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Document Version
Final published version

Published in:
The Journal of Technology Transfer

DOI:
10.1007/s10961-023-10052-8

Publication date:
2024

The Journal of Technology Transfer
https://doi.org/10.1007/s10961-023-10052-8

International inventor teams and technological variety in multinational enterprises

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Accepted: 20 November 2023

Abstract
This study investigates the relationship between international inventor teams and the technological variety of multinational enterprises. We frame this relationship conceptually by considering two possible attributes of diversity in international inventor teams: cultural differences and heterogeneous knowledge. We employ a dataset for 454 multinational enterprises with 71,126 subsidiaries across 185 countries that applied for 139,066 priority patents during the period 2007–2014. Fixed-effects panel estimations indicate that international inventor teams are positively associated with both related and unrelated technological variety at the level of the MNE. Such relationships display diminishing marginal returns, pointing to management and coordination costs reducing the benefits from international inventor teams. In addition, we find that MNEs with higher technological innovation capability deal with the additional complexity from managing and coordinating international inventor teams by consolidating technological variety.

Keywords Multinational enterprise · Inventor team · Technological variety · Knowledge sourcing · Knowledge recombination

JEL Classification O32 · F23 · O14

1 Introduction

Variety in the knowledge base is essential for innovation, since it determines the range of possible reconfigurations of knowledge (Arthur, 2007; Basalla, 1988; Nelson & Winter, 1982; Schumpeter, 1934). Weitzman (1998) concludes that '… *the ultimate limits to growth*

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Published online: 23 December 2023

may not lie so much in our abilities to generate new ideas, as in our abilities to process to fruition an ever-increasing abundance of potentially fruitful ideas' (p. 359). Choices regarding variety play an important role in economics and innovation management, but often remain implicit (Van den Bergh, 2008).

Previous research dealt with strategies of multinational enterprises (MNEs) to maintain *variety* through *diversification of technology* drawing on evolutionary concepts such as path dependency and technological accumulation (see for example Cantwell, 1995; Piscitello, 2000; Cantwell & Piscitello, 2014) and the capability-based view of the firm (Granstrand, 1998; Teece et al., 1997). This line of thought suggests that firms diversify primarily into 'related' technological assets to retain patterns of corporate coherence (Breschi et al., 2003; Piscitello, 2004; Teece & Pisano, 1994; Teece et al., 1994). In terms of cognitive proximity, some degree of relatedness is required to recombine existing pieces of knowledge for incremental innovation by the firm. However, firms also diversify into unrelated technologies, thereby combining previously unconnected knowledge domains. While such recombination is more likely to fail, resulting innovations, when successful, are more likely to be of a radical nature (Fleming, 2001).

This study is one of the first to analyse determinants of the creation of technological variety within firms. While there is evidence that technological variety increases innovation in firms (Fleming, 2002; Garcia-Vega, 2006; Miller et al., 2007; Nesta & Saviotti, 2005; Quintana-Garcia & Benavides-Velasco, 2008) through access to a broader set of recombination paths, we find very little research on the determinants of and mechanisms for the creation of technological variety by firms (see Nerkar & Paruchuri, 2005; Cecere & Ozman, 2014).

Our analysis focuses on international inventor *teams* as a source of technological variety in MNEs. Recent studies emphasise that intra-firm knowledge transfer and integration ultimately depend upon the actions and interactions of individuals, such as inventors, sharing knowledge within the MNE (Castellani et al., 2022). Structural characteristics of individual inventors affect not only dissemination but also the recombination of knowledge throughout the organisation (Nerkar & Paruchuri, 2005; Paruchuri & Awate, 2017).

This study moves beyond individual inventor characteristics by inquiring whether and, if so, how international *inventor teams* create technological variety in MNEs. We posit that international inventor teams create novelty through the recombination of knowledge. Drawing from organisation research, we argue that novelty emerges from cultural differences and heterogeneous knowledge embedded in international inventor teams. *Cultural differences* create value by drawing from diverse perspectives (DiStefano & Maznevski, 2000; Lane et al., 2009), deemed particularly beneficial for conceptual and creative tasks (Hoever et al., 2012; Marino & Quatraro, 2022; McLeod et al., 1996). The second attribute, *heterogeneous knowledge*, reflects differences in know-how and expertise. We reason that this attribute is more prevalent in international inventor teams compared to domestic ones, since differences in technological specialisations are larger across than within countries (Archibugi & Pianta, 1992; Cantwell & Vertova, 2004; Picci & Savorelli, 2013).

However, diversity is a 'double-edged sword' (Milliken & Martins, 1996, p. 403). Excessive levels of diversity may also cause disparate mental models and interpersonal tensions, which might hinder the team's ability to develop creative outcomes (Bassett-Jones, 2005; Khedhaouria & Jamal, 2015). Cultural differences within teams may inhibit their ability to develop a task strategy, resolve conflicts, and build cohesion (Anderson, 1983; Kirchmeyer & Cohen, 1992; Kirkman & Shapiro, 2005; Watson et al., 1993, 2002). Knowledge heterogeneity can be counterproductive due to a lack of coordination among otherwise homogenous groups (Cegarra-Navarroa et al., 2021; Zhang & Li, 2016). *Thus,* *we propose a non-linear relationship*: International inventor teams increase the possibility for knowledge recombination within and across technological domains, which, in turn, would be a source for related and unrelated technological variety at the level of the MNE. However, we expect that coordination and management costs associated with the integration of knowledge from inventor teams spreading over too many countries reduce the benefits from international inventor team diversity upon technological variety. We suggest that MNEs' technological innovation capability could mitigate potentially negative effects from diversity in international inventor teams related to cultural differences and heterogeneous knowledge.

We tested these conjectures empirically, using a patent-firm-level dataset for a sample of MNEs headquartered in EU15[1] countries. We analysed data for 454 MNEs with 71,126 subsidiaries across 185 countries with 139,066 priority patent applications during the observation period 2007–2014. Fixed-effects panel estimations on variety measures computed on MNE patent portfolios indicate that international inventor teams are positively associated with both related and unrelated technological variety. However, such relationships display diminishing marginal returns, pointing to management and coordination costs reducing the benefits of cultural diversity and heterogeneous knowledge in international inventor teams. In addition, we find that multinational enterprises with higher technological innovation capability deal with the additional complexity of managing and coordinating international inventor teams by consolidating technological variety in the firm.

Section 2 provides a conceptual framework and develops three hypotheses on the relation between international inventor teams and technological variety in MNEs. Section 3 introduces data and descriptive statistics, as well as the measures and methods. In Sect. 4, we present the findings from the analysis and Sect. 5 concludes with a discussion.

2 Conceptual framework

2.1 Related and unrelated technological variety

Greater diversity in knowledge inputs means a greater potential for creative combinations (Weitzman, 1998; Van den Bergh, 2008). To produce new knowledge, firms use external sources in conjunction with internal R&D, which has been framed as an open innovation model (Almirall & Casadesus-Masanell, 2010; Benkler, 2006; Chesbrough, 2003; Dahlander & Gann, 2010; von Hippel, 2001, 2005). Searching broadly enhances firms' knowledge through variation and novelty of the knowledge employed by the external source (Laursen & Salter, 2006; Teodoridis et al., 2019). Technological recombination requires language and interface commonality to be able to enter and be diffused within an organization (Forman & van Zeebroeck, 2019; Savino et al., 2017; Trantopoulos et al., 2017; Vaccaro et al., 2009). Today, there is a broad consensus that the probability of a firm, region, or country launching new and specific activities is a function of the number of the related activities they are specialised in (see for example, Frenken et al., 2007; Boschma & Iammarino, 2009; Neffke et al., 2011; Boschma et al., 2015; Hidalgo et al., 2018).

[1] Member states of the European Union (EU) as of 2014: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and United Kingdom.

From a technological point of view, relatedness refers to the fact that although no two technologies are identical, they often share commonalities (Nooteboom, 2000). Proximity, commonality, and complementarity of knowledge are factors that might help to explain why firms diversify predominantly into related technologies (Breschi et al., 2003). Knowledge proximity refers to firms' learning processes via unintended spillovers (Griliches, 1979; Henderson & Cockburn, 1996), as well as intended learning by focusing on technological domains that present similarities in problem-solving and knowledge bases (Dosi, 1997; Nelson & Winter, 1982). Knowledge commonality implies that the same type of knowledge is used in various technologies, whereas knowledge complementarity arises from the need to use technologies jointly (Milgrom & Roberts, 1990; Pavitt, 1998; Scott, 1993). Decision-makers may have limited cognitive capabilities to identify potentially fruitful combinations of pieces of knowledge unrelated to their existing knowledge bases and/or to each other (Nightingale, 1998; Nooteboom, 2000). While recombination of previously unconnected knowledge domains is more likely to fail, resulting innovations, when successful, are often of a radical nature as recombination across unrelated technologies can lead to completely new operational principles, functionalities and applications (Fleming, 2001).

Extant literature offers insights into the extent to which related and unrelated technological variety increases firms' innovation through the recombination of knowledge (Aarstad et al., 2016; Fleming, 2002; Fornahl et al., 2011; Garcia-Vega, 2006; Miller et al., 2007; Nesta & Saviotti, 2005; Quintana-Garcia & Benavides-Velasco, 2008; Solheim et al., 2020). However, research on the determinants of and mechanisms for changes in related and unrelated technological variety is much more limited (Juhacz et al., 2020; Menzel, 2015).

2.2 Capabilities-based view on technological diversification in the MNE

The capabilities-based approach distinguishes the theory of the MNE from a mere special case of the theory of the firm, based on the specificities of the dynamic and continuous cross-border interaction of MNEs (Cantwell, 2014). To innovate, MNEs build synergistic or complementary portfolios of capabilities drawn from different locational contexts, which involve multidirectional knowledge transfer (Cantwell, 2009). The capabilities-based approach explains the process of corporate technological diversification as an outcome of more closely integrated MNE networks and their internationalisation (Cantwell & Piscitello, 2000, 2014; Castellani & Zanfei, 2006; Rahko, 2016).

Over the decades, we gained important insights into MNE strategies to maintain variety through the diversification of technology. Firstly, technological competencies are multi-field as they include technological fields outside firms' distinctive cores (Patel & Pavitt, 1997). Technological diversification is usually greater than product diversification and often anticipates product and market diversification (Pavitt, 1998). Operating within environments of converging or increasingly interrelated technologies, large firms develop and maintain a broad technological base, thereby becoming multi-technology corporations (Granstrand, 1998; Granstrand & Sjölander, 1992; Granstrand et al., 1997; Patel & Pavitt, 1997). Secondly, firms' technological diversification changes only slowly because of the inertia of specialisation and incremental changes in knowledge production (Cantwell & Andersen, 1996; Fai & von Tunzelmann, 2001), as well as sunk costs of R&D (Narula, 2014). Thirdly, while specialisation results in economies of scale associated with the learning process and knowledge transfer between the core technologies of the firm (Breschi et al., 2003; Garcia-Vega, 2006), diversification generates economies of scale and scope due to cross-fertilisation between core and peripheral technologies (e.g., Granstrand, 1998; Granstrand & Sjölander, 1992; Granstrand et al., 1997; Piscitello, 2000; Suzuki & Kodama, 2004).

2.3 Role of inventors for variety in MNEs

Knowledge transfer and integration are highly dependent on the actions and interactions of individuals, such as inventors, sharing knowledge within the MNE (Castellani et al., 2022). When it comes to the circulation of technological knowledge, inventors are the key characters to observe (Fleming, 2001; Miguelez & Morrison, 2023), since they carry out the actual knowledge-creation processes (Allen & Cohen, 1969). Yet not all inventors are equally effective knowledge creators. For example, cross-border mobility of inventors within an MNE enables the temporary co-location of mobile inventors and, in turn, wider dissemination of their knowledge within the organisation (Castellani et al., 2022). Organisation research also hints at a relation between individual inventors' structural characteristics, especially the centrality of inventors and the spanning of structural holes, and the processes of recombination of knowledge (Nerkar & Paruchuri, 2005). Inventors who span many structural holes are aware of and have access to organizational knowledge that is distributed in diverse pockets of the organization (Paruchuri & Awate, 2017). When such inventors generate innovations by recombining organisational knowledge, they gain a wider reach in the intra-organizational inventor network. Similarly, there is evidence of a positive relationship between the strength of intra-firm inventors' ties and technological variety (Cecere & Ozman, 2014). However, if inventors are excessively embedded in networks, they become more like each other, which reduces opportunities for novel combinations of knowledge (ibid).

2.4 Hypothesis development

Moving beyond individual inventor characteristics, this paper looks at international inventor *teams* as a possible source for technological variety in MNEs. Previous research argued that multinational breadth, in terms of the dispersion of subsidiaries across countries, correlates positively with investments in R&D (Castellani et al., 2017) and also diversifies an MNE's knowledge base, which increases the likelihood of discovering new and valuable combinations of ideas (Kafouros et al., 2012). MNEs undertake international R&D via strategic alliances (Almeida et al., 2002), acquisition of external R&D facilities (Awate et al., 2015), knowledge acquisition from local suppliers (Li et al., 2010), collaboration with foreign universities (Belderbos et al., 2020, 2021; Ivarsson et al., 2017), or 'listening posts' (Gassmann & von Zedtwitz, 1999; Monteiro & Birkinshaw, 2017). All these modes can involve a team of international inventors that appropriates the returns from R&D in the form of a cross-country patent application with inventors residing in different countries (Alkemade et al., 2015; Frost & Zhou, 2005; Laurens et al., 2015). Thus, 'international inventor teams' reflect not only the outcome of joint R&D (collaboration in a strict sense) but also the results of R&D contracts (acquisition) and R&D advice (services) (Bergek & Bruzelius, 2010). We already know that MNEs use international teams to coordinate dispersed but interdependent R&D activities (Ambos & Schlegelmilch, 2004). Furthermore, the value of innovative work by international inventor teams can exceed the returns from purely domestic inventor teams of the same MNE (Kerr & Kerr, 2018). *This study* *investigates whether and, if so, how diversity associated with international inventor teams shapes technological variety in MNEs.*

2.4.1 Diversity as a driver of variety within international inventor teams

Team diversity favours the search for innovative solutions by introducing more heterogeneous sources of knowledge (March, 1991). Cognitive diversity is often associated with the generation of ideas and creativity (Farr et al., 2003). Diversity as a team characteristic denotes the extent to which members differ with regard to a given attribute (Joshi & Roh, 2009; van Knippenberg & Schippers, 2007). This view focuses upon underlying differences in perspectives on a task as the more proximal indicator of a team's increased cognitive resources (Harrison & Klein, 2007; van Knippenberg et al., 2004). Regarding international inventor teams, our argument focuses on two possible attributes: *cultural differences* and *heterogeneous knowledge.*

International inventor teams with members representing two or more cultures leverage creativity for product and service innovation more effectively than single-culture teams (e.g. Bouncken et al., 2015; DiStefano & Maznevski, 2000; Hoever et al., 2012; Jang, 2017; Lane et al., 2009). *Diversity in cultural background* is particularly salient (Stahl et al., 2010) because it affects the team members' beliefs, attitudes, and mindsets (van Knippenberg et al., 2013). Although 'domestic' teams can also be multi-cultural, international inventor teams are so by definition.

The second attribute, *heterogeneous knowledge*, reflects differences in terms of technological knowledge and expertise rather than differences in perspectives. We also find heterogeneous knowledge in exclusively domestic inventor teams. However, we expect this attribute to be more extensive in international inventor teams, since differences in technological specialisations are larger across than within countries (Archibugi & Pianta, 1992; Cantwell & Vertova, 2004; Picci & Savorelli, 2013). This provides a higher potential for knowledge complementarities in international inventor teams compared to purely domestic ones. Team members can acquire knowledge from one another to make further abstractions and analogies between problems and, thus, use experience-based skills to solve new problems (Zhuge et al., 1997).

Given that MNEs locate foreign R&D predominantly in host countries with a technological specialisation, to exploit an already existing technological advantage at home (Laurens et al., 2015; Le Bas & Sierra, 2002), international inventor teams in such R&D projects are likely to focus on technological domains that present high similarities in problem-solving and knowledge bases. In this case, collaboration within international inventor teams facilitates the effective exchange of proximate knowledge to work on incremental innovations. This collaboration often requires face-to-face communication and personal feedback to overcome the ambiguities of tacit knowledge (Teece, 1981). Knowledge proximity lowers the cost of combining knowledge and enables systematic and creative work, which is likely to foster *related technological variety* within the MNE.

Since competence-exploitation and competence-creation strategies are often employed simultaneously, MNEs also use foreign R&D to explore and search beyond existing technological specialisations at home (Cantwell & Mudambi, 2005, 2011; De Beule & Van Beveren, 2019). In this case, we would expect the diversity of knowledge within international inventor teams to be relevant, since it offers the opportunity to develop a broader set of recombination paths. These are essential for more radical innovations (Fleming, 2002), which are rare but usually come from a recombination of already existing knowledge

(Hargadon, 2003), often based on the combination of mature and emerging technologies (Schoenmakers & Duysters, 2010). International inventor teams could be a way to access emerging technologies developing abroad for integration with existing technologies of the MNE. Thus, international teams could be a mechanism to attain greater *unrelated technological variety within* an MNE. Against this background, we hypothesise:

H1 Other things equal, the presence of international inventor teams is associated with greater technological variety of the MNE.

2.4.2 Coordination and management costs of international inventor teams

Diversity favours the opportunity for creativity, while at the same time increasing the likelihood that some team members will feel dissatisfied and detached from the group (Bassett-Jones, 2005; Milliken & Martins, 1996). Organisation research confirms that an excessive level of diversity may cause disparate mental models and interpersonal tensions, which hinder a team's ability to develop creative outcomes (Khedhaouria & Jamal, 2015). Cultural differences within a team may inhibit the team's ability to develop a task strategy, resolve conflicts, build cohesion, and foster effective interaction among team members (Anderson, 1983; DiStefano & Maznevski, 2000; Kirchmeyer & Cohen, 1992; Kirkman & Shapiro, 2005; Watson et al., 1993, 2002). Negative social interaction and group incohesiveness are also likely to reduce the benefits from heterogeneous knowledge in international inventor teams in the effective creation of technological variety (Huang, 2009; Nissen et al., 2014). Maintaining regular international knowledge exchange, in turn, is costly, and spreading MNE networks across a larger number of countries increases organisational complexity (Castellani et al., 2017).

Knowledge heterogeneity of international inventor teams itself could be counterproductive if coordination is lacking among otherwise homogenous groups (Cegarra-Navarroa et al., 2021; Zhang & Li, 2016). MNE research team geographic diversity has a curvilinear relationship with the team's innovation performance (Seo et al., 2020), which implies that some degree of homogeneity in collaborative research teams is beneficial (Coad et al., 2017). We would, therefore, expect that coordination and management costs associated with integrating knowledge from multinational inventor teams reduces the benefits from diversity upon technological variety at the level of the MNE. Thus, we hypothesise:

H2 Other things equal, there are diminishing marginal returns from the breadth of knowledge sourcing via international inventor teams upon an MNE's technological variety.

2.4.3 Technological innovation capability as a moderator

Arguably, some MNEs are better than others at managing international knowledge flows to create technological variety. Many studies in innovation performance focus on R&D investments (e.g., Ahuja & Katila, 2001; Castellani et al., 2017; Mairesse & Mohnen, 2005). Others emphasize non-R&D inputs. For example, Bell (2009) refers more broadly to firms' '*capability to create new configurations of product and process technology and to implement changes and improvements to technologies already in use*' (p. 11). Such innovation capability consists of various assets related to physical capital, knowledge capital, human capital, and organisational capital (ibid.). The latter has been recognised as an important element in firms' searches for innovative inputs from external sources (e.g., Katila & Ahuja, 2002; Laursen & Salter, 2006).

We expect that MNEs with higher innovation capability are better positioned to identify and integrate knowledge flows from international inventor teams, so that stronger positive effects upon technological variety can materialise. This, for example, could be facilitated by access to superior R&D equipment, staff experienced in international R&D collaborations, or a larger stock of previous knowledge within the MNE. Such *technological* innovation capability would then mitigate the potentially negative effects from diversity in international inventor teams related to cultural differences and heterogeneous knowledge. Therefore, we hypothesise:

H3 Other things equal, technological innovation capability positively moderates the relation between the presence of international inventor teams and an MNE's technological variety.

3 Data, measurement and method

3.1 Data

Extant research used firm-level databases with information on patent applicants to measure R&D internationalisation and/or to approximate the incidence of foreign R&D (Alkemade et al., 2015; Dernis et al., 2015; Laurens et al., 2015). We extend this approach by accounting for affiliates' entries into and exits from MNEs groups over time to relax the restrictive assumption of static MNE ownership structures (see for example Dernis et al., 2015 for a discussion of this limitation). This increases precision in the allocation of patents to the actual patent owners over time. We employ a dataset for 454 MNEs headquartered in the EU15 for the observation period 2007–2014.

Our data source is the BvD ORBIS database. We started by extracting data on active enterprises headquartered in an EU15 country, with at least 100 employees, being active and not dissolved, classified as an industrial company, having manufacturing as a primary activity (NACE Rev. 2 Section code C) and having at least one foreign subsidiary in 2014. Based on individual ownership links, we derived an historical ownership hierarchy for each MNE for each year of the observation period.[2] We excluded individuals or financial entities as global ultimate owners (GUOs) and instead selected the next industrial entity in the hierarchy as GUO. Then, we extracted all patent documents available in the patent section of ORBIS for all MNEs and their subsidiaries. The identified patent documents were matched with PATSTAT (Version 2019a) through the application number and the corresponding identification number of the entity.[3] This enabled us to identify priority patent applications,

[2] We calculated the combined ownership from any entity connected to another, either directly or through a path of subsidiaries, with ownership exceeding 25%. For example, an MNE directly owns an 80% equity stake in a subsidiary. If the subsidiary in turn owns a 50% equity stake in another subsidiary, the total ownership that the MNE holds over the latter subsidiary is calculated to 40% (80%*50%). By establishing hierarchical ownership structures, we can track ownership changes for each subsidiary, on an annual basis. In case of missing information, we identified gaps and, when possible, imputed missing data through interpolation.

[3] BvD matches entities to patents with the OECD Harmonised Applicants' Names Database (see Thoma et al., 2010).

their associated International Patent Classification (IPC) codes, and the countries of residence of their inventors. Using priority applications[4] reduces country bias and enables a more accurate representation of inventor locations (De Rassenfosse et al., 2013). In line with existing research (see for example Picci & Savorelli, 2013; Laurens et al., 2015; Alkemade et al., 2015), we inferred the inventors' location from the addresses of residence of the inventors, as indicated in the priority patent application.

This process yielded our final sample, which includes 454 MNEs with 71,126 subsidiaries across 185 countries and 139,066 priority patent applications. The average MNE was observed in the sample for 4.5 years and accounted for about 68 priority applications per year (see Appendix Table 3). Nearly all patent applications were made by inventor teams (only 0.2% report a single inventor). Inventors whose listed address is not in their MNE's headquarters country constitute a relevant phenomenon: about 1 of every 5 inventors are foreign (i.e. 19.2%, 12.1% residing in the EU15 and 7.1% outside it) and about 1 of every 4 (i.e. 26.1%) patent teams are international, i.e. include a foreign inventor (see Appendix Tables 4, 5). Aggregated across the parent and subsidiaries, we found that 78% of MNE-year observations had patent applications with more than one IPC code and about 48% had inventors from more than one country (see Appendix Table 6).

3.2 Measurements and methods

Earlier studies also used patents as proxies for codified technological knowledge and used patent classifications to measure various aspects of technological relatedness and coherence at the level of the firm (e.g., Breschi et al., 2003; Colombelli et al., 2014; Nesta & Saviotti, 2005). Technological proximity can be estimated in several ways (Juhacz et al., 2020). We applied a hierarchical technological classification scheme as an ex-ante imposed structure that defines relatedness and unrelatedness. We computed entropy measures using the hierarchical structure of 610 IPC subclasses that fall exclusively under one of the IPC's eight sections.[5] Formally, in the equations that follow, k denotes IPC subclasses, j IPC sections and S_j the set of IPC subclasses belonging to section j. We first computed the IPC subclass shares $p_{i,t,k}$ as the sum of the full count of patent applications of MNE group i falling in IPC subclass k in year t.[6] Then, we computed the IPC section share $P_{i,t,j}$ by summing the IPC subclass shares $p_{i,t,k}$ of MNE group i falling in IPC section j in year t. Unrelated technological variety $UV_{i,t}$ of MNE i in year t is then given by:

$$UV_{i,t} = \sum_{j=1}^{8} P_{i,t,j} ln\left(\frac{1}{P_{i,t,j}}\right) \tag{1}$$

and related technological variety $RV_{i,t}$ by:

[4] A priority filing (or priority patent) is the first patent application filed to protect an invention. It represents the total number of patent families, regardless of their spatial protection scope.

[5] Human necessities, performing operations and transporting, chemistry and metallurgy, textiles and paper, fixed constructions, mechanical engineering, physics, and electricity.

[6] We replicated the analysis using the sum of the fractional count (rather than the full one) of patent applications to compute the IPC subclass shares $p_{i,t,k}$. As shown in Table 2, the results of the analysis do not change.

$$RV_{i,t} = \sum_{j=1}^{8} P_{i,t,j} H_{i,t,j}, \text{where} H_{i,t,j} = \sum_{k \in S_j} \frac{p_{i,t,k}}{P_{i,t,j}} ln\left(\frac{1}{(p_{i,t,k}/P_{i,t,j})}\right) \tag{2}$$

Thus, to account for cognitive proximity between technologies in an MNE's patent portfolio, unrelated variety measures the extent of technological diversity across the eight broad IPC sections. MNE groups that patent in more sections have a higher index value for unrelated technological variety. Related variety, in turn, measures the extent of technological diversity within each IPC section across IPC subclasses and is larger for MNEs whose patents are distributed across more IPC subclasses within a single IPC section.

To test our first hypothesis (H1), we regressed our technological variety measures on variables based on the location of the corresponding inventors and other MNE characteristics. We applied a fixed-effect panel regression specified by:

$$TV_{i,t} = \beta_1 MNInv_{i,t} + \beta_2 NCInv_{i,t} + \delta' Z_{i,t-1} + d_t + u_i + \varepsilon_{i,t} \tag{3}$$

$TV_{i,t}$ indicates the respective technological variety measure for MNE group i (i = 1, …, 454) at year t (t = 2008, …, 2014); β_1 is the parameter of $MNInv_{i,t}$, a dummy that indicates whether one or more patents applied by MNE i in year t includes a team of inventors with different countries of residence[7]; β_2 is the parameter of $NCInv_{i,t}$, which is the number of the countries of residence of the inventors in the pool of patent applications made by MNE i in year *t ('breadth of international knowledge sourcing')*; δ' is a vector of parameters associated to a vector of time-varying MNE-specific controls $Z_{i,t-1}$; d_t denotes year fixed effects; u_i is an MNE-specific time-invariant fixed effect; and $\varepsilon_{r,t}$ is the error term.[8] The vector $Z_{i,t-1}$ includes the number of patent applications ($NPat_{i,t-1}$, in log) made by MNE i, the number of subsidiaries (in log), the share of foreign subsidiaries to take into account MNE's internationalisation of production, the number of employees and the value of intangible assets (both in logs) as well as measures for MNE related and unrelated variety across industries. All control variables are lagged by one year in order to minimise the impact of simultaneity between MNE's attributes and technological variety.

Appendix Table 8 shows descriptive statistics of the variables entering the regression analysis.[9] MNEs in the sample are large (about 20,000 employees on average) and highly innovative (with intangible assets and yearly R&D expenditures of about 1,750 and 289 million Euro, respectively, on average). They have a broad geographical presence, with 105 foreign subsidiaries spanning 23.6 countries, on average. They file an average of about 69 patents every year, about half of which involve international inventors spanning five countries of residence.

[7] We follow an approach introduced by the European Commission's Joint Research Centre and the OECD, which exploits information on the location of the inventors of corporate patents to approximate 'international knowledge sourcing' (Dernis et al., 2015) and/or the incidence of 'foreign R&D' (Laurens et al., 2015). In our case, 'MNE patents' refer to all priority patents applied for by the GUO of the MNE, as well as those applied for by any domestic or any foreign subsidiary of the focal MNE in the respective year.

[8] Notice we link an input – international knowledge measured through the location country of inventors – and an output – technological variety in the corresponding pool of patents – in the MNE innovation process. Innovation activities in general, and technological ones in particular, are uncertain and typically time-consuming, giving rise to a volatile and erratic output path. Thus, we measure the input and the output of the innovation process using the same pool of patents in order to avoid capturing spurious volatility rather than meaningful time changes in the relationship of interest. Control variables, by contrast, enter the model with one year lag in order to minimize potential simultaneity issues.

[9] Appendix Table 7 reports the definition of all variables used in the analysis.

To test for decreasing marginal returns from the breadth of knowledge sourcing via international inventor teams on technological variety (H2), Eq. (4) introduces an additive quadratic term of the number of countries of residence of inventors ($NCInv_{i,t}$):

$$TV_{i,t} = \beta_1 MNInv_{i,t} + \beta_2 NCInv_{i,t} + \beta_3 NCInv^2_{i,t} + \delta' Z_{i,t-1} + d_t + u_i + \varepsilon_{i,t} \tag{4}$$

Finally, we tested for the role of innovation capability in moderating the effects of international knowledge sourcing on technological variety (H3) by augmenting Eq. (5) with an interaction term: the product of the number of countries of residence of inventors ($NCInv_{it}$) and the number of patent applications[10] ($\mathrm{NPat}_{i,t-1}$):

$$TV_{i,t} = \beta_1 MNInv_{i,t} + \beta_2 NCInv_{i,t} + \beta_4 \mathrm{NPat}_{i,t-1} + \beta_5 NCInv_{i,t} * \mathrm{NPat}_{i,t-1} + \delta' Z_{i,t-1} + d_t + u_i + \varepsilon_{i,t} \tag{5}$$

Regression parameters' of models (3)–(5) may suffer from endogeneity issues that our fixed effects panel estimators can not address, and should therefore be interpreted as correlates of technological variety. While sources of potential endogeneity with an inventor team's composition and diversity look hard to identify, the relationship between technological variety and technological capacity at the core of H3 seems trickier. In fact, time-varying omitted shocks that are specific to certain countries, industries or technological fields, induced for instance by national policies encouraging innovation in specific domains, the upsurge of technological breakthroughs, and market dynamics entailing changes in the demand for products, might influence both the number of patents and the variation of MNEs patenting across fields. In order to attenuate biases coming from such potential confounders, we also considered models' specifications that include a time-varying measure of the technological specialization[11] of the MNE's headquarters country, as well as year-specific controls for MNE industry and headquarters country. The inclusion of these additional controls left the parameters of interest unaltered, so we opted to exclude them from our baseline specification for the sake of parsimony.

4 Findings

Table 1 shows the estimation results of fixed effects regression models for related and unrelated variety. It reports the results of four specifications for each variety measure. All models include a dummy for the presence of international inventors and the number of

[10] Patent applications belong to firms' intangible assets, which in turn, constitute one type of capital that constitute 'innovation capability' as defined by Bell (2009).

[11] Following Miguelez and Moreno (2015), we computed the following measure of technological specialization:

$$Patent\ specialisation\ index_{it} = \frac{1}{2}\sum_j \left| \frac{pat^j_{it}}{pat_{it}} - \frac{pat^j_t}{pat_t} \right|$$

where pat^j_{it} is the number of patents (filed under the Patent Cooperation Treaty) in country i, time t and technology j, pat_{it} is the number of patents in country i and time t in all technologies, pat^j_t is the number of world patents in time t and technology j, and pat_t is the number of world patents in time t in all technologies. We considered 35 technology classes as defined by Schmoch (2008).

Table 1 Fixed effects models on MNEs' technological variety

	Related variety				Unrelated variety			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Presence of international inventors' teams	0.104***	0.076***	0.066***	0.063***	0.087***	0.067**	0.066***	0.061**
	(0.022)	(0.023)	(0.023)	(0.023)	(0.024)	(0.026)	(0.026)	(0.026)
Nr. of inventors' countries	0.021***	0.046***	0.067***	0.069***	0.015***	0.032***	0.040***	0.042***
	(0.005)	(0.010)	(0.011)	(0.011)	(0.004)	(0.009)	(0.011)	(0.011)
Ln(Nr. patents)	0.033**	0.033**	0.065***	0.061***	– 0.010	– 0.010	0.008	0.002
	(0.014)	(0.014)	(0.015)	(0.016)	(0.012)	(0.012)	(0.014)	(0.016)
Squared Nr. of inventors' countries		– 0.001***		– 0.000		– 0.001***		– 0.001
		(0.000)		(0.000)		(0.000)		(0.000)
Nr. of inventors' countries x Ln(Nr. patents)			– 0.011***	– 0.009***			– 0.006***	– 0.004
			(0.002)	(0.003)			(0.002)	(0.003)
MNE-level controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MNE fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of MNEs	454	454	454	454	454	454	454	454
Observations	2,032	2,032	2,032	2,032	2,032	2,032	2,032	2,032

Robust standard errors clustered by MNE group are shown in parentheses. All models also include the number of subsidiaries (in log), the share of foreign subsidiaries, the number of employees (in log), the value of intangible assets (in log) and related and unrelated variety computed across industries. Control variables enter the model with one-year lag. $^{*}p<0.10$; $^{**}p<0.05$; $^{***}p<0.01$

inventor countries of residence,[12] which we expected to be positively associated with the variety measures. Models (2) and (6) introduce a quadratic term of the number of inventor countries of residence to test potential diminishing marginal returns. Models (3) and (7) introduce an interaction term between the number of inventor countries and the number of patent applications. Models (4) and (8) include all variables, i.e. the quadratic specification of the number of inventor countries and its interaction with the number of patents.

In line with H1, the dummy indicating the presence of international inventor teams is positive and significant across all specifications. Thus, the presence of international inventor teams is positively associated with both related and unrelated technological variety. The same applies to the number of inventor countries of residence. However, the quadratic term introduced in models (2), (4), (6) and (8) is negative, though not significantly different from zero when the interaction between the number of inventors' countries and the number of patents is also introduced in the model (models (4) and (8)). The result indicates the presence of positive correlations between variety measures and the number of inventor countries (breadth of knowledge sourcing). However, these positive correlations fall slightly as the number of inventor countries increases.

Models (3) and (4), which include the interaction term between the number of inventor countries and the number of patents, show negative and significant estimates for related variety. The sign is negative also for unrelated variety, but the estimate becomes statistically non-significant in model (8), which also includes the quadratic term of the number of inventors' countries.

In order to better assess the relationships between international inventor teams and technological variety in the models that include the quadratic and interaction terms, Fig. 1 plots the average marginal effects (AMEs) of the number of inventor countries on technological variety. Figure 1 indicates that the AMEs fall for both related and unrelated variety as the number of inventor countries itself and the number of patents increase. Statistically significant positive effects are present for low numbers of inventor countries and patent applications, but are not statistically different from zero at high values. Figure 1 also indicates that point estimates become increasingly imprecise as the number of inventor countries increases, with the confidence interval getting larger as the number of data points decreases. Yet, this feature of the specifications does not affect the qualitative pattern of the focal relationships. In line with H2, the results provide evidence for decreasing marginal returns as the breadth of international inventor teams across countries becomes increasingly broad.

As for the moderating role of innovation capability, we find, in contrast with H3's expectation, that higher innovation capability is associated with a lower correlation between multinational inventor teams and MNE's technological variety. As for the other explanatory variables, the direct effect of innovation capability is positive and significant for related variety, and not statistically different from zero at standard confidence levels for unrelated variety. Thus, diversification into related technologies increases with higher innovation capability; diversification into unrelated technologies does not. Most of the coefficients of other explanatory variables, shown in Appendix Table 9, are not statistically significant.[13]

[12] All models also control for the number of patent applications (in log), as well as time-varying MNE-specific characteristics and year common effects.

[13] Most of the control variables, in particular the number of subsidiaries, employees as well as the value of intangible assets, show limited variance within MNEs across years (see Appendix Table 8), so their effects are likely to be captured by the time-invariant MNE -specific fixed effects.

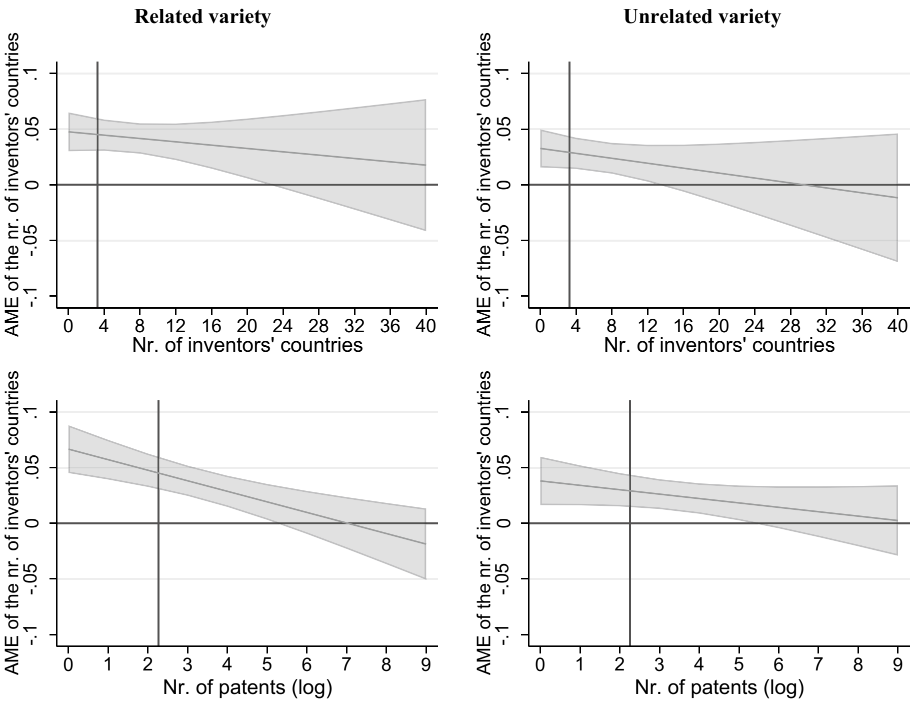

Fig. 1 Average marginal effects of the number of inventor countries on technological variety. Notes: Average marginal effects' (AMEs) are derived using the sample mean of all explanatory variables other than the number of inventors' countries and the number of patents. The vertical lines indicate the means of the number of inventors' countries and the number of patents. The graphs for related variety use model (4)'s estimates (Table 1), while the graphs for unrelated variety use model (8)'s estimates. The grey area indicates 95% confidence intervals

The results of the analysis are robust to a series of robustness checks shown in Table 2, which reports estimates of baseline (models (4) and (8) of Table 1) and alternative fixed effects models.[14] First, we use fractional rather than full counting for the patents with multiple applicants in the construction of variety measures.[15] Estimates of models (2) and (8) in Table 2 are nearly unchanged with respect to the relevant baseline.

Second, we replicate the analysis using only MNEs-years observations with more than 5 patents.[16] Variety measures show quite large variation, also for MNEs with one or few patents because most patents (78%, see Appendix Table 6) are associated to multiple IPC classes. This enables us to test that results are not driven by MNEs with few patents. Also, in this case, estimates of models (3) and (9) in Table 2 are very similar to the relevant baseline as the estimated coefficients display the same sign and significance. With respect to the

[14] Full models of all robustness checks are found in Appendix Table 10.

[15] The sample includes 1,799 patents with multiple applicants belonging to 10% (203) of MNEs-years observation.

[16] MNEs-years observations with 5 or less patents represent 43% of the sample (see Appendix Table 6).

baseline, we notice a larger positive association between innovation capabilities and related variety.

Third, we estimated a model that also includes R&D expenditure (in log and lagged by one year). R&D expenditures are an important input for an MNE's innovative activities and could influence variety measures. While we do not use R&D expenditures in the baseline models due to a high number of missing values in the sample (25%), models (4) and (10) in Table 2 indicate that, once innovation capability and international knowledge sourcing are controlled for, R&D expenditures are not associated with an MNE's technological variety. In brief, the results of the baseline models do not change when R&D expenditures are included.

In addition, we tested the robustness of our baseline models by excluding countries that could bias our findings. Models (5) and (11) in Table 2 exclude Germany, which is the most-represented country in the sample, accounting for about 31% of MNEs (see Appendix Table 3). While the the dummy variable indicating the presence of international inventor teams becomes statistically non-significant due to an increase of the associated standard error leading the p-value to 0.103, at the edge of statistical significance at the 90% level in the case of related variety, the findings of the baseline analysis are substantially confirmed for both related and unrelated variety. We also report estimates of models excluding MNEs from the UK, which account for about 17% of MNEs in the sample but show comparatively low patent intensity (on average, 11 patents per year versus 68 by the average MNE).[17] All results are very similar to those of baseline models (see models (6) and (12) in Table 2).

Results are also confirmed by further robustness checks that we do not report for the sake of brevity.[18] In order to test how the financial crisis may have influenced our estimates, we augment the baseline specification, which simply controls for common year effects, with country- and industry-specific business-cycle variables. In particular, results do not change when we include unemployment rates in MNE headquarter-countries and industry-specific (at the NACE Rev. 2 Section level) GDP levels and growth rates. Models' results are also robust to the inclusion of a time-varying measure of the technological specialization of the MNE headquarters country (computed over alternative time windows to smooth potential volatility in patenting activities across technological fields, especially for smaller countries), as well as of year-specific dummies for the industry and MNE headquarter-countries. Finally, in order to test the extent to which our results change when using lag structures that allow for more time for a patent to be generated, we lagged control variables by two and three years, re-estimated all models, and find no substantial difference with the findings obtained in the baseline using a one-year lag.

[17] While the issues of coverage and data availability are known limitations of ORBIS, these are by far outweighed by its advantage of offering a comprehensive cross-country micro-level dataset for scientific research purposes (e.g. Gal, 2013). See Appendix Tables 3 and 6 for a detailed distribution of MNEs and patents across countries.

[18] Tables available upon request from the authors.

Table 2 Robustness checks

	Baseline	Fractional counting	MNEs with more than 5 patents	Including R&D expenditures	Excluding DE MNEs	Excluding UK MNEs	Baseline	Fractional counting	MNEs with more than 5 patents	Including R&D expenditures	Excluding DE MNEs	Excluding UK MNEs
	Related variety						Unrelated variety					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Presence of multinational inventors	0.063***	0.063***	0.077***	0.082***	0.052	0.052**	0.061**	0.061**	0.089***	0.062**	0.053*	0.051*
	(0.023)	(0.023)	(0.028)	(0.027)	(0.032)	(0.024)	(0.026)	(0.027)	(0.030)	(0.028)	(0.032)	(0.029)
Nr. of inventors' nationalities	0.069***	0.068***	0.066***	0.072***	0.090***	0.070***	0.042***	0.042***	0.020*	0.041***	0.059***	0.048***
	(0.011)	(0.011)	(0.012)	(0.011)	(0.015)	(0.012)	(0.011)	(0.011)	(0.011)	(0.012)	(0.015)	(0.012)
Ln(Nr. patents)	0.061***	0.054***	0.151***	0.085***	0.080***	0.052***	0.002	0.003	0.034	0.005	0.006	− 0.002
	(0.016)	(0.017)	(0.027)	(0.021)	(0.023)	(0.016)	(0.016)	(0.016)	(0.026)	(0.018)	(0.020)	(0.018)
Squared Nr. of inventors' nationalities	− 0.000	− 0.001	0.000	− 0.000	− 0.001	− 0.000	− 0.001	− 0.001	− 0.000	− 0.001	− 0.001	− 0.001
	(0.000)	(0.001)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)
Nr. of inventors' nationalities x Ln(Nr. patents)	− 0.009***	− 0.008***	− 0.013***	− 0.011***	− 0.012***	− 0.010***	− 0.004	− 0.004	− 0.003	− 0.004	− 0.007**	− 0.004

Table 2 (continued)

	Baseline	Fractional counting	MNEs with more than 5 patents	Including R&D expenditures	Excluding DE MNEs	Excluding UK MNEs	Baseline	Fractional counting	MNEs with more than 5 patents	Including R&D expenditures	Excluding DE MNEs	Excluding UK MNEs
	Related variety						Unrelated variety					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.003)
Ln(R&D)				− 0.022						− 0.019		
				(0.027)						(0.016)		
MNEs-level controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MNEs fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of MNEs	454	454	247	315	313	376	454	454	247	315	313	376
Observations	2,032	2,032	1,159	1,521	1,281	1,730	2,032	2,032	1,159	1,521	1,281	1,730

Robust standard errors clustered by MNE group are shown in parentheses. All models also include the number of subsidiaries (in log), the share of foreign subsidiaries, the number of employees (in log), the value of intangible assets (in log) and related and unrelated variety computed across industries. The baseline models are model (4) of Table 1 for related variety and model (8) of Table 1 for unrelated variety. Control variables enter the model with a one-year lag. *p < 0.10; **p < 0.05; ***p < 0.01

5 Discussion

5.1 Main findings and contributions

This research builds upon the capability-based view that international integration of MNE networks facilitates the diversification of corporate technology (Cantwell, 2009; Cantwell & Piscitello, 2000, 2014; Castellani & Zanfei, 2006; Rahko, 2016). We advance the state-of-the-art in two ways. Firstly, this is one of the first studies to focus on the determinants rather than on the consequences of variety by using the related and unrelated technological variety of MNEs as *dependent variables*. Secondly, we focus on international inventor *teams* as creators of technological variety in firms. Conceptually, we frame this relationship by considering two possible attributes of diversity in international inventor teams: cultural difference and heterogeneous knowledge.

Our econometric results indicate that international inventor teams might enhance both related and unrelated technological variety of MNEs. This suggests that, in principle, MNEs can overcome the need for spatial proximity in the creation of *related* variety, which has been postulated in the literature on evolutionary economic geography (Boschma & Iammarino, 2009; Frenken et al., 2007). Our results also suggest that international inventor teams enhance an MNE's ability to create *unrelated* variety, which might reflect their quest to combine previously unconnected knowledge domains, which in turn are key to rare radical or breakthrough innovations (Castaldi et al., 2015; Fleming, 2001; Solheim et al., 2020). This finding challenges the conclusion from previous research that '…*firms go abroad for augmenting or exploiting their home base, not for acquiring new bits of knowledge outside the technologies they master at home*' (Laurens et al., 2015, p. 773).

In line with H1, our econometric results document that the breadth of MNEs inventor countries increases technological variety. However, in line with H2, increases in variety flatten as the number of inventor countries increases. These diminishing marginal returns could be explained by cognitive limits to knowledge identification (Noteboom, 2000), disparity between originating ideas (Olsson & Frey, 2002), inhibited social interaction and group cohesion due to cultural differences within international teams (DiStefano & Maznevski, 2000; Kirkman & Shapiro, 2005; Lane et al., 2009) – all resulting in increasing costs for coordination and management of knowledge transfer and integration from international R&D (Castellani et al., 2017; Narula, 2014). Our finding of diminishing marginal returns supports the view that team diversity might both provide opportunities for creativity and hinder a team's ability to develop creative outcomes (Bassett-Jones, 2005; Khedhaouria & Jamal, 2015; Milliken & Martins, 1996).

We also find that an MNE's technological innovation capability, approximated by the number of previous patents, is an important direct predictor of related variety. Unrelated variety, by contrast, shows similar values for MNEs with patent portfolios of varying sizes. Thus, diversification into related technologies gains in importance as an MNE's innovation capability increases. This finding supports the view that technological diversification is characterised by expansion into related assets to establish patterns of corporate coherence (Breschi et al., 2003; Piscitello, 2004; Teece & Pisano, 1994; Teece et al., 1994). Our results also indicate that international knowledge sourcing via multinational inventor teams for MNEs with lower innovation capability might complement strategies that aim to create unrelated rather than related technological variety. This can be associated with the argument that it is possible for MNEs to 'jump' stages of technological evolution via international knowledge sourcing (see, for example, Enderwick & Buckley, 2021).

Finally, in contrast to H3, our results show that the positive contribution of international inventor teams upon technological variety declines as an MNE's innovation capability increases. This finding could suggest that MNEs with higher technological innovation capability deal with the higher complexity of managing and coordinating heterogeneous inventors from different countries by reducing technological diversity *more* than MNEs with a lower technological innovation capability. In other words, it is likely that MNEs with higher technological innovation capability engage in international knowledge sourcing in ways that reflect consolidation towards their technological core, rather than diversification into related or unrelated variety—given that they already operate at a higher level of variety than MNEs with lower technological innovation capability.

5.2 Limitations

This study exploits a firm-patent level dataset that is not exempt from limitations. First, even though control variables are introduced in the empirical analysis with a one-year lag to minimise the impact of the potential simultaneity between MNEs' attributes and technological variety, the results should be interpreted as descriptive of the variety of an MNE's patent portfolio, without any presumption of causality.

Second, the observation period is restricted to eight years.[19] This is relatively short in comparison to studies of long-term patterns of firm-level technological change (e.g., Cantwell & Vertova, 2004), though it compares well to most studies on technological variety at the firm level (e.g., Aarstad et al., 2016; Capozza et al., 2020; Solheim et al., 2020). In addition, our observation period includes the global financial crisis, which may distort the relationships of interest due to firms having scaled back their R&D (OECD, 2009). Yet, due to sunk and opportunity costs, firms may have reduced R&D less than other expenditures for other functions such as sales, marketing and post-sales activities during the crisis (Rafferty, 2003). Moreover, during the crisis, the existence of an internal R&D department, as well as strategies aimed at exploring new markets and new product developments, proved to be important determinants of the persistence of innovation (Archibugi et al., 2013).

Finally, our approach exploits patents to measure firms' technological knowledge, which have limitations well known and extensively discussed in previous studies (e.g. Griliches, 1990; Hall et al., 2014; Hussinger, 2006; Pavitt, 1988). However, previous studies highlighted the usefulness of patents as measures of the discovery of new knowledge. In particular, a firm's patent portfolio is a reliable measure of technological knowledge and innovation usable for production, especially as compared to innovation measures based on surveys (Acs et al., 2002).

5.3 Future research

In this study, we do not differentiate intra-organisational vs. inter-organisational MNE networks in the production of technological variety. MNEs might rely primarily on internal

[19] A historical expansion of the firm-level dataset is limited by the fact that the online Orbis version offers ownership data (and other firm level data) for only 9 years backward. The time lag in the registration patent applications (about 3 years) limits a forward expansion much beyond 2018 at the time we conducted our study.

networks between international inventors to create *related variety* but might shift to external networks to diversify towards *unrelated variety*. This aspect might also be important, since organisational research has argued that institutional diversity hampers effective knowledge sharing and negatively affects innovation outcomes of international R&D teams (Brunetta et al., 2020). Differentiating between MNE's inventor teams involving internal and external networks was beyond the scope of this study but could be accomplished empirically by analysing patent citations (Frost, 2001). Future research could also investigate whether the mode of entry helps to explain the diminishing marginal returns from international inventor teams on technological variety, since the cost of coordination and organisational complexity could be higher in case of acquired MNE units vs. greenfield projects.

Finally, future research could question how the presence of international inventor teams moderates the relationship between technological variety and the innovative performance of MNEs. This would integrate previous research in evolutionary economic geography that considers the effect of unrelated and related variety on innovation performance depending on firm location (see for example, Solheim et al., 2020) with research that looks at the effect of foreign knowledge networks on MNEs' radical vs. incremental innovation (see for example, Berry, 2018). While we focused on the 'international' dimension of knowledge sourcing, future research could employ a research design that allows for within-country variation in the international search for technological variety.

Appendix

See. Tables 3, 4, 5, 6, 7, 8, 9 and 10

Table 3 Number of patents and MNEs by country in the sample

Country of HQ	Total number of patents	Total number of MNE	Average number of years per MNE	Average number of yearly patents per MNE	Total number of observations
AT	1,150	12	5.3	18.3	63
BE	719	14	4.7	10.9	66
DE	87,563	141	5.3	116.6	751
DK	737	18	3.8	10.7	69
ES	215	19	2.6	4.4	49
FI	5,857	28	4.9	42.8	137
FR	24,419	48	5.0	101.7	240
GR	28	1	7.0	4.0	7
IE	193	5	4.0	9.7	20
IT	1,622	39	2.7	15.3	106
LU	74	1	5.0	14.8	5
NL	2,921	26	4.3	25.8	113
PT	15	1	5.0	3.0	5
SE	10,175	23	4.3	102.8	99
UK	3,378	78	3.9	11.2	302
Total	139,066	454	4.5	68.4	2,032

Table 4 Inventors team size by country

Country of HQ	Mean number of inventors	% of patents by number of inventors						Mean number of foreign inventors	% of patents by number of foreign inventors						
		1	2	3	4	5	6+		0	1	2	3	4	5	6+
AT	3.07	0.1	41.9	30.6	14.2	8.6	4.6	0.80	63.0	13.5	12.0	6.7	3.3	1.0	0.5
BE	3.42	0.0	25.6	34.6	20.9	13.2	5.7	1.39	51.0	11.5	9.6	14.2	6.1	4.9	2.6
DE	3.59	0.1	30.0	28.3	19.4	11.0	11.3	0.46	81.7	5.7	5.0	3.4	2.3	1.0	0.9
DK	3.21	0.3	37.9	32.2	15.3	6.9	7.5	1.12	51.3	15.3	16.3	10.3	3.4	2.0	1.4
ES	3.58	0.5	31.6	27.0	18.6	8.8	13.5	0.80	62.3	14.0	11.6	7.0	3.7	1.4	0.0
FI	3.59	0.2	27.9	30.2	19.0	11.9	10.8	0.89	63.5	12.5	9.7	7.0	4.2	1.6	1.5
FR	3.24	0.1	35.3	29.8	20.1	8.8	5.8	0.53	78.9	5.1	6.8	5.0	2.4	1.2	0.7
GR	6.07	0.0	0.0	3.6	7.1	25.0	64.3	0.29	92.9	0.0	0.0	0.0	7.1	0.0	0.0
IE	3.18	0.0	40.9	22.3	22.8	8.3	5.7	2.88	4.1	2.1	41.5	22.8	19.2	6.2	4.1
IT	3.00	0.2	41.3	32.7	15.8	6.7	3.3	2.47	14.1	2.5	35.2	28.5	12.7	5.2	1.8
LU	2.41	0.0	62.2	36.5	0.0	1.4	0.0	2.41	0.0	0.0	62.2	36.5	0.0	1.4	0.0
NL	3.32	4.4	30.3	28.6	18.3	9.7	8.8	2.31	24.1	9.2	22.6	21.0	11.7	6.1	5.3
PT	4.67	0.0	20.0	40.0	6.7	20.0	13.3	0.27	86.7	0.0	13.3	0.0	0.0	0.0	0.0
SE	3.40	0.4	27.0	32.6	23.0	10.3	6.7	1.43	39.5	18.4	18.8	13.3	5.8	2.7	1.6
UK	3.29	0.1	35.0	30.6	18.4	9.1	6.9	1.57	44.8	8.9	18.4	13.7	7.1	3.4	3.6
Total	3.49	0.2	31.0	29.1	19.6	10.4	9.6	0.67	73.8	7.1	7.8	5.6	3.2	1.4	1.1

Statistics computed on the sample of patents (N = 139,066)

Table 5 Frequent combinations of MNEs' HQ countries and inventors' countries of residence

MNEs' HQ country	Inventors' country of residence	% of total combinations
Domestic combinations		80.8
Foreign combinations		19.2
Intra-EU15 foreign combinations		12.1
DE	FR	2.8
DE	AT	1.3
FR	DE	1.1
DE	ES	0.7
SE	IT	0.5
IT	FR	0.5
SE	DE	0.5
DE	GB	0.4
GB	DE	0.4
DE	DK	0.3
Other intra-EU15 combinations		3.6
Extra-EU15 foreign combinations		7.1
NL	KR	0.8
DE	US	0.5
DE	KR	0.5
FR	US	0.4
SE	CN	0.3
FI	US	0.3
SE	US	0.3
FI	CN	0.2
SE	KR	0.2
DE	IN	0.2
Other extra-EU15 combinations		3.4

Computed on all combinations of HQ country and foreign inventors' countries (N combinations: 484,908). Domestic combinations: same country for MNEs' HQs and inventors' residence. Foreign combinations: distinct HQ and inventor country

Table 6 Number of inventors, patents and IPC classes by country in the sample

Country of HQ	Share of (MNE-years) observations							
	1 inventors' country of residence	2–5 inventors' countries of residence	6 + inventors' countries of residence	1–5 patents	6–50 patents	51 + patents	1 IPC	with 2 + IPC
	(1)	(2)	(3)	(4)	(5)	(7)	(8)	(9)
AT	28.6	54.0	17.5	41.3	49.2	9.5	15.9	84.1
BE	37.9	51.5	10.6	60.6	36.4	3.0	19.7	80.3
DE	50.2	35.0	14.8	31.4	45.1	23.4	17.7	82.3
DK	33.3	63.8	2.9	52.2	47.8	0.0	24.6	75.4
ES	69.4	30.6	0.0	81.6	18.3	0.0	34.7	65.3
FI	33.6	47.4	19.0	45.3	34.3	20.4	24.8	75.2
FR	37.5	34.2	28.3	37.1	29.6	33.3	17.9	82.1
GR	85.7	14.3	0.0	85.7	14.3	0.0	42.9	57.1
IE	10.0	85.0	5.0	45.0	50.0	5.0	20.0	80.0
IT	63.2	26.4	10.4	78.3	15.0	6.6	53.8	46.2
LU	80.0	20.0	0.0	20.0	80.0	0.0	0.0	100.0
NL	32.7	52.2	15.0	42.5	47.8	9.7	15.9	84.1
PT	60.0	40.0	0.0	100.0	0.0	0.0	20.0	80.0
SE	25.3	37.4	37.4	26.3	46.4	27.3	15.2	84.8
UK	47.7	45.7	6.6	55.6	39.1	5.3	27.8	72.2
Total	44.3	40.4	15.3	43.0	39.6	17.4	22.1	77.9

Statistics computed on the sample of MNE-year observation (N = 2,032)

Table 7 Definition of variables

Variable	Definition
Technological unrelated variety	Unrelated variety, entropy at the IPC section level
Technological related variety	Related variety refers to the weighted sum of IPC subclasses entropy in each IPC section
Presence of international inventor teams (*dummy*)	Dummy variable, where 1 indicates that there is at least one priority application with inventors located in different countries
Nr. of inventors' countries of residence (*breadth*)	Nr. of different inventor countries of residence in total priority patents
Ln(Nr. patents)	log-transformed total number of priority patent applications with full information of patent
Ln(Nr. subsidiaries)	log-transformed total number of subsidiaries (national and international)
Share of foreign subsidiaries	Number of international subsidiaries divided by the total number of subsidiaries
Ln(Intangible assets)	log-transformed value of intangible assets, like patents, copyrights, franchises, goodwill, trademarks, trade names and software of the MNE parent company, a constant is added for the logarithmic form
Ln(Nr. employees)	log-transformed number of employees of the MNE parent company, a constant is added for the logarithmic form
Sectoral unrelated variety	Unrelated variety of production, entropy at the NACE Rev. 2 2-digit
Sectoral related variety	Related variety of production refers to the weighted sum of NACE Rev. 2 4-digits entropy in each NACE Rev. 2 2-digit
Ln(R&D)	log-transformed Research & Development expenses

The variables are constructed pooling together the headquarters and subsidiaries (MNE group) for each year with the exceptions of Ln(Nr. employees), Ln(Intangible assets) and Ln(R&D) that refer to the headquarters only

Table 8 Descriptive statistics

Variable	Mean	Standard deviation			Min	Max
		Overall	Within	Between		
Technological related variety	0.85	0.55	0.23	0.48	0.00	2.66
Technological unrelated variety	0.68	0.47	0.25	0.42	0.00	1.95
Presence of international inventors (Dummy)	0.48	0.50	0.29	0.41	0.00	1.00
Nr. of inventors' countries of residence	3.26	4.03	1.13	3.26	1.00	39.00
Nr. patents	68.72	300.53	62.00	237.53	1.00	4,163.00
Nr. subsidiaries	137.64	243.15	54.30	199.71	1.00	2,064.00
Share of foreign subsidiaries	0.68	0.24	0.08	0.25	0.01	1.00
Intangible assets (in million Euro)	1,750.21	5,531.43	1,343.76	4,403.02	0.04	71,978.10
Number of employees (in thousand people)	20.06	41.22	4.63	34.27	0.05	427.00
Sectoral unrelated variety	1.49	0.51	0.15	0.50	0.00	2.57
Sectoral related variety	1.45	0.65	0.19	0.61	0.00	3.30
R&D (in million Euro)	289.13	792.78	104.46	673.20	0.99	5,191.00

All descriptive statistics are computed on the estimation sample (N = 2,032) but for ln(R&D) whose descriptives have been computed on the sample with valid cases (N = 1,521)

Table 9 Fixed effects full models on MNEs' technological variety

	Related variety				Unrelated variety			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Presence of interinational inventors' teams	0.104***	0.076***	0.066***	0.063***	0.087***	0.067***	0.067***	0.061**
	(0.022)	(0.023)	(0.023)	(0.023)	(0.024)	(0.026)	(0.026)	(0.026)
Nr. of inventors' countries of residence	0.021***	0.046***	0.067***	0.069***	0.014***	0.032***	0.039***	0.042***
	(0.005)	(0.010)	(0.011)	(0.011)	(0.004)	(0.009)	(0.011)	(0.011)
Ln(Nr. patents)	0.033**	0.033**	0.065***	0.061***	− 0.010	− 0.010	0.007	0.002
	(0.014)	(0.014)	(0.015)	(0.016)	(0.012)	(0.012)	(0.014)	(0.016)
Squared Nr. of inventors' countries		− 0.001***		− 0.000		− 0.001***		− 0.001
		(0.000)		(0.000)		(0.000)		(0.000)
Nr. of inventors' countries x Ln(Nr. patents)			− 0.011***	− 0.009***			− 0.006***	− 0.004
			(0.002)	(0.003)			(0.002)	(0.003)
Ln(Nr. subsidiaries)	0.012	0.011	0.010	0.010	− 0.009	− 0.011	− 0.008	− 0.009
	(0.026)	(0.026)	(0.025)	(0.025)	(0.032)	(0.031)	(0.031)	(0.031)
Share of foreign subsidiaries	0.042	0.044	0.053	0.052	− 0.076	− 0.075	− 0.070	− 0.071
	(0.078)	(0.078)	(0.077)	(0.077)	(0.079)	(0.079)	(0.079)	(0.079)
Sectoral unrelated variety					− 0.015	− 0.016	− 0.021	− 0.020
					(0.049)	(0.049)	(0.049)	(0.049)
Sectoral related variety	0.019	0.016	0.027	0.025				
	(0.039)	(0.039)	(0.039)	(0.039)				
Ln(Intangible assets)	0.013	0.010	0.015	0.014	0.019	0.017	0.020	0.018
	(0.014)	(0.014)	(0.014)	(0.014)	(0.017)	(0.017)	(0.017)	(0.017)
Ln(Nr. employees)	0.027	0.031	0.027	0.028	0.007	0.010	0.007	0.009
	(0.024)	(0.024)	(0.025)	(0.025)	(0.036)	(0.036)	(0.036)	(0.036)
MNEs fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of MNEs	454	454	454	454	454	454	454	454
Observations	2,032	2,032	2,032	2,032	2,032	2,032	2,032	2,032

Robust standard errors clustered by MNE group are shown in parentheses. All models also include year dummies. Control variables enter the model with one year lag. *$p<0.10$; **$p<0.05$; ***$p<0.01$

Table 10 Robustness checks—full models on MNEs' technological variety

	Baseline	Fractional counting	MNEs with more than 5 patents	Including R&D expenditures	Excluding DE MNEs	Excluding UK MNEs	Baseline	Fractional counting	MNEs with more than 5 patents	Including R&D expenditures	Excluding DE MNEs	Excluding UK MNEs
	Related variety						Unrelated variety					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Presence of international inventor teams	0.063***	0.063***	0.077***	0.082***	0.052	0.052**	0.061**	0.061**	0.089***	0.062**	0.053*	0.051*
	(0.023)	(0.023)	(0.028)	(0.027)	(0.032)	(0.024)	(0.026)	(0.027)	(0.030)	(0.028)	(0.032)	(0.029)
Nr. of inventors' countries of residence	0.069***	0.068***	0.066***	0.072***	0.090***	0.070***	0.042***	0.042***	0.020*	0.041***	0.059***	0.048***
	(0.011)	(0.011)	(0.012)	(0.011)	(0.015)	(0.012)	(0.011)	(0.011)	(0.011)	(0.012)	(0.015)	(0.012)
Ln(Nr. patents)	0.061***	0.054***	0.151***	0.085***	0.080***	0.052***	0.002	0.003	0.034	0.005	0.006	− 0.002
	(0.016)	(0.017)	(0.027)	(0.021)	(0.023)	(0.016)	(0.016)	(0.016)	(0.026)	(0.018)	(0.020)	(0.018)
Squared Nr. of inventors' countries	− 0.000	− 0.001	0.000	− 0.000	− 0.001	− 0.000	− 0.001	− 0.001	− 0.000	− 0.001	− 0.001	− 0.001
	(0.000)	(0.001)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)
Nr. of inventors' countries x Ln(Nr. patents)	− 0.009***	− 0.008***	− 0.013***	− 0.011***	− 0.012***	− 0.010***	− 0.004	− 0.004	− 0.003	− 0.004	− 0.007**	− 0.004
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.003)
Ln(R&D)				-0.022						-0.019		
				(0.027)						(0.016)		

Table 10 (continued)

	Baseline	Fractional counting	MNEs with more than 5 patents	Including R&D expenditures	Excluding DE MNEs	Excluding UK MNEs	Baseline	Fractional counting	MNEs with more than 5 patents	Including R&D expenditures	Excluding DE MNEs	Excluding UK MNEs
	Related variety						Unrelated variety					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Ln(Nr. subsidiaries)	0.010	0.008	-0.023	-0.029	0.020	0.016	-0.009	-0.012	-0.020	-0.054	-0.038	-0.013
	(0.025)	(0.026)	(0.034)	(0.042)	(0.052)	(0.025)	(0.031)	(0.032)	(0.034)	(0.042)	(0.051)	(0.033)
Share of foreign subsidiaries	0.052		0.057	0.084	− 0.016	0.120	− 0.071	− 0.019	− 0.038	0.092	− 0.093	− 0.048
	(0.077)		(0.105)	(0.151)	(0.157)	(0.081)	(0.079)	(0.049)	(0.099)	(0.149)	(0.175)	(0.081)
Sectoral unrelated variety		0.021					− 0.020		− 0.030	0.008	0.088	− 0.020
		(0.040)					(0.049)		(0.052)	(0.063)	(0.074)	(0.052)
Sectoral related variety	0.025	0.014	− 0.014	0.087*	0.052	− 0.008		0.019				
	(0.039)	(0.015)	(0.052)	(0.050)	(0.058)	(0.040)		(0.017)				
Ln(Intangible assets)	0.014	0.038	0.019	0.018	0.003	0.019	0.018	0.009	− 0.006	0.020	0.017	0.017
	(0.014)	(0.026)	(0.015)	(0.014)	(0.021)	(0.015)	(0.017)	(0.036)	(0.021)	(0.018)	(0.024)	(0.018)
Ln(Nr. employees)	0.028	0.056	0.022	0.027	0.034	0.032	0.009	− 0.062	0.041	0.013	0.005	0.021
	(0.025)	(0.079)	(0.026)	(0.028)	(0.033)	(0.026)	(0.036)	(0.080)	(0.041)	(0.039)	(0.045)	(0.039)
Number of MNEs	454	454	247	315	313	376	454	454	247	315	313	376

Table 10 (continued)

	Baseline	Fractional counting	MNEs with more than 5 patents	Including R&D expenditures	Excluding DE MNEs	Excluding UK MNEs	Baseline	Fractional counting	MNEs with more than 5 patents	Including R&D expenditures	Excluding DE MNEs	Excluding UK MNEs
	Related variety						Unrelated variety					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Observations	2,032	2,032	1,159	1,521	1,281	1,730	2,032	2,032	1,159	1,521	1,281	1,730

Robust standard errors clustered by MNE group. All models also include year dummies. Control variables have one year lag. $^{*}p<0.10$; $^{**}p<0.05$; $^{***}p<0$

Funding Open Access funding enabled and organized by Projekt DEAL.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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