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Information technology and external search in the open innovation age: New findings from Germany

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ABSTRACT

In light of the fact that firms increasingly use information technology (IT) for open innovation initiatives, this paper explores how IT investment influences their external search from multiple perspectives: breadth, and depth along vertical, horizontal and societal dimensions. The basic premise is that IT investment has inverted U-shaped relationships with external search breadth and depth. On the one hand, IT investment enhances firms' ability to acquire more information from external knowledge sources. On the other hand, however, IT investment can bring abundant information from external knowledge sources to firms, making it increasingly difficult to widely and deeply use the information from available sources. Beyond a certain threshold, excessive IT investment is likely to cause information overload, forcing firms with limited attention to narrow down and go less deeply into their external knowledge sources. By using a large-scale panel data set from German firms, we find empirical evidence corroborating our theory.

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1. Introduction

In today's fast-changing markets, knowledge plays a central role in the creation of innovation opportunities and competitive advantage (Grant, 1996; Dong et al., 2017; Dong and Yang, 2016; Messeni Petruzzelli and Savino, 2014; Nonaka, 1994; Nonaka and Takeuchi, 1995; Wang et al., 2016). To overcome the limits of a firm's internal knowledge, external knowledge sources are often needed to complement own cognition and competences (Chesbrough and Crowther, 2006; Nonaka and Takeuchi, 1995; Savino et al., 2017). As a result, open innovation is indisputable to search for external knowledge on global scale (Chesbrough, 2003; Hagedoorn, 2002; Kovács et al., 2015; Martini et al., 2016). In the open innovation research, the concept of external search has been used to address this practice (Laursen and Salter, 2006, 2014).

External search has been examined from different perspectives such as breadth and depth (Katila and Ahuja, 2002; Laursen and Salter, 2006), where external search breadth reflects how widely a firm uses external knowledge sources and external search depth reflects how deeply a firm uses external knowledge sources. Although past research has documented that external search breadth and depth are positively

associated with innovation performance (e.g., Foss et al., 2013; Laursen and Salter, 2006, 2014; Leiponen and Helfat, 2010, 2011; Rosenkopf and Almeida, 2003; Rosenkopf and Nerkar, 2001), prior work has paid little attention to the antecedents of external search breadth and depth. This is an important gap in the search literature. If external search breadth and depth are critical for innovation, it is unclear what firms can do to enhance them. Given the fact that external search has become a common practice across industries, it is of great importance to enrich our understanding about the antecedents of external search breadth and depth.

Firms need to invest considerable amount of resources in search for external knowledge (Laursen and Salter, 2006; Savino et al., 2017). Whether such investment for external search, however, pays off is also unclear in the search literature. Information technology (IT) has been recently found as a key resource input to firms' innovation activity (e.g., Dong and Wu, 2015; Joshi et al., 2010; Kleis et al., 2012; Tambe et al., 2012; Xue et al., 2012). In particular, firms' IT investment has been found to be associated with their absorptive capacity to acquire external knowledge (Dong and Yang, 2015; Joshi et al., 2010; Roberts et al., 2012). For example, firms such as Procter & Gamble (Huston and Sakkab, 2006), Dell and Starbucks (Dong and Wu, 2015), open themselves up to a wide range of external sources of ideas by investing in all kinds of IT resources. While it has been shown that IT investment is critical for innovation performance, how IT investment influences external search – the missing link that generates the innovation

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performance, especially the breadth and depth of external search respectively, is unclear.

This paper aims to fill these gaps by theorizing and empirically examining the nuanced impacts of IT investment on external search breadth and depth. We not only distinguish breadth and depth of external search but also extend our conceptualization of external search depth by considering vertical knowledge sources (suppliers and customers), horizontal knowledge sources (competitors), and societal knowledge sources (consultancies, universities, other research institutions, etc.) respectively, because firms that deeply use one type of external knowledge sources do not necessarily use another type deeply. Since prior literature has revealed that a firm's IT resources are complementary to each other and functional as a whole system (Aral and Weill, 2007), we focus on the overall IT investment rather than the investment in a specific technology.

We draw on the attention-based view of the firm (Ocasio, 1997, 2011; Simon, 1947) to propose that the impacts of IT investment on external search breadth and depth are likely to be of inverted U-shape. On the one hand, IT investment enhances firms' ability to acquire more information from a wider scope of external knowledge sources. On the other hand, however, IT investment can bring abundant information from external knowledge sources to firms, making it increasingly difficult to use information from available sources. Beyond a certain threshold, excessive IT investment is also likely to cause information overload, forcing firms with limited attention to narrow down and go less deeply into their external knowledge sources. We construct a large-scale panel data set from all German industries consisting of 2657 firm-year observations to test our theory. The results provide strong support for the inverted U-shaped relationships between IT investment and external search breadth and depth.

Our study makes several important contributions to the search literature. First, we contribute to the search literature by showing that IT investment is a key driver of external search breadth and depth along multiple dimensions. Thus, scholars should take this into account when conducting research on external search and open innovation and managers should be aware of the fact that too much IT investment can be as bad as too little when investing resources in search. Second, we further contribute important insights on the impacts of IT investment on external search breadth and depth, as IT investment is not the more the better but only beneficial up to a point. Excessive IT investment may do more harm than good by causing information overload, making the breadth and depth of external search decline. Finally, we enrich the empirical evidence in the search literature by utilizing a relatively new data source from Germany, complementing past research based on the data from Belgium (Cassiman and Veugelers, 2002), Denmark (Foss et al., 2013), Finland (Leiponen and Helfat, 2010, 2011), The Netherlands (Poot et al., 2009), the U.K. (Laursen and Salter, 2006, 2014), and the U.S. (Rosenkopf and Almeida, 2003; Rosenkopf and Nerkar, 2001).

The rest of paper is organized as follows. In the next section, we theorize the impacts of IT investment on external search breadth and depth and develop associated hypotheses. We then describe the methods used in this study. Furthermore, the results are presented. Finally, we discuss the theoretical and managerial implications, as well as limitations and directions for future research.

2. Theory and hypotheses

2.1. External search breadth and depth

Open innovation model highlights the interactive nature of firms' innovation process, suggesting that innovative firms rely on their interaction with external parties in the environment (Chesbrough, 2003). It also proposes that the advantages that firms gain from internal R&D will decline as many innovative firms spend little in R&D and succeed in innovation by drawing on knowledge from a wide scope of external

sources. Therefore, a firm's openness to its external environment improves its ability to achieve and sustain innovation. A central move toward open innovation model is a change in the way firms search for new ideas from internal sources to external sources.

Multiple perspectives exist in the search literature. In the open innovation context, a firm needs to search more widely and deeply to leverage external knowledge sources that are critical for its innovation. Accordingly, Laursen and Salter (2006: 134) developed the concepts of *external search breadth* defined as "the number of external sources or search channels that firms rely upon in their innovative activities", and *external search depth* defined as "the extent to which firms draw deeply from the different external sources or search channels". These two concepts jointly represent firms' openness to external environment, with a focus on search channels, such as suppliers, customers, competitors, consultancies, universities and other research institutions, etc., reflecting the variety of channels used by a firm in its external search. Each channel is deemed as a separate search spectrum encompassing distinct norms, habits and rules, requiring different practices to render the search effective (Laursen and Salter, 2006).

We extend this typology of external search by further considering different dimensions of external search depth, which involves distinct interaction with different external parties. Unlike external search breadth simply reflecting the scope of available sources, external search depth can be multi-dimensional. Firms that deeply use one type of external knowledge sources do not necessarily use another type deeply. Following Cassiman and Veugelers (2002) and Poot et al. (2009), we distinguish *vertical*, *horizontal* and *societal* dimensions of external search depth, as vertical knowledge sources include suppliers and customers, horizontal knowledge sources include competitors, and societal knowledge sources include consultancies, universities and other research institutions, etc.

2.2. IT investment and external search breadth

Open innovation model highlights that fact that the network of relationships between a focal firm and its external environment plays an important role in shaping innovation (Laursen and Salter, 2006). IT investment is a key input to building a knowledge network as it allows firms to improve their absorptive capacity to acquire external knowledge (Dong and Yang, 2015; Joshi et al., 2010; Roberts et al., 2012), through, but not limited to, establishing relationships (Rai and Tang, 2010; Rai et al., 2012), improving communication (Barua et al., 2004; Malhotra et al., 2005), and better integration (Rai et al., 2006; Saraf et al., 2007). IT investment also makes a firm in favor of external search as the eased knowledge transfer can substantially lower the information deficiencies (Li et al., 2006) and the possibility of opportunism occurring (Brynjolfsson et al., 1994), thereby enhancing the trust to exchange knowledge between the focal firm and external parties. Firms with greater IT investment are therefore likely to get access to a wider scope of external knowledge sources.

The attention-based view suggests that the firm can be seen as a system that structurally distributes attention (Ocasio, 1997, 2011; Simon, 1947), where attention refers to the ability to process differential sources of information and simultaneously extract information that is useful for certain tasks (Garcia et al., 2000). This view has acknowledged that managerial attention is the most precious resource in the firm (Dong, 2016), and the allocation of attention is a key factor in explaining why some firms can successfully adapt to environmental changes through innovation (Laursen and Salter, 2006). The decision makers in firms, therefore, need to "concentrate their energy, effort and mindfulness on a limited number of issues" (Ocasio, 1997: 203). With increasing external knowledge sources due to IT investment, they are processing more and more information and may find it more and more difficult to handle new external knowledge sources. When IT investment is excessive, they may be even overwhelmed as a result of information overload, and have to narrow their attention down to a smaller number of

external knowledge sources. In this case, the number of external knowledge sources and thereby external search breadth will decrease with “too much” IT investment.

Therefore, we expect that the overall impact of IT investment on external search breadth is positive with a diminishing rate because of extensive information acquisition from available sources due to IT investment. It implies that IT investment initially increases external search breadth, but only up to a certain point, more IT investment will induce a decline in external search breadth. This logic indicates an inverted U-shaped relationship (Haans et al., 2016). Thus, we have the following hypothesis.

H1. IT investment has an inverted U-shaped relationship with external search breadth.

2.3. IT investment and external search depth

Since IT investment allows firms to improve their ability to acquire external knowledge (Dong and Yang, 2015; Joshi et al., 2010; Roberts et al., 2012), it allows firms to use more information from all available (new or existing) external knowledge sources. Firms with greater IT investment are therefore likely to go deep into external knowledge sources. However, the attention-based view suggests that the decision makers in firms may not be capable to process all available information with their limited attention (Dong, 2016; Ocasio, 1997). As in the case of external search breadth, they will be increasingly less capable for processing the abundant information from external knowledge sources due to IT investment. When IT investment is excessive, they may be even overwhelmed as a result of information overload, and have to narrow their attention down to part of, rather than all, information from external knowledge sources. In this case, the number of external knowledge sources and thereby external search depth will decrease with “too much” IT investment.

Therefore, we expect that the overall impact of IT investment on external search depth is positive with a diminishing rate because of extensive information acquisition from available sources due to IT investment. It implies that IT investment initially increases external search depth, but only up to a certain point, more IT investment will induce a decline in external search depth. This logic indicates an inverted U-shaped relationship (Haans et al., 2016). While external search depth may vary across different dimensions (vertical, horizontal, and societal), the impact of IT investment on external search depth is not specific to any of the dimensions and is likely to be true for all the dimensions. Thus, we have the following hypotheses.

H2a. IT investment has an inverted U-shaped relationship with external search depth (vertical).

H2b. IT investment has an inverted U-shaped relationship with external search depth (horizontal).

H2c. IT investment has an inverted U-shaped relationship with external search depth (societal).

3. Methods

3.1. Data

A large-scale panel data set from German firms was constructed based on Mannheim Innovation Panel (MIP) database¹ to test our hypotheses. MIP database was collected by the Center for European Economic Research (ZEW) on behalf of the German Federal Ministry of Education and Research (BMBF). In every year since 1993, a survey is conducted for a representative sample of German firms across all

industries. Usually, the same set of firms is sampled again in the next year to allow a panel structure. On the basis of the innovation capacity index in 2001 (at the time that the data we use in this study were collected), German firms were very innovative comparable to that of Finland, Switzerland, the U.K. and the U.S. (Porter and Stern, 2001). Thus, our findings are likely to be generalizable to other countries with a considerable innovation capacity.

MIP database is the German part of Community Innovation Survey (CIS), which has been carried out in numerous member states of the European Union since 1993. The survey is established through the use of the core methodologies and measures developed by the Organization for Economic Cooperation and Development (OECD). The core methodologies and measures can be found in the Oslo Manual (Eurostat, 2005), which contributes to the reliability of the collection and interpretation of data by providing well-grounded and established guidelines. Besides MIP database, CIS uses the same instruments across countries; the understandability, reliability and validity of the survey questionnaires have been extensively tested through the use of pilot tests in each country (Ziegler and Nogareda, 2009). While MIP database has been used in past research (e.g., Böhringer et al., 2012; Horbach, 2008; Kaiser, 2002; Ziegler and Nogareda, 2009), the portion of data that we use in this study is new and more recent up to 2005.

Our sample was drawn from MIP database with the criteria that the data for IT investment and external search are available. These criteria limit our sample to specific years with the questions about IT expenditure and external knowledge sources. Due to the fact that the question about IT expenditure was included in every two years since 1995 and was totally excluded after 2003, IT investment data are only available for 1995, 1997, 1999, 2001 and 2003. Moreover, the questions about external knowledge sources were surveyed in every four years from 1997 to 2009, making external search data only available for 1997, 2001, 2005 and 2009. Accordingly, we try our best to apply a research design with time lag between IT investment and external search and include firms that participated in the survey over two three-year periods (1999–2001 and 2003–2005). In other words, we use the data for IT investment and other control variables in 1999 and 2003, and link them to the data for external search in 2001 and 2005 respectively. Such time lag between independent and dependent variables can avoid reverse causality and reduce common method bias as the survey respondents could vary across years (Podsakoff et al., 2003). Finally, it results a sample of 2657 firm-year observations with some variables containing missing values.

3.2. Measures

3.2.1. External search breadth

We closely follow prior literature to measure external search breadth. There are ten questions about the knowledge sources that a firm uses for its innovation activity, including one internal source and nine external sources such as 1) suppliers, 2) customers, 3) competitors, 4) commercial research institutions and consultancy firms, 5) universities and educational institutions, 6) public and non-profit research institutions, 7) trade fairs and exhibitions, 8) technical conferences, specialist journals and literature, and 9) professional associations. We follow Laursen and Salter (2006, 2014) and Leiponen and Helfat (2010, 2011) to code these sources in a binary scale as 0 being not use and 1 being use of the given knowledge source. We then simply add the nine external knowledge sources up as the measure for external search breadth. Thus, a firm gets a 0 if no external knowledge source is used and gets up to 9 if all external knowledge sources are used. External search breadth is measured in 2001 and 2005.

3.2.2. External search depth

The questions about knowledge sources also ask the importance of each source for a firm's innovation activity in a 4-point scale (0 = no; 1 = low; 2 = medium; 3 = high). Following Laursen and Salter (2006), we rely on these questions to measure external search depth,

¹ Available on <http://doi.org/10.7806/zew.mip.2013.v1.suf>.

as the external knowledge sources that are important for a firm's innovation activity are often deeply used by the firm. Similar to Cassiman and Veugelers (2002) and Poot et al. (2009), we distinguish external search depth along three dimensions: vertical, horizontal and societal. External search depth (vertical) is measured by a composite score as the average importance of external knowledge from 1) suppliers and 2) customers (Cronbach's alpha: 0.776); external search depth (horizontal) is measured by the importance of external knowledge from competitors; external search depth (societal) is measured by a composite score as the average importance of external knowledge from the rest of sources, including 1) commercial research institutions and consultancy firms, 2) universities and educational institutions, 3) public and non-profit research institutions, 4) trade fairs and exhibitions, 5) technical conferences, specialist journals and literature, and 6) professional associations (Cronbach's alpha: 0.830). Thus, a firm gets a 0 if a specific type of external knowledge sources is not important for its innovation activity and gets up to 4 if it is important. External search depth is measured in 2001 and 2005.

3.2.3. IT investment

We also follow prior literature to measure IT investment, as a firm's total expenditure in IT hardware, software, services and labor scaled by its total sales (Bardhan et al., 2013; Han and Mithas, 2013; Mithas et al., 2012; Mithas et al., 2013). While specific technologies that a firm invests in may vary in their purposes,² IT resources are often complementary to each other and functional as a whole system (Aral and Weill, 2007). In particular, IT infrastructure (e.g., networks and computers) that provides the shared basic functions for all IT applications (e.g., software) is highly correlated with the overall IT investment (Hitt and Brynjolfsson, 1996). Following past research (e.g., Bardhan et al., 2013; Dong and Yang, 2015; Kleis et al., 2012; Xue et al., 2012), we focus on the overall IT investment rather than the investment in a specific technology to facilitate the knowledge accumulation and comparison with prior findings. Looking at specific technology might miss the holistic picture and generate misleading conclusion, because it is only useful when other technologies are present due to the overall IT investment. IT investment is measured in 1999 and 2003.

3.2.4. Control variables

We control several factors that might influence external search breadth and depth, which are all measured in 1999 and 2003. First, R&D intensity represents a firm's reliance on internal knowledge source (Laursen and Salter, 2006) and its effort to develop absorptive capacity (Cohen and Levinthal, 1990). We control *R&D investment* as a firm's R&D expenditure scaled by its total sales (Shimizutani and Todo, 2008). Second, we control *firm size* by the natural logarithm of the number of employees, which may influence a firm's resource availability for innovation activity (Laursen and Salter, 2006). Third, we control *firm age* by a binary variable indicating whether a firm is a new startup established within 3 years or more mature (0 = >3 years; 1 = within 3 years), as they may act differently in strategic choices for innovation (Laursen and Salter, 2006). Fourth, we control a firm's *geographic location* in West or East Germany (0 = West; 1 = East) to account for region-specific impact due to historical and economic differences in Germany (Van de Vrande et al., 2011). Finally, we include an *industry dummy* to indicate whether a firm belongs to manufacturing or service industry (0 = service; 1 = manufacturing) to control for sectoral differences (Kaiser, 2002), and a *year dummy* indicating the data were collected in the first or the second period (0 = 1999–2001; 1 = 2003–2005) to control for temporal differences (Dong and Yang, 2016). Table 1 provides a summary of our measures, and Table 2 presents the descriptive statistics and correlations of our variables.

4. Results

4.1. Hypotheses testing

Since our dependent variables take non-negative integer values, a negative binominal model in the case of overdispersion and a Poisson model in the case of underdispersion might be seen as a justifiable choice. However, our scales of dependent variables are restricted by an upper bound of 9 or 3, which are therefore closer to a Likert scale rather than a count scale, making a negative binomial or Poisson model not appropriate to use (Laursen and Salter, 2014). Instead, a linear model is often seen as a more robust solution in our case when the residuals meet the assumption that they are normally distributed. We conducted a quantile-quantile plot, which confirmed the normality of distribution (Bai and Ng, 2005).

To fit a linear model to panel data, fixed effects or random effects are often preferable because the ability to control for time-invariant unobservable characteristics and mitigate endogeneity (Greene, 2000). We conducted a Hausman test and found that the estimates are not systematically different between fixed effects and random effects models ($p > 0.1$), suggesting the choice of random effects model because it is more efficient than fixed effects model that is costly in terms of degrees of freedom lost (Greene, 2000: 576). Thus, we use generalized least squares (GLS) regression to estimate a random effects model in hypotheses testing. To test an inverted U-shaped relationship, we follow the guidance of Aiken and West (1991: 63) and Haans et al. (2016: 1181) to add a quadratic form of IT investment to the regression.

Table 3 presents the regression results for external search breadth. We first estimated a control model, and then added IT investment into the model, and finally further added the squared IT investment into the model. We found that R&D investment was positively associated with external search breadth, which might be explained by the fact that firms with greater R&D investment have stronger absorptive capacity to acquire external knowledge from a variety of sources. We also found that larger and younger firms had higher external search breadth, which might be due to their resource richness and intrinsic needs of external knowledge. Furthermore, firms in manufacturing industries demonstrated higher external search breadth, and firms' reliance on a variety of external knowledge sources increases over time consistent with the open innovation trend.

After adding IT investment into the control model, we did not observe any statistically significant effect. It suggests that the relationship between IT investment and external search breadth is not linear. In the full model with both IT investment and squared IT investment, however, we found that IT investment had a statistically significant and positive effect on external search breadth whereas squared IT investment had a statistically significant and negative effect on external search breadth. These results jointly suggest an inverted U-shaped relationship between IT investment and external search breadth. Thus, H1 was supported.

Table 4 presents the regression results for external search depth (vertical). R&D investment and larger size were found to lead to deeper use of vertical knowledge sources. Firms use vertical knowledge sources more deeply in manufacturing industries and in recent years. We again found that IT investment alone did not have statistically significant effect on external search depth (vertical). In the full model, IT investment had a statistically significant and positive effect on external search depth (vertical) whereas squared IT investment had a statistically significant and negative effect on external search depth (vertical). These results jointly suggest an inverted U-shaped relationship between IT investment and external search depth (vertical). Thus, H2a was supported.

Table 5 presents the regression results for external search depth (horizontal). Control variables had similar effects comparable to the case of external search depth (vertical). We still found that IT investment alone did not have statistically significant effect on external search depth (horizontal). In the full model, IT investment had a statistically significant and positive effect on external search depth (horizontal).

² We thank one anonymous reviewer who suggested this point.

Table 1
Summary of measures.

Variable	Description	Scale	References
External search breadth	The number of distinct external knowledge sources: 1) suppliers, 2) customers, 3) competitors, 4) commercial research institutions and consultancy firms, 5) universities and educational institutions, 6) public and non-profit research institutions, 7) trade fairs and exhibitions, 8) technical conferences, specialist journals and literature, and 9) professional associations	0–9	Foss et al. (2013), Laursen and Salter (2006), Leiponen and Helfat (2010)
External search depth (vertical)	The average importance of external knowledge from 1) suppliers and 2) customers	0 = no; 1 = low; 2 = medium; 3 = high	Laursen and Salter (2006), Leiponen and Helfat (2010), Poot et al. (2009)
External search depth (horizontal)	The importance of external knowledge from competitors	0 = no; 1 = low; 2 = medium; 3 = high	Laursen and Salter (2006), Leiponen and Helfat (2010), Poot et al. (2009)
External search depth (societal)	The average importance of external knowledge from 1) commercial research institutions and consultancy firms, 2) universities and educational institutions, 3) public and non-profit research institutions, 4) trade fairs and exhibitions, 5) technical conferences, specialist journals and literature, and 6) professional associations	0 = no; 1 = low; 2 = medium; 3 = high	Laursen and Salter (2006), Leiponen and Helfat (2010), Poot et al. (2009)
IT	IT expenditure in hardware, software, services and labor scaled by total sales	Ratio	Bardhan et al. (2013), Han and Mithas (2013)
R&D	R&D expenditure scaled by total sales	Ratio	Shimizutani and Todo (2008)
Size	The natural logarithm of the number of employees	Continuous	Laursen and Salter (2006)
Age	Whether a firm was established in <3 years	0 = no; 1 = yes	Laursen and Salter (2006)
Location	Whether a firm locates in East Germany or West Germany	0 = West; 1 = East	Van de Vrande et al. (2011)
Industry dummy	Whether a firm belongs to manufacturing or service industries	0 = service; 1 = manufacturing	Kaiser (2002)
Year dummy	The data were collected in the first or the second period	0 = 1999–2001; 1 = 2003–2005	Dong and Yang (2016)

whereas squared IT investment had a statistically significant and negative effect on external search depth (horizontal). These results jointly suggest an inverted U-shaped relationship between IT investment and external search depth (horizontal). Thus, H2b was supported.

Table 6 presents the regression results for external search depth (societal). The effects of control variables remained similar, except that firms in East Germany were found to use societal knowledge sources more deeply than firms in West Germany. We again found that IT investment alone did not have statistically significant effect on external search depth (societal). In the full model, IT investment had a statistically significant and positive effect on external search depth (societal) whereas squared IT investment had a statistically significant and negative effect on external search depth (societal). These results jointly suggest an inverted U-shaped relationship between IT investment and external search depth (societal). Thus, H2c was also supported.

In Fig. 1, we plot the relationships between IT investment and external search breadth and depth based on regression results. The plot shows that with increasing IT investment, both external search breadth and depth increase first and then decrease after certain points. Furthermore, the turning points of these curves all locate within the data range of IT investment. Taken together, our results meet the three criteria of testing an inverted U-shaped relationship in Lind and Mehlum (2010): 1) the quadratic form is significantly smaller than zero; 2) the slope is sufficiently steep at both ends of the data range; and 3) the turning point locates within the data range. Thus, we conclude that all our hypotheses are strongly supported by the data.

4.2. Robustness checks

We conducted several robustness checks. Since firms' IT investment is endogenously determined, we used instrumental variable to address the endogeneity. Because random effects model with time lag has been used in hypotheses testing, our results are not likely to be driven by reverse causality or time-invariant unobservable characteristics. However, the results are still likely to be not consistent if the omitted variables simultaneously influencing IT investment and external search breadth and depth are variant over time. For example, the changing strategic choices made by managers may simultaneously determine the level of firms' IT investment and the use of external knowledge sources.

To address this issue, we followed prior literature and selected the average IT investment in an industry as the instrumental variable (Kleis et al., 2012). A firm's IT investment has been found to be strongly influenced by the industry norm (Mithas et al., 2013; Salge et al., 2015), while other firms' IT investment should not directly affect the focal firm's external search breadth and depth. We calculated the average IT investment for each firm's industry by summing up all other firms' IT investment in the same industry and then dividing it by the number of other firms in the industry. Following Bound et al. (1995), we tested the validity of our instrument and found that it was significantly correlated with IT investment ($p < 0.05$) but not with external search breadth and depth ($p > 0.1$). We then used two-stage least squares (2SLS) regression with instrumental variable to test our hypotheses again. Consistent with our findings, the fitted values of IT investment were

Table 2
Descriptive statistics and correlations.

	Obs.	Mean	SD	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) External search breadth	2136	3.65	3.38								
(2) External search depth (vertical)	2002	1.02	1.04	0.85							
(3) External search depth (horizontal)	2095	0.95	1.05	0.74	0.69						
(4) External search depth (societal)	2053	0.58	0.64	0.91	0.71	0.67					
(5) IT	1994	0.02	0.08	−0.04	−0.02	−0.01	−0.02				
(6) R&D	2116	0.02	0.04	0.37	0.31	0.26	0.38	0.03			
(7) Size	2226	3.63	1.51	0.21	0.19	0.18	0.18	−0.10	−0.06		
(8) Age	2205	0.04	0.19	0.06	0.05	0.06	0.07	0.04	0.13	−0.06	
(9) Location	2226	0.43	0.50	−0.03	−0.07	−0.04	0.02	−0.01	0.03	−0.12	−0.02

Note: Correlations in bold are significant with $p < 0.05$.

Table 3
Random effects GLS regression results for external search breadth.

	(1)	(2)	(3)
IT		−0.314 (0.967)	17.197*** (3.629)
IT ²			−24.490*** (4.895)
R&D	27.394*** (1.793)	27.305*** (1.848)	25.310*** (1.878)
Size	0.474*** (0.045)	0.465*** (0.049)	0.479*** (0.049)
Age	0.708** (0.360)	0.657* (0.398)	0.574 (0.395)
Location	0.005 (0.135)	0.027 (0.145)	0.039 (0.144)
Industry dummy	0.664*** (0.170)	0.652*** (0.174)	0.759*** (0.175)
Year dummy	1.436*** (0.155)	1.458*** (0.170)	1.456*** (0.243)
Constant	0.363* (0.208)	0.390 (0.240)	0.156 (0.243)
Within R ²	0.068	0.094	0.082
Between R ²	0.270	0.249	0.261
Wald chi-square	684.860***	567.160***	600.320***
n	2016	1816	1816

Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$. Standard errors are in parentheses. Dependent variable is external search breadth.

Table 4
Random effects GLS regression results for external search depth (vertical).

	(1)	(2)	(3)
IT		−0.192*** (0.311)	5.121*** (1.155)
IT ²			−7.464*** (1.563)
R&D	6.173*** (0.576)	6.058*** (0.596)	5.427*** (0.607)
Size	0.117*** (0.014)	0.109*** (0.016)	0.113*** (0.016)
Age	0.149 (0.119)	0.146 (0.130)	0.121 (0.129)
Location	−0.060 (0.043)	−0.058 (0.046)	−0.054 (0.046)
Industry dummy	0.291*** (0.053)	0.293*** (0.055)	0.326*** (0.055)
Year dummy	0.543*** (0.050)	0.543*** (0.055)	0.541*** (0.054)
Constant	0.065 (0.067)	0.101 (0.077)	0.030 (0.078)
Within R ²	0.116	0.107	0.108
Between R ²	0.255	0.227	0.238
Wald chi-square	612.560***	484.270***	513.920***
n	1894	1719	1719

Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$. Standard errors are in parentheses. Dependent variable is external search depth (vertical).

significant and positive and the squared fitted values of IT investment were significant and negative, for both external search breadth and depth. Thus, endogeneity is not a concern.

Using the quadratic term in a linear model to test an inverted U-shaped relationship is one of the possible approaches. Lind and Mehlum (2010) proposed another method – appropriate test for examining whether the slope of an inverted U-shaped relationship is increasing at low values and decreasing at high values within the data range. While our plot has shown this is the case, we followed Lind and Mehlum (2010) to formally test it in the appropriate test.³ The results

of this test are very much in line with our findings, showing that the relationships between IT investment and both external search breadth and depth are of inverted U-shape ($p < 0.01$). Therefore, we conclude that our results are robust.

5. Discussion and conclusion

5.1. Implications for theory and practice

In this study, we theorize and empirically examine the impacts of IT investment on external search breadth and depth. By doing so, our study provides several important theoretical implications to the

³ This can be estimated in Stata by using the “utest” command.

Table 5
Random effects GLS regression results for external search depth (horizontal).

	(1)	(2)	(3)
IT		0.173 (0.321)	4.325*** (1.220)
IT ²			− 5.799*** (1.644)
R&D	6.557*** (0.622)	6.531*** (0.627)	6.060*** (0.639)
Size	0.123*** (0.015)	0.122*** (0.016)	0.126*** (0.016)
Age	0.306** (0.122)	0.163 (0.132)	0.142 (0.132)
Location	− 0.046 (0.046)	− 0.034 (0.049)	− 0.032 (0.049)
Industry dummy	0.206*** (0.058)	0.203*** (0.058)	0.228*** (0.058)
Year dummy	0.084 (0.053)	0.098* (0.057)	0.098* (0.057)
Constant	0.290*** (0.071)	0.279*** (0.080)	0.224*** (0.081)
Within R ²	0.013	0.001	0.000
Between R ²	0.121	0.121	0.129
Wald chi-square	260.910***	231.090***	245.010***
n	1980	1784	1784

Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$. Standard errors are in parentheses. Dependent variable is external search depth (horizontal).

search literature. First, we contribute to the search literature by showing that IT investment is an important enabler of external search. Although past research has shown that external search breadth and depth are positively associated with innovation performance (Laursen and Salter, 2006, 2014; Leiponen and Helfat, 2010, 2011), none of prior work has documented the antecedents of external search. To our best knowledge, our study is the first to explore the antecedents of external search breadth and depth. We find that firms' IT investment supports their open innovation initiatives through broadening the breadth and deepening the depth of external search.

Second, we contribute a new understanding about the nuanced impacts of IT investment on external search, as IT investment is not the more the better but only beneficial up to a point. We draw on and extend the attention-based view of the firm (Ocasio, 1997,

2011; Simon, 1947) to the open innovation context to explain the downside of excessive IT investment. Although prior research has revealed that more IT investment is beneficial for innovation (e.g., Dong and Yang, 2015; Joshi et al., 2010; Kleis et al., 2012; Tambe et al., 2012; Xue et al., 2012), we show that excessive IT investment may do more harm than good by causing attention problems, making the breadth and depth of external search decline. Our findings depart from prior work by reminding the danger of oversimplifying the role of IT in open innovation, which may be a double-edged sword to facilitate external search on the one hand and hinder external search on the other as too much IT investment is as bad as too little.

Finally, we enrich the empirical evidence in the search literature by utilizing a relatively new data source from Germany, complementing past research based on the data from Belgium (Cassiman and Veugelers, 2002), Denmark (Foss et al., 2013), Finland (Leiponen and

Table 6
Random effects GLS regression results for external search depth (societal).

	(1)	(2)	(3)
IT		− 0.160 (0.198)	2.324*** (0.723)
IT ²			− 3.478*** (0.974)
R&D	5.851*** (0.358)	5.860*** (0.369)	5.574*** (0.376)
Size	0.082*** (0.009)	0.080*** (0.010)	0.082*** (0.010)
Age	0.139* (0.072)	0.129* (0.079)	0.118 (0.078)
Location	0.045* (0.027)	0.050* (0.029)	0.052* (0.029)
Industry dummy	0.081** (0.033)	0.077** (0.034)	0.092*** (0.034)
Year dummy	0.181*** (0.031)	0.186*** (0.034)	0.185*** (0.034)
Constant	0.024 (0.041)	0.032 (0.047)	− 0.001 (0.048)
Within R ²	0.022	0.056	0.049
Between R ²	0.231	0.216	0.223
Wald Chi-square	533.070***	455.600***	471.640***
n	1943	1752	1752

Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$. Standard errors are in parentheses. Dependent variable is external search depth (societal).

Fig. 1. The relationships between IT investment and external search breadth and depth.

Helfat, 2010, 2011), The Netherlands (Poot et al., 2009), the U.K. (Laursen and Salter, 2006, 2014), and the U.S. (Rosenkopf and Almeida, 2003; Rosenkopf and Nerkar, 2001). While German data have been used in past research, the portion of data that we use in this study is new and recent.

Our study also has several managerial implications to guide managers' decisions to invest in search. When firms want to complement their own knowledge with external knowledge sources through open innovation initiatives, they could invest in IT. However, IT investment is not the more the better and if firms invest too heavily in IT, they will suffer from attention problems limiting their use of more external knowledge sources. Similarly, firms can invest in IT to more deeply use external knowledge from suppliers and customers, competitors, or consultancies, universities and other research institutions, etc. Again, it is not the more the better because too much IT investment may make firms overwhelmed by "big data". Managers may take a stepwise approach with trial and error to figure out the optimal level of investment.

5.2. Limitations and future research

This study has some limitations. First, we follow prior literature and focus on the overall IT investment in this study (Bardhan et al., 2013; Dong and Yang, 2015; Kleis et al., 2012; Xue et al., 2012). This measure, however, provides a whole picture of IT resources that a firm owns rather than focusing on specific technologies. As an initial step, we have shown that firms' overall IT investment is important for broadening and deepening their external search. Future research may use granular IT measures for specific technologies that are relevant to external search — such as social media technologies (e.g., Dong and Wu, 2015) — to replicate our results.

Second, we follow prior literature and use the number of external knowledge sources and the importance of these sources to measure external search breadth and depth (Foss et al., 2013; Laursen and Salter, 2006, 2014; Leiponen and Helfat, 2010, 2011), which are however less discriminant. While prior study has revealed that external search breadth and depth often highly covary with each other (Laursen and Salter, 2006), future research may refine our measures by capturing external search breadth and depth respectively and replicate our study.

Third, our findings are derived from a large-scale panel data set collected in Germany. While these findings are not specific to the German

context, this context may not be comparable to a less innovative country. Thus, it should be cautious when generalizing our findings to other national contexts. Future research could collect data from developing countries and examine the findings of this study.

Last but not least, we try our best to leverage our data source under a longitudinal design over two recent periods (1999–2001 and 2003–2005). While our data are relatively recent up to 2005, digital technologies and innovation landscape may change rapidly in the past decade. Thus, it is important incorporate newer data in further research, which is an avenue for researchers to build upon our study.

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