We explore the roles of the breadth of knowledge search and the depth of inter-firm innovation collaboration conjointly with a firm's internal and external R&D capabilities in the firm's propensity to succeed in producing product innovation. In the empirical analysis, we use data concerning the innovation activities of 1564 Finnish firms combined with other firm-level data (i.e., financial data and data on the characteristics of firms' employees) for the years 2006-2008 and 2008-2010. Our estimation results provide support for knowledge complementarity of external R&D. Instead, our data provide no evidence on tacit knowledge complementary of external R&D generally. However, among the individual types of external R&D, the acquisition of a new technology (i.e., advanced machinery, equipment or software), appears to be tacit knowledge complementary.

OPEN INNOVATION AND EXTERNAL KNOWLEDGE SEARCH

There exists quite an extensive economic and management literature concerning the openness of a firm's innovation strategy; the role of externally acquired knowledge in the generation of innovations has gained substantial attention (see, e.g., Chesbrough, 2003; Laursen and Salter, 2006; Dahlander and Gann, 2010; Zhou and Li, 2012). One of the key issues is a firm's external knowledge search strategy, or how the breadth and depth of knowledge search affect innovation performance (see, e.g., Katila and Ahuja, 2002; Laursen and Salter, 2006). The breadth of external knowledge search refers to the diversity or number of external knowledge domains firm utilizes in its innovation process, while the depth of external knowledge search captures the scope of external knowledge domains that a firm deems important for its innovation process. Previous empirical studies indicate that though knowledge search is costly for a firm, broader search tends to enhance innovation (see, e.g., Leiponen and Helfat, 2010; Love et al., 2013). The exploitation of greater number of external linkages increases a firm's probability to acquire valuable, complementary knowledge for the development of innovation. However, various empirical studies suggest that there are diminishing returns of external search: the relationship between the breadth and depth of knowledge and innovation performance seems to be U-shaped (see, e.g., Laursen and Salter, 2006; Garriga et al., 2013).

The importance of direction of knowledge search for the innovation performance is also addressed in the previous studies. The resource based view of the management literature suggests that a firm chooses collaborative partners on the basis of their potential to provide complementary inputs for the firm to develop their dynamic capabilities (see, e.g., Miotti and Sachwald, 2003; Kale and Sighn, 2007). Science-based partners such as universities are chosen as they provide scientific or technical knowledge, while market-based partners such as customers function as a source of market knowledge. Closely relatedly, the organizational learning literature argues that product innovation is fundamental for the renewal of firm competencies (see, e.g, Dougherty, 1992), and firms learn about technologies and customers via the exploitation of product innovation (Maidique and Zirger, 1985). Danneels (2002) further suggests that second-order competences, or the competence at explorative learning, are crucial for firm renewal and success in innovation. The competence at explorative learning involves searching out and developing new competences; it is defined to be a firm's ability to identify, evaluate, and incorporate new technological and/or customer competences into the firm.[1]

Furthermore, Leiponen and Helfat (2010) provide empirical evidence that also the breadth of a firm's innovation objectives[2] relates positively to the firm's probability to succeed in producing an innovation. In other words, those firms that had more innovation objectives that were considered to be either important or very important to the firm tend to more likely introduce technological product or process innovation. The recent study of Love et al. (2013) further indicates that also learning from open innovation practices matters for the innovation performance supporting the evolutionary economics perspective of innovation as a cumulative, path dependent process (Nelson and Winter, 1982). Those firms that had prior experience of external collaboration were found to produce more innovative output from their contemporary open innovation practices. Concerning the breadth of external knowledge search, a firm's managers may learn to better select partners that provide biggest gains for the firm or the most appropriate complementary information for the firm's innovation process. Managers may further get better at managing external interactions as they learn best-practices for collaboration and the management of inter-firm interactions.[3] This accumulated experience of interacting and collaborating with external parties can further be expanded to the collaboration with a more diverse set of partners.

Only relatively few empirical studies have explicitly addressed the question of the complementarity of a firm's internal R&D and external R&D (see, e.g., Ceggagnoli et al., 2014). Ceccagnoli et al. (2014) empirically explore whether a firm's R&D intensity and its in-licensing investments are substitutes or complements in innovation production. They find that in the global pharmaceutical industry, on average, a firm's internal R&D and in-licensing investments are neither substitutes nor complements. Their split sample estimates, however, suggest that for firms with stronger absorptive capacity, economies of scope and past licensing experience internal and external R&D tend to be complementary.

[1] Relatedly, the study of Garriga et al. (2013) explores the role of "constraints on the application of resources of the firm toward innovation" (such as problems with new technologies and organization, lack of qualified human resources) in firms' external knowledge search strategy. They find that a higher number of constraints on resources toward innovation increase the search breadth, while they decrease the search depth.

[2] Innovation objectives comprise both product objectives such as the improvement of product quality or expand product assortment and process objectives such as reduction of labor costs or use of materials.

[3] See Ihl et al. (2012) for an empirical study concerning the impacts of the interaction of the breadth of external knowledge search and the management and organization of innovation on the innovation performance of a firm.

Relatedly, strategic management literature concerning R&D outsourcing has raised discussion on the importance of the organization and location of R&D activities for the presence of R&D complementarity or substitution (see, e.g., Bertnand and Mol, 2013). A firm may decide to undertake R&D inside of its boundaries or it may either outsource part or all of its R&D activities to the other firm(s) in the same country or to off-shore R&D abroad. The empirical study of Bertnand and Mol (2013) suggests that firms lacking internal R&D capabilities tend to outsource R&D in their home country, while firms with specialized R&D processes and overseas involvement use offshore R&D outsourcing to complement their own R&D. In other words, their study hints that locally outsourced R&D tends to substitute a firm's own R&D, while the acquisition of R&D from abroad tends to complement the firm's in-house R&D activities.

Our study differs from the previous ones as it tackles not only one but various measures of externally acquired R&D (i.e., R&D outsourcing, acquisition of machinery, equipment and software, acquisition of knowledge or intellectual property, and purchase of training of a firm's employees for innovative activities). More importantly, our research not only explores complementarity of a firm' internal and external R&D. It focuses on the potential complementarity of a firm's internal and external R&D capabilities with a firm's knowledge search strategy (or the order of magnitude of a breadth of a firm's knowledge search and the depth of its inter-firm innovation collaboration).

Most previously reported studies exploring the impacts of a firm's knowledge search strategy on the firm's innovation performance have not paid attention to the potential complementarity of a firm's R&D and its external knowledge search in innovation production. Laursen and Salter (2006) explore the interaction of a firm's own R&D and its external knowledge search strategy in innovation production though. Their empirical findings suggest substitution between a firm's internal R&D and openness. To our best knowledge, there are not any prior empirical studies addressing or empirically exploring knowledge complementarity of firms' externally acquired R&D capabilities. Our study contributes to the economic and management literature on open innovation and the organizational learning literature by first empirically exploring the relationship between the firm's internal and external R&D capabilities and its external knowledge search and innovation collaboration. Second, it aims at exploring whether a firm's investments in internal and external R&D are knowledge complementary and/or tacit knowledge complementary in innovation production.

EXTERNAL KNOWLEDGE SEARCH AND INNOVATION PRODUCTION

Complementarity of R&D capabilities and external knowledge search

We formulate a simple model which shows how the optimum volume of openness and a firm's internal and externally acquired R&D capabilities and can be detected analytically. The open innovation practices may involve substantial costs arising, e.g., from time used for gathering and evaluating the reliability of information, writing and maintaining contractual agreements and the organization of meetings (see, e.g., Baldwin and von Hippel 2010). These costs constrain the degree of openness in such a way that there exists an optimal level of openness after which the expected gains start do diminish. We assume that there are different costs related to the breadth of a firm's external knowledge search, to the depth of intra-firm collaboration and to a firm's internal and external R&D. Let the corresponding unit cost be denoted by p_B, p_D , p_R, and p_E.

We distinguish three dimensions of a firm's open innovation or knowledge search practices. First, *the breadth of knowledge search* captures the number of external knowledge domains a firms uses in its innovation process. Second, we measure the role of active inter-firm innovation collaboration: *the depth of inter-firm collaboration* is measured by the count of external partners firm is actively collaborating with and deems important for its innovation process. Third, an important dimension of a firm's open innovation or external knowledge search practices is the *acquisition of external R&D capabilities* such as purchase of external R&D, technology or training for innovation purposes.

Let the breadth of a firm's external knowledge search be given by n_B indicating the number of external knowledge sources the firm uses in its innovation process. Let n_D be the number of external partners with which the firm has active innovation collaboration and let n_R be the order of magnitude of a firm's own R&D and n_E be the order of magnitude of its acquisition of external R&D capabilities. Let α be the probability of an innovation based on the breadth of external knowledge search, β be the probability of an innovation based on the depth of inter-firm collaboration, and Υ and □ be the probabilities of an innovation resulting from a firm's own R&D and from the acquisition of external R&D capabilities, respectively. We endogenize these probabilities by making them functions of the activities they are related to, $\alpha(n_B)$, $\beta(n_D)$, □(n_R) and □(n_E). We assume these functions to be concave so that first derivatives are positive indicating that investments in internal and external R&D and knowledge search are productive, and second derivatives are negative implying diminishing marginal returns for these investments.

A firm generating an innovation can be expected to earn monopoly revenues from the innovation until it is available to others (e.g., after the expiration of a firm's patent on innovation) when these revenues drop to a competitive level. Denote these monopoly revenues by P. These are of course dynamic in the sense that they are related to the time period during which monopoly pricing can be used but since we are not looking at the dynamics we assume these revenues to be exogenous in this respect. Assuming a quadratic cost function the expected profits of innovation can now be stated as

$$\pi = \sigma P - \frac{1}{2}(ap_B n_B^2 + bp_D n_D^2 + cp_R n_R^2 + dp_E n_E^2) \ , \quad (1)$$

where $\sigma = \alpha(n_B)\beta(n_D)\gamma(n_R)\theta(n_E)$ and a, b , c and d are cost function parameter. Maximizing this with respect to n_B, n_D, n_R and n_E gives the first order conditions as

$$n_B^* = \frac{\sigma_B}{a}\frac{P}{p_B} \quad (2)$$

$$n_D^* = \frac{\sigma_D}{b}\frac{P}{p_D} \quad (3)$$

$$n_R^* = \frac{\sigma_R}{c}\frac{P}{p_R} \quad (4)$$

$$n_E^* = \frac{\sigma_E}{d}\frac{P}{p_E} \quad (5)$$

where σ_B, σ_D, σ_R and σ_E refer to the corresponding first derivatives of σ with respect to n_B, n_D, n_R and n_E., and, for instance, $\sigma_B = \alpha'(n_B)\beta(n_D)\gamma(n_R)\theta(n_E)$. These conditions are intuitive and interesting. The effort in both a firm's own R&D and external knowledge search through all the instruments should be increased when the monopoly revenues increase and diminished as the (unit) costs of the effort in question increase. The optimal levels of knowledge search are reached while the marginal probabilities still are positive, and the search should not be carried any further when the marginal probabilities turn to zero. And most interestingly from our point of view, when more effort is put to any of the instruments, the others should also be increased through their innovation probabilities effects but only in line with their corresponding marginal innovation probabilities.

We are especially interested in the relationship between external R&D efforts and breadth of other external knowledge search and depth of inter-firm collaboration since this has not been studied before. We can have a closer look at this by solving P from (5) and inserting this into (2) and (3) yielding

$$n_B^* = \frac{\sigma_B}{a}\frac{d}{\sigma_E}\frac{p_E}{p_B}n_E^* \qquad (6)$$

$$n_D^* = \frac{\sigma_D}{b}\frac{d}{\sigma_E}\frac{p_E}{p_D}n_E^*. \qquad (7)$$

Equations (6) and (7) indicate that the higher the costs of external R&D capabilities the more effort should be put to the breadth of knowledge search and the depth of inter-firm collaboration. This means that when, for instance, the outsourcing of R&D or purchasing or licensing of patents is relatively expensive, a firm aims at searching external knowledge required for developing an innovation by the firm itself rather than invests in external R&D capabilities. On the other hand, when a firm invests more in external R&D capabilities, n_E, also its investments in the breadth of external knowledge search and the depth of inter-firm collaboration tend to increase. Equivalent calculations with similar conclusions could be undertaken with respect to internal R&D by solving P from (4) and inserting this into (2) and (3).

The net effect of a marginal increase in a firm's investments in external R&D (or internal R&D) on the other innovation inputs is not obvious, however. R&D is complementary with an innovation input, if an increase in investments in R&D increases marginal profits or returns from the innovation input. The signs of the cross-partial derivatives of equation (1) with respect to n_B and n_E (n_D and n_E) thus indicate whether the breadth of knowledge search and external R&D (the depth of inter-firm innovation collaboration and external R&D) are complementary in innovation production. As the result of the cross-partial derivation using equations (6) and (7) comprises not only positive but also negative terms (i.e., $\sigma_{EE} = \alpha(n_B)\beta(n_D)\gamma(n_R)\theta''(n_E) < 0$) of which order of magnitude is unknown to us, the question whether a firm's external R&D complements the breadth of knowledge search and the depth of inter-firm collaboration in innovation production need to be determined empirically. The model provides similar conclusions on knowledge complementarity of a firm's internal R&D:

Innovation production function

The innovation production function of firm i can be written as follows: $I_i(n_{Bi}, n_{Di}, n_{Ri}, n_{Di,} C_i)$, where C refers to a vector of firm specific factors such as the quality of human capital affecting a firm's propensity to succeed in producing innovation. We assume that the first derivatives of $n_{Bi}, n_{Di}, n_{Ri},\ and\ n_{Di}$ are positive indicating that investments in all four innovation inputs are productive. The derivatives of these factors are assumed to be negative reflecting the prior findings of the diminishing returns of investments in (open) innovation practices. As the signs of the cross-partial derivatives of innovation inputs are not known and are left to be determined empirically, we use conceptual analysis for formulating hypotheses on the complementarity of a firm's internal and external R&D with the breadth of knowledge search and the depth of external innovation collaboration.

We are primarily interested in how the interaction of a firm's externally acquired knowledge capabilities and its knowledge search strategy (i.e., the breadth of external knowledge search and the depth of inter-firm collaboration) affect the firm's propensity to succeed in producing innovation. Thus, the more a firm invests in external R&D capabilities the more benefits accrue to it in the generation of innovation from a broader external knowledge search due to a greater absorptive capacity and ability utilize external knowledge for innovation. It seems thus likely that firms investing more heavily in open innovation practices by both acquiring more external R&D capabilities and using more broadly external knowledge sources in their innovation processes are more likely to succeed in generating an innovation. We thus propose the following hypothesis:

Hypothesis 1: A firm's investments in external R&D capabilities are knowledge complementary in the production of innovation, or the interaction of external R&D and the breadth of external knowledge search positively relates to the firm's propensity produce innovation.

Furthermore, as the external innovation collaboration partners provide complementary inputs for a firm's in-house R&D (Miotti and Sachwald, 2003), the greater number of innovation partners is likely to enhance the firm's innovation capability. Thus, it seems credible that the firms with a greater variety of external innovation partners are also better able to utilize broader external knowledge search in their innovation activities. Therefore, firms with a greater breadth of external knowledge search and also a greater number of external innovation collaborators are likely to reap more benefits from their investments in external R&D. This further suggests the following hypothesis:

Hypothesis 2: The combined effect of external R&D and the interaction of breadth of external knowledge search and the depth of inter-firm innovation collaboration is positive in innovation production.

Instead, it is not clear whether the acquisition of external R&D complements deep collaboration with a greater number of external partners. On the one hand, a firm's investments in external R&D capabilities (such as investments in new communication technologies or staff training) tend to improve its innovation capacity, and thus external R&D should complement deeper inter-firm innovation collaboration. Furthermore, the acquisition of external intellectual property (e.g., purchase of patents or other intellectual property) may prove to be beneficial for a firm as the firm may attract more or higher quality innovation partners and it may further enable more lucrative cross-licensing opportunities and more successful joint innovation projects with external parties. On the other hand, an increase in a firm's investments in external R&D, for instance, when a firm's new innovation partner has overlapping R&D capabilities may not increase marginal returns from deeper innovation collaboration. This may happen, for instance, due to asymmetric information between the innovation partners as firms tend to avoid disclosing all proprietary information concerning their strategic assets or technology for their partners (see, e.g. Mehlman et al. 2009). Thus, the impact of the interaction of a firm's greater investments in external R&D capabilities and deeper inter-firm collaboration on the firm's probability produce innovation is thus not unambiguous and it is left to be empirically determined.

Hypothesis 3: It is not clear whether a firm's investments in external R&D capabilities are tacit knowledge complementary, or the interaction of external R&D and the depth of a firm's innovation collaboration with external parties may have zero or positive relationship with the firm's propensity to produce innovation.

Also, we are interested in whether and how a firm' in-house R&D relates to the breath of external knowledge search and the depth of innovation collaboration with external parties in innovation production. Without a firm's ability to share and utilize information that is acquired outside the firm boundaries, external knowledge search is unlikely to contribute to the firm's innovation performance. A firm's R&D intensity is the fundamental determinant of its absorptive capacity, or its ability to utilize external knowledge (Cohen and Levinthal, 1990). Thus, it seems credible that the higher the R&D intensity of a firm is, the more it can benefit from the external information sources in the generation of new products and services. Also, it seems that a greater number of external parties a firm is actively collaborating with in innovation production provides also (tacit) knowledge that a firm may utilize in its in-house innovation activities. Consequently, we propose the following hypotheses:

Hypothesis 4: A firm's R&D intensity is knowledge complementary in the production of innovation, or the interaction of R&D intensity and the breadth of external knowledge search positively relates to the firm's propensity produce innovation.

Hypothesis 5: A firm's R&D intensity is tacit knowledge complementary in the production of innovation, or the interaction of R&D intensity and the depth of inter-firm innovation collaboration positively relates to the firm's propensity produce innovation.

We are also interested in the complementarity of a firm's internal and external R&D. One purpose of the acquisition of a firm's external R&D capabilities is to seek expertise not available internally by outsourcing a firm's R&D partly or totally (see, e.g., Howells et al., 2008), i.e. substituting intra-house R&D. Often though, firms invest in external R&D capabilites to augment a firm's internal R&D capability base by complementary capabilities (see, e.g., Lorenzoni and Lipparini, 1999). Complementary capabilities enhancing the firm's own innovation activities may comprise, for instance, the purchase of new, advanced machinery or investments in ICT, purchase or licensing of patents or other inventions, or purchase of training for the firm's personnel. The acquisition of complementary R&D capabilities strengthens a firm's internal innovation capability and therefore also the firm's ability to exploit external information. As the previous empirical literature does not provide conclusive evidence supporting either substitution or complementarity between internal and external R&D, the question is left to be determined empirically.

DATA AND VARIABLES

Our estimations comprise data from 1564 Finnish companies of which about 38 percent functioned in the service sector. Our data comprise information gathered by Statistics Finland via the CIS (Community Innovation Survey) questionnaires concerning firms' innovation activities for the years 2006-2008 and 2008-2010. The CIS data are further combined with other databases of Statistics Finland concerning firm-level financial information and data on the characteristics of firms' employees. Annex 1 provides details of the variables used in the estimations.

The dependent variable is the dummy variable INNOVATION that gets value 1 if a firm introduced new or significantly improved goods or services during the sample time period. The explanatory variable measuring the breadth of a firm's external knowledge search (i.e., the variable BREADTH) is calculated as the count of external sources of knowledge used for a firm's innovation activities. The Finnish CIS questionnaire covers the following seven external sources of knowledge for a firm: i) suppliers of equipment, materials, components or software, ii) clients or customers; iii) competitors or other enterprises in a firm's sector; iv) consultants, commercial labs, or private R&D institutes, v) universities or other higher education institutions, vi) government or public research institute, and vii) other sources (i.e., conferences, trade fairs and exhibitions, scientific journals and trade/technical publications, and professional and industrial associations).

Laursen and Salter (2006) define the depth of knowledge search as "the extent to which firms draw deeply from the different external sources or search channels". Their study - as well as the subsequent empirical studies typically - uses the count of knowledge sources that a firm has reported to have a high degree of importance for its innovation activities as a measure of the search depth. Here, we define that deep information exchange for innovation purposes requires innovation collaboration between the partners since without active or formal innovation collaboration firms tend not to enclose proprietary or tacit knowledge for other companies (see Mehlman et al, 2009). When the firms have joint R&D activities, both the breadth and depth of intellectual property disclosures increase dramatically.

We measure the depth of a firm's inter-firm collaboration (the variable DEPTH) by the number of partners that had active innovation cooperation[4] with a firm *and* that had a high degree of importance for the firm's innovation activities. The Finnish CIS questionnaire identifies seven potential innovation collaboration partners: i) other firms in the same consortium with a firm, ii) suppliers of equipment, materials, components or software, iii) clients or customers; iv) competitors or other enterprises in a firm's sector, v) consultants,

[4] In the CIS questionnaire innovation co-operation was defined to mean "active participation with other enterprises or non-commercial institutions on innovation activities. Exclude pure contracting out of work with no active co-operation."

commercial labs, or private R&D institutes, vi) universities or other higher education institutions, and vi) government or public research institutes

The (log) R&D intensity (the variable RD_IN) is used as a measure of a firm's internal R&D capability: it is calculated by dividing the firm's R&D expenditures by its turnover. We use the firm's R&D intensity in 2006 and 2008, respectively, to take into account the lagged effect of R&D on innovation production during the sample time periods 2006-2008 and 2008-2010.

The order of magnitude of a firm's investments in external R&D capabilities (the variable RD_EX) is measured by the count variable that is the sum of the following four dummy variables: i) *external R&D* (the variable RD_OUTSOURCE), dummy variable that gets value 1 if a firm has during the past three years purchased R&D activities from other enterprises (including other enterprises or subsidiaries within its group) or public or private research organisations, ii) *Acquisition of machinery, equipment and software* (the variable TECH_PURCHASE), dummy variable that gets value 1 if a firm has during the past three years acquired advanced machinery, equipment (including computer hardware) or software to produce new or significantly improved products and processes, iii) *Acquisition of external knowledge* (the variable KNOWLEDGE_PURCHASE), dummy variable that gets value 1 if a firm has during the past three years purchased or licensed patents and non-patented inventions, know-how, and other types of knowledge from other enterprises or organisations for the development of new or significantly improved products and processes and iv) *Training for innovative activities* (the variable RD_TRAINING), dummy variable that gets value 1 there has during the past three years been internal or external training for the firm's personnel specifically for the development and/or introduction of new or significantly improved products and processes.

We also control for firm size by the dummy variables for small (i.e, firms with 10-49 employees, medium-sized (i.e,. firms with 50-250 employees) and large (i.e., firms with over 250 employees) firms. The AGE variable controls for (log) a firm's age, or the years elapsed since the establishment of the firm. The role of the quality of human capital has deserved less attention in the prior empirical studies though it seems obvious that the qualities of a firm's employees are likely to affect the firm's innovation performance. We assume that both the education level and age structure of a firm's employees may influence innovation. The dummy variable EDUC_COLLEGE and EDUC_ACADEMIC control the shares of college and academically educated persons, respectively, of the total number of the firm's employees. The age structure of a firm's employees is captured by the dummy variables for the shares of employees in different age groups (i.e. the groups of 16-24, 25-34, 35-44, 45-54 and 55-70 years old employees).

We further use dummy variables to control for 21 industrial sectors, 6 geographical areas and the two observation periods.

EMPIRICAL ANALYSIS

We first estimated the pooled Poisson models with cluster-robust standard errors for the sample time periods 2006-2008 and 2008-2010 explaining the BREADTH and DEPTH variables. The idea here was to explore the relationship between a firm's own R&D and external R&D capabilities and the breadth of its external knowledge search and depth of inter-firm innovation collaboration. The estimation results show that there is a positive and statistically significant relationship between a firm's investments in external R&D capabilities and both the depth and breadth variables (see Table 1). In other words, firms acquiring more external R&D capabilities tend to explore external knowledge sources broader and have deeper inter-firm innovation collaboration than other firms. This further suggests that the benefits of external knowledge are greater and/or the costs of external knowledge search are relatively lower for firms investing more in external innovation capabilities generally.

Instead, a firm's higher R&D intensity relates statistically significantly only to the higher depth of inter-firm innovation collaboration but not to the breadth of external knowledge search. Also, the quality of a firm's human capital matters for the firm's open innovation strategy: the share of employees with university degree is clearly positively related to both DEPTH and BREADTH variables, while the estimated coefficient of the share of employees with upper secondary level education has a positive and statistically significant coefficient only in the equation explaining search breadth. In other words, firms with relatively more educated employees invest more in open innovation practices, or they tend to employ broader knowledge search and deeper innovation collaboration with external parties. Firm's age relates negatively and statistically significantly to the DEPTH variable indicating that older firms tend to have fewer (important) external innovation collaboration partners.

Table 1. The estimation results of the pooled Poisson model for the breadth of knowledge search and the depth of inter-firm collaboration, years 2006-2008 and 2008-2010

	Dependent variable	
Variable	**BREADTH**	**DEPTH**
RD_IN	0.003 (0.005)	0.078*** (0.026)
RD_EX	0.087*** (0.008)	0.395*** (0.043)
SMALL	-0.050 (0.05)	-0.004 (0.319)
MEDIUM	0.021 (0.048)	0.017 (0.329)
LARGE	0.084* (0.050)	0.149 (0.351)
AGE	-0.002 (0.008)	-0.090** (0.045)
AGE_16-24	-0.084 (0.134)	-0.960 (0.786))
AGE_35-44	-0.029 (0.093)	-0.891* (0.516)
AGE_45-54	-0.058 (0.094)	-0.637 (0.541)
AGE_55-70	-0.067 (0.094)	-0.319 (0.597)
EDUC_COLLEGE	0.191** (0.089)	0.620 (0.533)
EDUC_ACADEMIC	0.272*** (0.086)	2.335*** (0.511)
NR_UNITS	0.009 (0.008)	0.160** (0.069)
YEARS_2006-2008	0.050*** (0.013)	0.033*** (0.079)
Constant	1.493*** (0.136)	-2.061 (0.928)
+ dummies for 21 industrial sectors and 6 geographical areas		
Observations	1851	1851
Log pseudo likelihood	-3808.61	-1437.60

The robust standard errors are reported in the parentheses. Significance levels are reported on superscripts, where *** denotes significance level of 1%, ** significance level of 5% and * significance level of 10%.

Table 2. The estimation results of the pooled Probit model for product innovation, years 2006-2008 and 2008-2010

Variable	**Dependent variable: PRO**		
	Model I	**Model II**	**Model III**
BREADTH	0.053*** (0.021)	0.071 (0.122)	0.057** (0.021)
DEPTH	0.165*** (0.053)	-0.152 (0.254)	0.002 (0.191)
RD_IN	0.084*** (0.032)	-0.057 (0.103)	-0.029 (0.055)
BREADTH*RD_IN		0.009 (0.019)	
DEPTH*RD_IN		-0.018 (0.035)	
BREADTH*DEPTH *RD_IN			0.002 (0.055)
RD_EX	0.107*** (0.030)	0.195 (0.178)	0.3889*** (0.136)
BREADTH*RD_EX		0.030** (0.015)	
DEPTH*RD_EX		0.072 (0.049)	
BREADTH*DEPTH *RD_EX			0.014** (0.007)
RD_IN*RD_EX		0.044** (0.022)	0.049** (0.021)
SMALL	0.076 (0.245)	0.077 (0.245)	0.093 (0.244)
MEDIUM	0.137 (0.250)	0.131 (0.250)	0.152 (0.249)
LARGE	0.291 (0.266)	0.241 (0.267)	0.275 (0.265)
AGE	0.023 (0.040)	0.024 (0.040)	0.024 (0.040)
AGE_16-24	0.168 (0.549)	0.168 (0.549)	0.175 (0.548)
AGE_35-44	1.063*** (0.405)	1.067*** (0.403)	1.054*** (0.404)
AGE_45-54	0.086 (0.376)	0.164 (0.374)	0.128 (0.376)
AGE_55-70	-0.251 (0.415)	-0.326 (0.410)	-0.289 (0.413)

EDUC_COLLEGE	-0.345 (0.367)	-0.390 (0.369)	-0.361 (0.389)
EDUC_ACADEMIC	0.106 (0.431)	0.074 (0.432)	0.113 (0.433)
YEARS_2006-2008	-0.165** (0.069)	-0.167** (0.070)	-0.164** (0.070)
Constant	0.631 (0.714)	0.036 (0.966)	-0.052 (0.770)
+ dummies for 21 industrial sectors and 6 geographical areas			
Observations	1849	1849	1849
Dependent variable correctly classified	74.96 %	74.69%	74.80%
Log pseudo likelihood	-936.107	-928.72	-930.65

The robust standard errors are reported in the parentheses. Significance levels are reported on superscripts, where *** denotes significance level of 1%, ** significance level of 5% and * significance level of 10%.

We then estimated a benchmark model for the firm's propensity to succeed in producing product innovation (i.e., new good or service) (see Table 2, Model I).[5]. The estimation results of this pooled probit model with cluster-robust standard errors confirm the results of the previously reported studies. The breadth of knowledge search is positively and statistically significantly related to the probability of a firm succeeding in innovation creation. Also, the depth of inter-firm collaboration contributes statistically significantly to the firm's propensity to produce innovation. Likewise, the estimated coefficients of RD_IN and RD_EX are positive and statistically significant reflecting the importance of both the firm's internal and externally acquired R&D capabilities in the generation of new products and services. The age structure of a firm seem to also matter: the firms with a higher share of 35-44 years old employees more likely succeed in producing innovation than others.

[5] We also estimated the basic model for product innovation with endogenous BREADTH and DEPTH variables. The Wald exogeneity test, however, didn't reject the null hypothesis of exogeneity. Therefore, and as the interactions of BREADTH and DEPTH variables with a firm's R&D capability variables are of interest, we estimated the models for product innovation assuming exogenous knowledge search breadth and depth. This is also consistent with the previously reported empirical studies concerning the breadth and depth of knowledge search and innovation performance (see, e.g., Love et al., 2013).

Model II (Table 2) comprises also the interaction variables of BREADTH and DEPTH with the firm's R&D intensity and its acquisition of external R&D capabilities. The data provides support for Hypothesis 1 as the variable BREADTH*RD_EX appears positive and statistically significant in explaining the firm's propensity to succeed in product innovation production. In other words, the broader external knowledge search combined with greater investments in external R&D capabilities increases the probability of a successful creation of product innovation. Instead, the data provide no evidence on the joint contribution of the depth of innovation collaboration and external R&D in innovation production. Thus, our data suggest that external R&D is knowledge complementary but not tacit knowledge complementary in innovation production.

We find no support for Hypotheses 4 and 5, i.e., complementarity of a firm's own R&D with the breadth of external knowledge or the depth of inter-firm innovation collaboration in innovation production. Thus, the data do not provide any evidence on the (tacit) knowledge complementarity of a firm's own R&D. However, the estimated coefficient of the variable RD_IN*RD_EX is positive and statistically significant reflecting complementarity of a firm's internal R&D capabilities and its externally acquired R&D capabilities. Model III (Table 2) replicates the estimation results of Model II using, instead of separate interactions for BREADTH and DEPTH variables, the joint interaction of BREADTH; DEPTH and R&D variables. The estimated coefficient of the variable BREADTH*DEPTH*RD_EX is positive and statistically significant supporting Hypothesis 2, and further suggesting that the firms that rely more heavily on the variety of open innovation practices tend to succeed better in innovation generation.

Model IV (Table 3) focuses on the importance of different types of external R&D capabilities for a firm's innovation performance. It comprises individual dummies for the different types of external R&D capabilities a firm has acquired (but not any interaction variables among the variables capturing a firm's innovation practices). In this model, the variables BREADTH, DEPTH and RD_IN are all positive and statistically significant. It seems that among the different types of externally acquired R&D types, particularly the outsourcing of R&D and the acquisition of external knowledge such as purchasing or licensing of patents contribute positively to a firm's propensity to produce product innovation.

Table 3. The estimation results of the pooled Probit model for product innovation, 2006-2008 and 2008-2010

Variable	**Dependent variable: PROD_INNO** **Model IV**	 **Model V……………**	 **Model VI**
BREADTH	0.051*** (0.021)	0.199* (0.120)	0.055*** (0.021)
DEPTH	0.154*** (0.053)	-0.172 (0.263)	-0.007 (0.195)
RD_IN	0.078** (0.033)	-0.113 (0.105)	0.061* (0.036)
BREADTH*RD_IN		0.032* (0.017)	
DEPTH*RD_IN		0.015 (0.034)	
BREADTH*DEPTH*RD_IN			0.009* (0.005)
RD_OUTSOURCE	0.231*** (0.080)	0.517* (0.277)	0.242*** (0.088)
TECH_PURCHASE	-0.118 (0.089)	-1.041*** (0.240)	-0.315*** (0.095)
KNOWLEDGE_PURCHASE	0.191** (0.078)	0.203 (0.302)	0.233*** (0.088)
RD_TRAINING	0.081 (0.075)	0.026 (0.273)	0.090 (0.084)
BREADTH*RD_OUTSOURCE		-0.054 (0.048)	
DEPTH*RD_OUTSOURCE		0.059 (0.132)	
BREADTH*DEPTH *RD_OUTSOURCE			0.002 (0.021)
BREADTH*TECH_PURCHASE		0.144*** (0.043)	
DEPTH*TECH_PURCHASE		0.597*** (0.136)	
BREADTH*DEPTH *TECH_PURCHASE			0.114*** (0.022)
BREADTH*KNOWLEDGE_PURCHASE		0.006 (0.051)	
DEPTH*KNOWLEDGE_PURCHASE		-0.144 (0.124)	

BREADTH*DEPTH *KNOWLEDGE_PURCHASE			-0.007 (0.018)
BREADTH*RD_TRAINING		0.008 (0.047)	
DEPTH*RD_TRAINING		-0.010 (0.114)	
BREADTH*DEPTH*RD_TRAINING			-0.006 (0.018)
SMALL	0.053 (0.244)	-0.003 (0.248)	-0.007 (0.250)
MEDIUM	0.103 (0.248)	0.036 (0.253)	0.039 (0.255)
LARGE	0.264 (0.264)	0.136 (0.270)	0.170 (0.271)
AGE	0.033 (0.040)	0.038 (0.040)	0.031 (0.040)
AGE_16-24	0.159 (0.547)	0.341 (0.552)	0.351 (0.549)
AGE_35-44	1.087*** (0.403)	1.161*** (0.408)	1.110*** (0.404)
AGE_45-54	0.027 (0.377)	0.182 (0.380)	0.107 (0.380)
AGE_55-70	-0.227 (0.413)	-0.164 (0.415)	-0.139 (0.416)
EDUC_COLLEGE	-0.324 (0.370)	-0.374 (0.379)	-0.372 (0.374)
EDUC_ACADEMIC	0.030 (0.434)	0.061 (0.435)	0.059 (0.435)
YEARS_2006-2008	-0.151** (0.070)	-0.162** (0.071)	-0.161** (0.071)
Constant	0.614 (0.719)	-0.182 (0.999)	0.654 (0.744)
Observations	1849	1849	1849
Dependent variable correctly classified	75.34 %	75.66%	75.18%
Log pseudo likelihood	-930.54	-909.15	-915.68

The robust standard errors are reported in the parentheses. Significance levels are reported on superscripts, where *** denotes significance level of 1%, ** significance level of 5% and * significance level of 10%.

When the interaction variables are added to the model (see Table 2, Models V-VI), the variable DEPTH does not explain statistically significantly a firm's propensity to generate a product innovation. The acquisition of machinery, equipment and software (the variable TECH_PURCHASE) is negatively related to the firm's propensity to generate innovation. However, the variables DEPTH*TECH_PURCHASE and BREADTH*TECH_PURHASE in Model V and the variable BREADTH*DEPTH_TECH_PURCHASE relate positively and statistically significantly to the probability of a firm to produce product innovation. These results suggest that mere investments in new technology may not significantly facilitate innovation. New technology as such may require learning that hinders the innovation process, at least temporarily. Instead, when a firm invests not only in new technology, particularly in ICT, but also in external knowledge search and/or inter-firm innovation collaboration, it can accrue notable benefits in terms of innovation success.

Furthermore, the interaction of BREADTH and DEPTH variables with individual dummy variables for different types of external R&D shed light on the tacit knowledge complementarity of external R&D. It seems that though we don't find a statistically significant relationship between the interaction of a firm's external R&D investments and its depth of external innovation collaboration and innovation generation generally, certain types of external R&D (i.e., a firm's investments in advanced machinery, equipment or software) are tacit knowledge complementary.

Interestingly, our estimation results suggest that the quality of human capital, particularly a firm's age structure, affects the firm's propensity to produce innovation. The variable AGE_35-44 is positive and statistically significant in all of the estimated equations indicating that the firms that have a relatively high share of 35-44 years old employees tend to be more innovative than others. The variables capturing the educational level of a firm's employees are not, however, statistically significant in any of the estimated equations. One potential reason is the positive relationship between academic education and openness of innovation practices (see the estimation results of Table 1).

EXTENSION: INNOVATION PRODUCED IN COLLABORATION VS. ALONE

We were further interested in whether the production of product innovations produced by the firm alone and those product innovations produced in collaboration with external parties differ from the average product innovation production function[6]. We therefore further estimated models exploring whether the determinants, and particularly the importance of the breadth of external knowledge search, depth of inter-firm innovation collaboration and external R&D differ between the different types of innovation (i.e., between those developed in collaboration and those developed solely inside the firm boundaries).

We replicated the estimations of Model 1 of Table 2 using the dummy variable that gets value 1 if a firm has developed innovation solely by itself, without external collaboration, as the dependent variable (see Annex 2 for the estimation results). The estimations were undertaken given that a firm had reported to have innovation collaboration with external parties, i.e. the sample was restricted to the firms with innovation collaboration. The estimation results of this model are similar with respect to the DEPTH variable to those obtained from the basic model. However, the estimated coefficient of the variable BREADTH is not statistically significant. Also, externally acquired R&D capabilities play an important role in the successful collaborative development of innovation. Instead, neither a firm's own R&D nor the age structure of its employees explains statistically significantly the generation of innovation developed in collaboration. It seems that when a firm develops innovation in collaboration with external parties the firm's internal innovation capabilities and the breadth of its knowledge search are of lesser important than otherwise.

We then replicated the estimations of Model 1 of Table 2 for the sample of firms that had reported that they had no innovation collaboration with external parties during the sample years (see Annex 2 for the estimation results). The idea here was to shed light on the factors affecting a firm's propensity to develop product innovation without external collaboration. For natural reason, the variable DEPTH measuring the importance of innovation collaboration for a firm was not included to the equations explaining the probability of occurrence of innovation developed by a firm alone. The estimation results of the model predicting the probability of occurrence of innovation that a firm has developed completely alone suggest that the sole innovator firms also benefit from the broader external knowledge search in innovation production. It further seems that the sole innovator firms that have succeeded in developing a new product or service do not deviate statistically significantly

[6] Over half (18 percent) of the sample firms reported that they had generated product innovation solely by themselves (in collaboration with external parties) during the years 2006-2008, while only about quarter (44 percent) of the firms told that they had produced innovation alone (in collaboration with external parties) during the years 2008-2010. These descriptive findings suggest that the trend has been towards more open and collaborative innovation practices.

from the other firms (i.e., non-innovators) that have chosen a non-cooperative R&D strategy with respect to their orders of magnitudes of internal and external R&D investments. The age structure of the firm's employees matters though: the firms with a relatively higher share of employees between 35 and 44 years old tend to be more successful also in the generation of innovation developed without external collaboration.

CONCLUSIONS

The reported research uses data from over 1500 Finnish companies for the years 2006-2008 and 2008-2010 to explore complementarity of a firm's R&D strategy with its external knowledge acquisition and innovation collaboration strategies. Our empirical findings suggest that firms investing for a greater variety of external R&D capabilities tend to also use external knowledge sources more broadly and have deeper inter-firm innovation collaboration than other firms. We further find that the firms with a higher share of employees with university degree relates positively to the broader external knowledge search and deeper innovation collaboration with external partners. The quality of a firm's human capital thus, indeed, is connected with the openness of the firm's innovation strategy.

Furthermore, our data provide evidence on the knowledge complementarity of external R&D in innovation production: greater investments in external R&D capabilities combined with a broader external knowledge search increase a firm's propensity to succeed in generating product innovation. This finding provides support to our argument that the successful implementation of external knowledge search strategy is tightly related to the order of magnitude of a firm's investments in external R&D. Our data further indicate that among the individual types of external R&D, particularly the acquisition of new technology (i.e., advanced machinery, equipment or software) is knowledge complementary. Furthermore, though our data provide no evidence on tacit knowledge complementary of external R&D generally, our empirical findings suggest that a firm's acquisition of new technology appears to be also tacit knowledge complementary.

The results of our empirical analysis thus strongly suggest that a firm's investments in up-to-date technology are fundamental for the successful exploitation of open innovation strategies. It would seem credible that knowledge complementary acquisition of external R&D involves investments in ICT as such investments are likely to facilitate both external knowledge search and inter-firm collaboration. More detailed information on the types of technologies the firms have invested in would be required to confirm this conclusion though.

Another question that would deserve a more detailed analysis concerns the qualities of the firms' employees in the implementation of open innovation practices and further in the successful innovation activities. This is a topic that has deserved a very little attention in the prior empirical studies on the determinants of innovation generally. Our empirical findings suggest that certain age groups of employees (i.e., those between 35 to 44 years old) tend to be more productive in the generation of new products and services than others. We were, however, able to control only for the education and age structure of the sample firms' employees but not certain other potentially important factors such as work experience. A more thorough analysis concerning the characteristics of the employees and their role in the successful open innovation activities in different contexts (e.g., in different industries, in the generation of different types of innovation) would be welcome.

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Annex 1. Description of variables

Description of variable	**Variable name**	**Mean (S.D.)**
Dependent variable:		
Dummy variable that gets value 1 if a firm has during the years 2006-2008 (2008-2010) introduced a new good or service.	PROD_INNO	0.74 (0.44)
Explanatory variables (for the two sample time periods, years 2006-2008 and 2008-2010):		
Breadth of knowledge search; number of external knowledge sources firm has used in its innovation activities: i) suppliers of equipment, materials, components or software, ii) clients or customers; iii) competitors or other enterprises in a firm's sector; iv) consultants, commercial labs, or private R&D institutes, v) universities or other higher education institutions, vi) government or public research institute, and vii) other sources (i.e., conferences, trade fairs and exhibitions, scientific journals and trade/technical publications, and professional and industrial associations).	BREADTH	5.65 (1.74)
Depth of inter-firm innovation collaboration: count of innovation partners (partners are categorized as i)-vi) for BREADTH) that had high degree of importance for firm's innovation activities.	DEPTH	
Firm's R&D intensity: R&D expenses/turnover in 2006 (2008)	RD_IN	0.01 (0.05)
Firm's investments in external R&D capabilities are measured by the following dummy variables that get value 1 if a firm has during the sample years:		
i) purchased R&D activities from other enterprises or public or private research organisations,	RD_OUTSOURCE	0.63 (0.48)
ii) acquired advanced machinery, equipment (including computer hardware) or software to produce new or significantly improved products and processes	TECH_PURCHASE	0.75 (0.43)
iii) purchased or licensed of patents and non-patented inventions, know-how, and other types of knowledge from other enterprises or organisations for the development of new or significantly improved products and processes	KNOWLEDGE_PURCHASE	0.49 (0.50)
iv) organized internal or external training for its personnel specifically for the development and/or introduction of new or significantly improved products and processes.	RD_TRAINING	0.46 (0.50)
The order of magnitude of a firm's investments in external R&D capabilities; sum of the above four dummy variables.	RD_EX	2.34 (1.30)
Share of a firm's 16-24 years old employees.	AGE 16-24	0.08 (0.08)
Share of a firm's 25-34 years old employees.	AGE_25-34	0.27 (0.14)
Share of a firm's 35-44 years old employees.	AGE 35-44	0.26 (0.10)
Share of a firm's 45-54 years old employees.	AGE 45-54	0.24 (0.11)
Share of a firm's 54-70 years old employees.	AGE 55-70	0.14 (0.10)
Share of a firm's employees with upper secondary level education.	EDUC_COLLEGE	0.73 (0.13)
Share of a firm's employees with university degree.	EDUC_ACADEMIC	0.11 (0.14)
Dummy variable that gets value 1 if a firm has 10-49 employees, and 0 otherwise.	SMALL	0.45 (0.50)
Dummy variable that gets value 1 if a firm has 50-249 employees, and 0 otherwise.	MEDIUM	0.33 (0.47)
Dummy variable that gets value 1 if a firm has at least 250 employees, and 0 otherwise.	LARGE	0.19 (0.40)
Firm's age.	AGE	21.24 (19.46)
+ 21 industry dummies + locational dummies for 6 geographical areas		

Annex 2. The estimation results of the pooled Probit model for a) innovation developed in collaboration with external parties and b) innovation developed alone by the firm

Variable	**a) innovation developed in collaboration**	**b) innovation developed alone**
BREADTH	0.050 (0.043)	0.054** (0.024)
DEPTH	0.228*** (0.051)	
RD_IN	0.001 (0.031)	0.074 (0.048)
RD_EX	0.139*** (0.042)	0.046 (0.038)
SMALL	-0.061 (0.345)	-0.043 (0.286)
MEDIUM	-0.040 (0.354)	-0.036 (0.300)
LARGE	-0.047 (0.369)	-0.377 (0.354)
AGE	-0.013 (0.052)	-0.038 (0.055)
AGE_16-24	-0.038 (0.979)	0.634 (0.660)
AGE_35-44	0.660 (0.625)	1.148*** (0.483)
AGE_45-54	0.097 (0.580)	0.251 (0.468)
AGE_55-70	-0.717 (0.636)	0.337 (0.519)
EDUC_COLLEGE	-0.856 (0.574)	-0.279 (0.456)
EDUC_ACADEMIC	-0.371 (0.574)	0.445 (0.571)
YEARS_2006-2008	-0.953** (0.098)	-0.315*** (0.096)
Constant	0.302 (0.903)	5.709 -
+ dummies for 21 industrial sectors and 6 geographical areas		
Observations	922	927
Dependent variable correctly classified	71.04 %	68.61%
Log pseudo likelihood	-529.18	534.91

The robust standard errors are reported in the parentheses. Significance levels are reported on superscripts, where *** denotes significance level of 1%, ** significance level of 5% and * significance level of 10%.