A SEAT AT THE TABLE: VENTURE CAPITAL AND TECHNOLOGY SPILLOVERS

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ABSTRACT

The influence that venture capital (VC) directors have on technology spillover is examined with respect to VC-backed firms in the semiconductor industry. Despite a plethora of research into technology spillovers, we still do not have a clear understanding of how VC directors affect the technological outcomes of a firm's innovation efforts. Examined in the context of semiconductor firms between 1980-2005, my findings highlight the pivotal role that VC directors play in augmenting a firm's ambidexterity. This research contributes new insights into the mechanisms by which VC directors introduce external knowledge that augments a firm's spillovers into new technological domains and has important implications for entrepreneurs and their search strategies.

INTRODUCTION

According to research firm Gartner, in 2017, the value of the global semiconductor industry was estimated at $419 billion (Gartner, 2018). The semiconductor industry is characterized by rapid technological change and short product life cycles. Instrumental in the growth of the semiconductor industry was venture capital. Venture capital financing has been an indispensable part of the semiconductor industry since its inception, backing many notable semiconductor firms including Advanced Micro Devices (AMD), Broadcom, and Intel.

Technology spillovers occur when a technology within a particular domain surpasses its technological boundaries and "spills over" into other domains where it may then influence the technological trajectory of those other domains. The extant literature has examined technology spillovers from multiple perspectives, including innovation (Nemet & Johnson, 2012; Operti & Carnabuci, 2014), universities (Rosell & Agrawal, 2009), boundary spanning (Rosenkopf & Nerkar, 2001), clusters (Gilbert, McDougall, & Audretsch, 2008), and foreign investment (Gu & Lu, 2011). Furthermore, research into the mechanisms by which this knowledge is transferred have focused on direct transfer from one party to another (e.g., sharing knowledge), workforce mobility (Almeida & Kogut, 1999), or public domain disclosure (e.g., patents).

Despite extensive research into knowledge spillovers, we still lack a clear understanding of how the presence of a VC director on the board affects the technological outcomes of a firm's innovation efforts. Much of the extant literature is primarily concerned with directors' demography, human capital, and social capital (Johnson, Schnatterly, & Hill, 2013). These studies rarely draw a distinction between executives of other companies who serve as directors and VC investors who also serve as directors. There are distinct differences, however, between these two types of directors, which affects a firm's technology spillovers. Hence, it is important to develop a better understanding of the role that VC directors play in the evolution and diffusion of technologies and the unique mechanisms by which this is done. Therefore, for venture capital-backed firms, how do VC directors influence a firm's technology spillovers?

This study examines the effect of having a VC on the board and their effect on a firm's technology spillovers. This study contributes to the extant literature in several ways. First, this study expands our understanding of how VC directors augment a firm's search for external knowledge and how this affects a firm's technology spillovers. Furthermore, this study sheds new light onto the mechanisms by which VCs promulgate a firm's technology spillovers. This study is also the first to examine the moderating role of financing stage on technology spillovers. This study highlights the pivotal role that VC directors play in augmenting a firm's ambidexterity and has important implications for entrepreneurs' search strategies.

LITERATURE REVIEW

Patents and Technology Spillovers

Patents provide firms with a competitive advantage. Investors also see patents as a signal that the firm employs high-quality technical talent who can create new patentable innovations in the future (Stuart, Hoang, & Hybels, 1999; Hsu & Ziedonis, 2008). Prior studies have shown that patents that are cited more frequently (i.e., forward citations) have greater technological and economic importance (Hall, Jaffe, & Trajtenberg, 2001; Trajtenberg, 1990). Forward citations represent the descendants of a focal technology and are also commonly used to measure knowledge flows (Jaffe & Rassenfosse, 2017). If a focal patent is cited by patents within the same technological field, it has spurred the development of new technologies proximate to its domain and there is little technology spillover. However, if a focal patent is cited by patents from different technological fields, then it has spurred the development of new technologies in unrelated domains, so there is greater technology spillover. Patented technologies that spill over into adjacent or distant domains tend to be cited more frequently.

Patent law grants inventors the right to exclude someone else from making, using, selling, offering for sale, or importing the invention for a limited time in exchange for public disclosure of the invention. Once in the public domain, however, the originating firm's invention can be viewed by anyone (i.e., a recipient). While patent laws are intended to prevent recipients from exploiting the disclosed invention, in many cases, the recipient firm combines this knowledge with their own idiosyncratic knowledge (Sorenson, Rivkin, & Fleming, 2006) or with external knowledge to create new technologies and, thereby, exploit the spillover. In each case, the recipient firm benefits from the sweat equity of the originating firm without having incurred the costs of developing that knowledge on their own. Hence, technology spillovers result from an originating firm's inability to effectively employ protection mechanisms and a recipient firm's ability to act on that external knowledge (Griliches, 1992).

Search

Innovation is a process of finding solutions to complex and challenging problems via search (Dosi, 1988). As the fundamental mechanism that drives the evolution of knowledge, path-dependent exploration that involves search is what differentiates those firms who can innovate consistently from those who do not (Rosenkopf & Nerkar, 2001). Rosenkopf and Nerkar (2001) identified four categories of exploratory search: local, internal boundary spanning, external boundary spanning, and radical. Local search is the process by which firms search for solutions within the neighborhood of its current knowledge or expertise (March & Simon, 1958; Nelson & Winter, 1982; Stuart & Podolny, 1996). By focusing on local search, firms build their expertise in a particular technological domain, which increases the likelihood of successful technology development in that area (Stuart & Podolny, 1996), but often at the expense of producing only incremental innovations (Rosenkopf & Nerkar, 2001).

Firms that focus on exploratory search alone risk expending resources on ongoing search and experimentation without realizing any returns (Leonard-Barton, 1992). Conversely, firms that focus on exploiting closely related technologies are more likely to develop core rigidities (Leonard-Barton, 1992) and fall into competency traps (Levinthal & March, 1993) because of their reliance on internally developed technologies (Rosenkopf & Nerkar, 2001). To avoid these pitfalls, firms need to either create new knowledge or assimilate external knowledge from distant technological domains (e.g., alliances). Barringer and Harrison (2000) find that participating in alliances offers firms an opportunity to improve their centrality within their network of relationships, thereby enhancing organization learning and sharing of heterogeneous knowledge.

Ambidexterity

Whereas exploration involves the creation of new technologies from new knowledge sources, either internal or external to the firm, exploitation is the creation of new technologies from existing knowledge stocks (March, 1991). The degree to which a firm can pursue both exploration and exploitation activities concurrently is its level of ambidexterity. The extant literature highlights how organizational ambidexterity has a positive impact on firm performance (Cao, Gedajlovic, & Zhang, 2009) and allows firms to address uncertainty (Gibson & Birkinshaw, 2004).

Both exploration and exploitation activities compete for resources, which can induce organizational tensions that reduce the effectiveness of ambidexterity (Stettner & Lavie, 2014). While the payoff for engaging in exploration is distant and unknown, the payoff for exploitation is proximate and easier to forecast (Lewin, Long, & Carroll, 1999). As a result, firms must decide how best to allocate their scare resources given the stage of development (Barringer & Harrison, 2000; Levinthal & March, 1993; March 1991). But striking the right balance between exploration and exploitation can be difficult (Benner & Tushman, 2003). Due to a scarcity of resources, firms often opt for the relative certainty of exploitation, which only reduces incentives for engaging in exploration activities in the future (Christensen & Bower, 1996).

External Directors and Search

Depending upon the stage and size of the investment, a VC may take a seat on the board even though they're not a majority shareholder (Pahnke, Katila, & Eisenhardt, 2015). A seat on the board also allows VC directors to exercise greater influence over technical, product development, and strategy decisions (Pahnke et al., 2015). In addition to their human and social capital, VC directors serve in a boundary spanning capacity (Sapienza, 1992). Boundary spanning is an exploratory process of establishing linkages between a firm's internal networks and external sources of knowledge (Tushman, 1977). Thus, by facilitating the spanning of both organizational and technological boundaries, VC directors link the firm's internal knowledge networks with external sources of information in a meaningful way. As a result, VC directors not only serve as conduits for the diffusion of idiosyncratic external knowledge, but also augment a firm's search strategies, enhance organizational learning, and provide access to more diverse networks such that technology spillovers are increased. Therefore, I hypothesize:

H1: Firms with a VC director on the board will exhibit increased technology spillover.

Interlocking Directorships

Venture capitalists may hold more than one board appointment (Palmer, Jennings, & Zhou, 1993). Known as interlocking directorships, these VCs bring a wealth of experience and idiosyncratic knowledge to the firm (Haunschild, 1993). Multiple board appointments can enhance a firm's innovation and organizational learning (Barringer & Harrison, 2000; Haunschild, 1993). In addition to serving as conduits that enhance the exchange of knowledge between firms, the heightened status associated with these interlocking VCs provides a signal that enables them to exert greater influence over strategic decisions, such as whether to engage in acquisitions (Haunschild, 1993), form alliances/joint ventures (Gulati & Westphal, 1999), and adopt new processes (Shropshire, 2010). This heightened status also draws more attention to the focal firm from other firms, which increases technology spillovers. Therefore, I hypothesize:

H2: Firms with an interlocking VC director on the board will exhibit increased technology spillover.

Cross-Pollination

As an industry characterized by rapid technological change, semiconductor firms rely on external knowledge to build new competencies (Teece, Pisano, & Shuen, 1997). As a result of their unique knowledge and positioning, VCs are more likely to recognize when the technology of a focal firm may complement the technology of a portfolio firm. With a portfolio of companies under management, VCs can influence technology spillovers via cross-pollination with other firms within their portfolios (Lee & Pollock, 2007). Gonzalez-Uribe (2014) finds that following a VC financing event, the number of citations that a patented technology receives from other companies within the VC's portfolio actually increases, which affects the technology's spillover. Cross-pollination contributes to the diffusion of technologies among firms within and adjacent to the semiconductor industry in addition to bridging knowledge gaps and spanning technological boundaries. Therefore, I hypothesize:

H3: Firms will generate greater technology spillover if a VC director cross-pollinates the focal firm's technologies among its portfolio companies.

VC Prominence

Venture capitalists develop an intricate network of relationships by participating in syndicates (Hochberg, Ljungqvist, & Lu, 2007). The better quality these network relationships are, the better the performance of the VC firm and the greater the influence they have over other VC firms (Hochberg et al., 2007). The more central a VC is within its network, the greater its prominence among its peers (Hochberg et al., 2007). As the venture capital "elite," high-prominence VCs have greater experience, access to resources, and idiosyncratic knowledge. Occupying a pivotal position within their networks, high-prominence VCs promote greater diffusion of knowledge across geographical and industrial boundaries, which results in increased technology spillovers. This forms the basis for the following hypothesis:

H4: Firms with a prominent VC director on the board will exhibit increased technology spillover.

Financing Stage Moderator

VC investments into start-ups are allocated over the course of a series of staged financing rounds (Stuart et al., 1999). Although the amount of VC financing tends to be less during the seed and early financing stages, prototyping and experimentation are the norm as new knowledge is discovered and applied to the development of products with unknown demand. VC directors support exploratory search by providing entrepreneurs with access to not only their personal idiosyncratic knowledge, but also the external knowledge embedded in their networks, which results in greater technology spillovers. Since technologies developed in the seed and early financing stages tend to be more innovative, they also tend to be cited more frequently and from more diverse technological domains, which results in greater technology spillover.

In the later stages, greater amounts of financing are typically available. During this period, exploitation dominates as firms try to get the most mileage out of the knowledge stocks they've accumulated, which manifests itself as incremental improvements to the firm's existing technologies. In the later stages, firms tend to strategically patent incremental improvements in order to expand the area of protection around a focal technology, but these are also typically cited less frequently and tend to be within the same technological domain, which results in less technology spillover.

In addition to variations in financing amount and patenting across stages, there are also variations in the quantity and quality of VC investors across stages. Over time, additional VCs may co-invest in the firm and, depending on how much capital they invest, may require a seat on the board. As more VC directors come on board, the number of board interlocks is expected to increase across stages. Furthermore, these additional VC directors manage portfolios of investments, which increases the opportunity for cross-pollination among these portfolio companies across stages. Due to uncertainties associated with investing in start-up firms, high-prominence VCs may be reluctant to make earlier stage investments, but may come in on later financing rounds. Hence, there is variation in the signaling strength of VC directors across stages, which affects an entrepreneur's access to VC networks, capital, and pool of idiosyncratic knowledge. Combined, these arguments suggest that we should expect to see differences in technology spillover across financing stages and form the basis for the following hypotheses:

H5a: A firm's financing stage positively moderates the relationship between having an interlocking VC director on the board and technology spillover.

H5b: A firm's financing stage positively moderates the relationship between having a VC director cross-pollinate the focal firm's technologies among its portfolio companies and technology spillover.

H5c: A firm's financing stage positively moderates the relationship between having a prominent VC director on the board and technology spillover.

METHODS

Sample & Data Sources

I test my hypotheses using a data set consisting of 275 VC-backed semiconductor firms founded between 1980-2005. Focusing on one specific industry allows for industry-specific patenting characteristics to be controlled. Venture capital investment and executive data was obtained from the VentureXpert database. This data was augmented with company profile, board composition, and director information obtained from the U.S. Securities and Exchange Commission 10-K reports, Bloomberg, CrunchBase, Pitchbook, Hoovers, LinkedIn, company websites, and internet archives. The final sample consists of 221 U.S. firms and 54 foreign firms accounting for 75 public firms, 109 acquired firms, and 91 private firms. Information on patents, forward citations, and patent classes was obtained from the United States Patent and Trademark Office and cross-referenced with assignee forward citations and patent classes using Google Patents. In all, the sample consisted 12,554 patents and 211,759 forward citations.

Dependent Variable

Following Yang and Steensma (2014), I calculate technology spillover as the log transformed cumulative difference between a focal patent's International Patent Classification (IPC) classes and the IPC classes of its forward citations. Because the number of forward citations a patent receives increases over time, I control for this by counting the number of forward citations a patent received over a 5-year window as recommended by Jaffe and Rassenfosse (2017). Furthermore, I exclude self-citations because this would bias the measure of technology spillover (Jaffe & Rassenfosse, 2017).

Independent Variables

I measure *external director* as the cumulative number of VCs with seats on a focal firm's board of directors at each stage. Venture capitalists may sit on the boards of more than one company. Hence, I construct *board interlock* as the cumulative number of board seats occupied by each VC director on the boards of firms other than the focal firm. With a portfolio of companies under management, VCs can cross-pollinate a focal firm's technologies within their portfolio. I construct *VC cross-pollination* as a dummy variable taking a value of 1 if at least one VC portfolio company patent cites a focal firm's granted patents and 0 otherwise. With greater access to resources and networks, prominent VCs can enhance the effect of knowledge flows through cross-pollination within their portfolio companies. VC prominence was established by examining the frequency of co-investment with other VCs within its network (see Figure 1) (Hochberg et al., 2007). Pahnke, McDonald, Wang, & Hall (2015) used the VC's eigenvector centrality in their syndication networks to assess its prominence. Following Pahnke et al. (2015), a VC was considered to be prominent if its eigenvector centrality was among the top 30 VCs. I construct *prominent VC* as a dummy variable taking a value of 1 if the firm has at least one prominent VC director and 0 otherwise. A firm's technology spillover is examined at four intervals (*seed stage*, *early stage*, *late stage*, and *exit stage* as defined by VentureXpert) using the *exit stage* as a baseline for comparison. Each stage variable is a dummy taking a value of 1 if the event occurs and 0 otherwise.

Insert Figure 1 about here

Control Variables

To minimize the possibility of omitted variable bias, I control for certain observable variables that could affect technology spillover. I control for *financing* as the log transformed dollar amount (000's) invested at each stage. Furthermore, because some firms patent more frequently than others, I follow prior literature and control for a firm's *knowledge base size* (Yayavaram & Ahuja, 2008). I also control for firm-specific differences in patenting propensity across technological classes by incorporating *technological fertility* (Ahuja, 2000). I control for the degree of specialization within a firm's knowledge base, *technology generality*, with the bias corrected Herfindahl index suggested by Hall, Jaffe, and Trajtenberg (2001). Following Yang, Phelps, & Steensma (2010), I control for the degree of *technological diversity* within a firm's knowledge base by using the bias corrected Herfindahl index suggested by Hall et al. (2001). I also control for a VC firm's *portfolio size, firm age,* and whether the venture is a *U.S. firm* or a foreign firm. Operationalizations of the variables are described in Table 1.

Insert Table 1 about here

Estimation Method

I use the Heckman (1979) selection model to account for selection bias along with a two-stage least squares (2SLS) estimation model to account for endogeneity. In the first stage, I estimate a probit model that predicts the probability of receiving VC investment, reflecting the VC selection equation, and calculates the inverse Mills ratio (Dutta & Folta, 2016). The inverse Mills ratio accounts for unobservable factors related to VC selection bias (Dutta & Folta, 2016).

In the second stage, I estimate a 2SLS regression model to address the concern of mutual causality using an instrumental variable (IV). Following the VC literature, (e.g., Mao, Tian, and Yu, 2014; Sun, Chen, Sunny, & Chen, 2018), I construct an instrumental variable *airport*. My instrumental variable relies on plausibly exogenous variation in VC investments captured by the proximity of the VC and invested firm to an international airport. The rationale behind this instrument is that if both the VC and invested firm headquarters are located near an international airport, then it facilitates the VC travelling to the invested firm. Furthermore, it is reasonable to believe that proximity to an international airport is not correlated with a firm's technology spillover. The inverse Mills ratio from the first stage is included in this second stage regression.

RESULTS

I report descriptive statistics and pairwise correlations between variables in Table 2. All correlations were below 0.8 (largest was 0.78). To assess whether multicollinearity was an issue, I calculated the variance inflation factor (VIF) and condition index for each equation. The largest mean VIF value was 2.94 and the largest condition number was 8.342. The VIF and condition number are indicative of multicollinearity when their values are greater than 10 and 15, respectively. Therefore, multicollinearity is not a significant issue.

Insert Table 2 about here

The results of the two-stage least squares regression models are reported in Table 3. In Model 1, I specify the baseline model. In Model 2, I build upon the baseline model to examine how the presence of external directors influences a firm's technology spillover. I find that the coefficient for *external director* ($\beta = 0.245$, $p < .01$) is positive and significant. This suggests that for one additional VC on the board of directors, the focal firm's technology spillover is expected to increase by 24.5%. Hypothesis 1 predicts that firms with a VC director on the board will exhibit increased technology spillover. Therefore, I find support for Hypothesis 1.

In Model 3, I examine how board interlocks among VC investors influence a firm's technology spillover. I find that the coefficient for *board interlock* (β = 0.055, $p < .01$) is positive and significant. This suggests that for each additional VC on the board who is interlocked (i.e., sits on the board of another firm) the focal firm's technology spillover is expected to increase by 5.5%. Hypothesis 2 predicts that firms with an interlocking VC director on the board will exhibit increased technology spillover. Therefore, I find support for Hypothesis 2.

In Model 4, I examine the effect of cross-pollination of a focal firm's technologies among VC investor portfolio companies. I find that the coefficient for *VC cross-pollination* (β = 0.825, $p < .01$) is positive and significant. This suggests that for each additional VC portfolio company that adopts a focal firm's technologies, the rate of technology spillover is expected to increase by 82.5%. Hypothesis 3 predicts that firms will generate greater technology spillover if a VC director cross-pollinates the focal firm's technologies among its portfolio companies. Therefore, I find support for Hypothesis 3.

In Model 5, I examine how the presence of prominent VC directors influences a firm's technology spillover. I find that the coefficient for *prominent VC* (β = 0.145, $p < .05$) is positive and significant. This suggests that for one additional prominent VC director, the focal firm's technology spillover is expected to increase by 14.5%. Hypothesis 4 predicts that firms with a prominent VC director on the board will exhibit increased technology spillover. Therefore, I find support for Hypothesis 4.

In Model 6, I examine the moderating role of financing stage on the relationship between board interlocks among VC investors and technology spillover, using the interaction between *board interlock* x *exit stage* as the benchmark. I find that the coefficients for the interactions between *board interlock* x *seed stage* (β = 0.061, $p < 0.01$), *board interlock* x *early stage* (β =

0.132, $p < 0.01$), and *board interlock* x *late stage* ($\beta = 0.051$, $p < 0.01$) are positive and significant. This suggests that, as compared to the exit stage, the presence of an interlocking VC on the board is expected to increase the focal firm's technology spillover by 6.1% in the seed stage, 13.2% in the early stage, and 5.1% in the late stage. Hypothesis 5a predicts that a firm's financing stage positively moderates the relationship between having an interlocking VC director on the board and technology spillover. Therefore, Hypothesis 5a is supported.

In Model 7, I examine the moderating role of financing stage on the relationship between the cross-pollination of a focal firm's technologies among VC investor portfolio companies and technology spillover, using the interaction between *VC cross-pollination* x *exit stage* as the benchmark. I find that the coefficients for the interactions between *VC cross-pollination* x *seed stage* ($\beta = 1.396$, $p < 0.05$), *VC cross-pollination* x *early stage* ($\beta = 1.634$, $p < 0.01$), and *VC cross-pollination* x *late stage* ($\beta = 1.253$, $p < 0.05$) are positive and significant. This suggests that, as compared to the exit stage, the cross-pollination of a focal firm's technologies among VC investor portfolio companies is expected to increase the focal firm's technology spillover by 139.6% in the seed stage, 163.4% in the early stage, and 125.3% in the late stage. Hypothesis 5b predicts that a firm's financing stage positively moderates the relationship between having a VC director cross-pollinate the focal firm's technologies among its portfolio companies and technology spillover. Therefore, Hypothesis 5b is supported.

In Model 8, I examine the moderating role of financing stage on the relationship between prominent VC investors and technology spillover, using the interaction between *prominent VC* x *exit stage* as the benchmark. I find that the coefficients for the interactions between *prominent VC* x *seed stage* ($\beta = 0.737$, $p < 0.01$), *prominent VC* x *early stage* ($\beta = 0.762$, $p < 0.01$), and *prominent VC* x *late stage* ($\beta = 0.684$, $p < 0.01$) are positive and significant. This suggests that, as compared to the exit stage, a prominent VC on the board is expected to increase the focal firm's technology spillover by 73.7% in the seed stage, 76.2% in the early stage, and 68.4% in the late stage. Hypothesis 5c predicts that a firm's financing stage positively moderates the relationship between having a prominent VC director on the board and technology spillover. Therefore, Hypothesis 5c is supported.

Insert Table 3 about here

To assess the relevance of the IV, *airport*, I examined the first-stage F-statistic of the 2SLS regressions (Bascle, 2008). This tests the hypothesis that the coefficient on the instrument is equal to zero in the structural equation. I find that the first-stage F-statistic of the 2SLS regressions is greater than the threshold value of 10 as suggested by Stock and Yogo (2005). Therefore, the IV satisfies the relevance condition and can be considered a strong instrument.

Robustness Checks

Robustness checks were conducted to test the sensitivity of the results against alternative operationalizations and estimation methods. In a first series of tests, I estimate a Heckman selection model along with a 2SLS estimation model using the Cooperative Patent Classification system as an alternative measure of technology spillover (Table 4). In a second series of tests, I estimate a Poisson regression model using the control function approach and proximity to an international airport as an instrumental variable (not reported). The results of the robustness checks showed that the coefficients on the variables remained consistent in sign and magnitude, suggesting that they are not sensitive to the specification or classification scheme used.

Insert Table 4 about here

DISCUSSION

In this study, I examined how entrepreneurs, in the process of search, turn to VC directors as sources of new, external knowledge and the effect this has on technology spillovers. VC directors augment a firm's exploratory search by serving as both a repository of untapped external knowledge and as a facilitator of connectivity between distant knowledge networks. Furthermore, with a unique endowment of characteristics, VC directors play a pivotal role in spanning both organizational and technological boundaries, which enhances spillovers.

The rate of technology spillover varies across financing stages. Those technological innovations produced in the early stage had the greatest spillover. Figure 2 illustrates that while patenting across financing stages demonstrated an increasing trend, technology spillover had an inverse U-shaped curve. Seed stage investments were rarely associated with a VC taking a board seat. However, this increased significantly with early stage investments. Furthermore, early stage investments were also accompanied by a greater frequency of VC syndication as compared to the seed stage. With more VCs involved in financing the startup, firms gained access to more diverse networks, which resulted in an increase in the amount of technology spillovers.

Insert Figure 2 about here

Figure 2 also illustrates a shift in organizational ambidexterity among VC-backed firms. During the seed and early stages, exploratory search dominates. Therefore, although the average number of patents a firm generates is relatively low in the seed and early stages, their influence spans many different technological domains, which results in increased technology spillovers. During the late and exit stages, however, exploitation dominates. While the average number of patents is greatest during this period, these technologies tend to be incremental improvements that draw upon the firm's existing knowledge base. As a result, these technologies have a narrower focus and do not span many technological domains.

Of the three mechanisms explored, cross-pollination had the greatest influence on technology spillovers. Hence, VC directors can facilitate the cross-pollination of technologies across seemingly unrelated or unconnected groups and have a significant impact on a firm's technology spillovers. This study also demonstrates that financing stage positively moderates the relationship between board interlocks, cross-pollination, and VC prominence and technology spillovers. For each mechanism, the moderating effect was greatest in the seed and early stages.

Contributions

This study makes several contributions to the literature. First, this study highlights the impact that VC directors can have on a firm's technology spillovers. In addition to idiosyncratic knowledge, resources, and networks, VC directors have multiple "levers" through which they can influence a firm's technology spillovers. Whether it is through the number of board interlocks, cross-pollination, or as a result of their prestige, VC directors play an important role in spanning boundaries and augmenting a firm's search for external knowledge.

Second, this study contributes to the ambidexterity literature by demonstrating the dichotomous nature of search across VC financing stages. During the seed and early stages, VC directors serve as conduits of external knowledge that complement exploratory search. However, there is a distinct shift in a VC's focus from exploration to exploitation shortly after the firm has completed product development. This is apparent in the inverse U-shaped relationship between technology spillovers and financing stage even though the rate of patenting continues to increase.

Third, this study is the first to examine the moderating role of financing stage on VC director board interlocks, cross-pollination, and VC prominence. These findings enhance our understanding of technology spillovers by demonstrating that the influence of these mechanisms is not static in nature, but rather is dynamic across financing stages. For example, the signaling strength of a prominent VC director varies across financing stages, which results in various degrees of influence on a firm's technology spillovers. Similarly, interlocking VC directors and cross-pollination also influence technology spillovers to varying degrees across financing stages.

Practical Implications

This study has several important implications for entrepreneurs. First, although the traditional view of technology spillovers suggests that it reduces an originator firm's ability to appropriate returns on their investment, originating firms can also benefit from spillovers by observing how their technologies are being built upon and by whom. In this manner, entrepreneurs may refine their search behaviors to better exploit spillovers themselves (Yang et al., 2010) and gain new insights into the advancement of a technology's trajectory.

Second, the shift in VC director focus from exploration to exploitation can upset a firm's ambidexterity. Startup firms' ambidexterity is often unbalanced from the beginning (i.e., heavily weighted towards exploration). However, entrepreneurs can expect to see a decline in a VC director's support for exploratory search once their focus shifts to exploitation so that they can make a successful exit. This pendulum shift can cause tension that reduces the effectiveness of ambidexterity. Hence, it is important for entrepreneurs to recognize and address this potentially disruptive shift by striking a balance between exploration and exploitation activities in order to appropriate returns in the short-term while still maintaining competitiveness in the long-term.

Limitations & Future Research

This study is not without its limitations. First, the small sample of semiconductor firms suggests that the findings reported here may not be generalizable to VC-backed firms as a whole.

Because patenting rates vary across high-tech industries, I limited this scope of this study to the semiconductor industry. The results, however, may be more likely to apply to similar high-tech industry contexts. Future research may examine other high-tech industries, such as biotech.

Second, this study examines venture capital and corporate venture capital (CVC) conjointly. CVCs are more focused on ensuring that the technologies developed by the venture are aligned with their interests and goals (Pahnke et al., 2015). Through the cross-pollination of technologies among its business units, CVCs can enhance inter-organizational knowledge flows and technology spillover. Future research should seek to provide new insights by studying the unique position that CVCs occupy and how this influences a technology's spillover.

Third, this study does not examine the influence of being geographically proximate to technology clusters as a mechanism that influences technology spillovers. Henderson, Jaffe, and Trajtenberg (2005) suggest that knowledge spillovers provide an incentive for firms to collocate and that collocation may stimulate cross-pollination of knowledge. Future studies can explore these geographical relationships in greater detail.

CONCLUSION

I set out to understand how VC directors affect a firm's technology spillovers. My findings highlight the pivotal role that VC directors play in the entrepreneurial search for external knowledge and their influence on a firm's spillovers into new technological domains. I find a distinct transition point between exploratory search and exploitation, which results in an inverse U-shaped relationship between technology spillovers and financing stage. This research also contributes new insights into ambidexterity and the mechanisms by which venture capitalists augment a firm's search capabilities. Furthermore, I expound on the moderating role that financing stage plays in regards to these mechanisms.

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Table 1: Variable Operationalizations

Variable	Operationalization	Reference
Technology Spillover (ln)	The log transformed cumulative difference between a focal patent's International Patent Classification (IPC) classes and the IPC classes of its forward citations over a 5-year window.	Yang & Steensma, 2014
External Director	The cumulative number of VCs with seats on a focal firm's board of directors at each stage.	Kang, Li, & Oh, 2018
Board Interlock	The cumulative number of board seats occupied by each VC director on the boards of firms other than the focal firm.	Bilimoria & Piderit, 1994
VC Cross-Pollination	Dummy = 1 if at least one VC portfolio company patent cites a focal firm's granted patents, 0 otherwise.	New operationalization
Prominent VC	Dummy = 1 if the firm has at least one prominent VC director, 0 otherwise.	Pahnke, McDonald, Wang, & Hallen, 2015
Seed Stage	Dummy = 1 if the firm is in the seed/startup stage as defined by VentureXpert, 0 otherwise.	Kim, Steensma, & Park, 2017
Early Stage	Dummy = 1 if the firm is in the early stage as defined by VentureXpert, 0 otherwise.	Kim, Steensma, & Park, 2017
Late Stage	Dummy = 1 if the firm is in the late/expansion stage as defined by VentureXpert, 0 otherwise.	Kim, Steensma, & Park, 2017
Exit Stage	Dummy = 1 if the firm is in the buyout/acquisition stage as defined by VentureXpert, 0 otherwise.	Kim, Steensma, & Park, 2017
Financing (ln)	The log transformed dollar amount (000's) invested at each stage.	Gompers, 1995
Knowledge Base Size (ln)	The log transformed total number of granted patents a firm has at each financing stage.	Yayavaram & Ahuja, 2008
Technological Fertility	The distribution of a focal firm's patenting efforts across classes	Ahuja, 2000
Technological Diversity	Adjusted Herfindahl index measure of patent classes in which a firm is granted patents.	Hall, Jaffe, & Trajtenberg, 2001
Technology Generality	Adjusted Herfindahl index measure of the percentage of forward citations received by a focal patent relative to patent classes.	Hall, Jaffe, & Trajtenberg, 2001
Portfolio Size (ln)	Natural log transformed cumulative number of firms that each VC has under management at each stage.	Wadhwa, Phelps, & Kotha, 2016
Firm Age	The number of years since the company's incorporation.	Kotha, Zheng, & George, 2011
U.S. Firm	Dummy = 1 if the VC-backed firm is headquartered in the U.S., 0 otherwise.	Vanhaverbeke, Gilsing, Beerkens, & Duysters, 2009

Table 2: Correlations

Variable	Mean	S.D.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. Technology Spillover	2.02	1.28	1.00															
2. External Director	1.10	1.33	0.07*	1.00														
3. Seed Stage	4.22	4.15	-0.01	-0.37*	1.00													
4. Early Stage	0.02	0.14	0.35*	-0.12*	-0.33*	1.00												
5. Late Stage	0.35	0.48	0.22*	0.25*	-0.33*	-0.33*	1.00											
6. Exit Stage	0.25	0.43	-0.58*	0.24*	-0.33*	-0.33*	-0.33*	1.00										
7. Board Interlock	0.25	0.43	0.29*	0.17*	-0.10*	0.16*	0.01	-0.06*	1.00									
8. VC Cross-Pollination	0.25	0.43	0.16*	0.03*	0.05	0.04	-0.03	-0.05*	0.08*	1.00								
9. Prominent VC	0.25	0.43	0.20*	0.13*	-0.15*	0.03	0.06*	0.06*	0.24*	0.05*	1.00							
10. Financing (ln)	7.03	3.48	0.37*	-0.22*	-0.04	0.26*	0.40*	-0.62*	0.03	0.02	0.01	1.00						
11. Knowledge Base Size	1.20	1.33	0.42*	0.10*	-0.20*	0.07*	0.20*	-0.08*	-0.06*	0.02	0.15*	0.17*	1.00					
12. Technological Fertility	3.96	1.36	0.53*	-0.21*	0.44*	0.18*	-0.10*	-0.52*	0.11*	0.08*	0.07*	0.21*	0.38*	1.00				
13. Technological Diversity	0.63	0.43	0.56*	0.16*	-0.13*	0.18*	0.12*	-0.18*	0.33*	0.08*	0.21*	0.13*	0.53*	0.42*	1.00			
14. Technology Generality	0.42	0.07	0.12*	0.17*	-0.10*	0.02	0.05*	0.03	0.09*	0.01	0.11*	0.06*	0.09*	0.07*	0.16*	1.00		
15. Portfolio Size (ln)	3.16	0.62	0.20*	0.25*	-0.00	-0.00	0.00	0.00	0.11*	0.06*	0.06*	-0.05	0.13*	0.19*	0.23*	0.15*	1.00	
16. Firm Age	22.77	5.94	0.14*	0.05*	0.00	0.00	0.00	0.00	0.01	-0.07*	0.08*	-0.17*	0.16*	0.28*	0.15*	-0.02	0.01	1.00
17. U.S. Firm	0.81	0.40	0.11*	0.16*	0.00	0.00	0.00	0.00	0.07*	-0.00	0.10*	-0.15*	0.02	0.20*	0.12*	-0.01	0.27*	0.32*

* Statistically significant ($p < .05$)

Table 3: Two-Stage Least Squares Regression Analysis (Using IPC)

Variable	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
External Director		0.245***	0.196***	0.193***	0.191***	0.082***	0.114***	0.106***
(*Instrumented*)		(0.039)	(0.039)	(0.039)	(0.039)	(0.031)	(0.032)	(0.031)
Board Interlock			0.055***	0.054***	0.050***	0.002	0.050***	0.050***
			(0.012)	(0.012)	(0.012)	(0.014)	(0.010)	(0.010)
VC Cross-Pollination				0.825***	0.815***	0.704***	-0.556	0.797***
				(0.252)	(0.253)	(0.165)	(0.516)	(0.167)
Prominent VC					0.145**	0.195***	0.233***	-0.290**
					(0.063)	(0.052)	(0.053)	(0.126)
Seed Stage						1.058***	1.389***	1.142***
						(0.135)	(0.112)	(0.120)
Early Stage						1.082***	1.770***	1.494***
						(0.132)	(0.110)	(0.114)
Late Stage						1.285***	1.463***	1.212***
						(0.136)	(0.109)	(0.114)
Board Interlock x Seed						0.061***		
						(0.018)		
Board Interlock x Early						0.132***		
						(0.016)		
Board Interlock x Late						0.051***		
						(0.018)		
VC Cross-Pollination x Seed							1.396**	
							(0.596)	
VC Cross-Pollination x Early							1.634***	
							(0.547)	
VC Cross-Pollination x Late							1.253**	
							(0.523)	
Prominent VC x Seed								0.737***
								(0.160)
Prominent VC x Early								0.762***
								(0.146)
Prominent VC x Late								0.684***
								(0.152)
Controls								
Financing (ln)	0.094***	0.110***	0.102***	0.103***	0.104***	-0.022*	-0.014	-0.018
	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)	(0.012)	(0.012)	(0.012)
Knowledge Base Size (ln)	0.061	0.027	0.104**	0.109**	0.101**	0.199***	0.211***	0.211***
	(0.038)	(0.038)	(0.043)	(0.043)	(0.043)	(0.032)	(0.032)	(0.032)
Technological Fertility	0.309***	0.400***	0.373***	0.364***	0.366***	0.136***	0.113***	0.108***
	(0.025)	(0.032)	(0.032)	(0.032)	(0.032)	(0.031)	(0.032)	(0.031)
Technological Diversity	1.148***	1.019***	0.748***	0.722***	0.715***	0.604***	0.599***	0.612***
	(0.074)	(0.077)	(0.089)	(0.089)	(0.088)	(0.068)	(0.075)	(0.074)
Technology Generality	0.365	-0.370	-0.139	-0.159	-0.249	0.723*	0.553	0.546
	(0.498)	(0.476)	(0.466)	(0.465)	(0.469)	(0.379)	(0.380)	(0.372)
Portfolio Size (ln)	0.090*	-0.023	-0.023	-0.023	-0.020	0.069*	0.078**	0.083**
	(0.049)	(0.057)	(0.055)	(0.055)	(0.055)	(0.038)	(0.040)	(0.038)
Firm Age	0.005	0.001	0.002	0.004	0.004	0.007	0.008*	0.007
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.004)	(0.005)	(0.004)
U.S. Firm	0.091	0.026	0.003	0.006	-0.007	-0.044	-0.021	-0.001
	(0.075)	(0.076)	(0.075)	(0.075)	(0.075)	(0.060)	(0.061)	(0.059)
Inverse Mills Ratio		1.692	0.501	1.575	1.022	0.098	-1.444	-1.550
		(4.613)	(5.944)	(5.850)	(5.910)	(4.261)	(3.673)	(3.013)
Intercept	-1.345***	-2.506	-1.635	-2.504	-2.039	-1.128	-0.116	0.188
	(0.265)	(3.714)	(4.774)	(4.699)	(4.745)	(3.423)	(2.959)	(2.433)
N	1,100	1,100	1,100	1,100	1,100	1,100	1,100	1,100
R^2	0.499	0.503	0.530	0.538	0.540	0.695	0.676	0.688
Condition Number	2.871	3.045	3.258	3.272	3.351	7.689	8.342	6.728
Mean VIF	1.44	1.45	1.52	1.49	1.48	2.83	2.94	2.40

* p < .10; ** p < .05; *** p < .01

Robust standard errors reported in parentheses.

Table 4: Two-Stage Least Squares Regression Analysis (Using CPC)

Variable	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
External Director		0.274***	0.218***	0.214***	0.212***	0.089***	0.124***	0.116***
(*Instrumented*)		(0.043)	(0.043)	(0.043)	(0.043)	(0.034)	(0.036)	(0.034)
Board Interlock			0.063***	0.062***	0.058***	0.004	0.058***	0.058***
			(0.013)	(0.013)	(0.013)	(0.015)	(0.011)	(0.011)
VC Cross-Pollination				0.904***	0.894***	0.773***	-0.600	0.875***
				(0.279)	(0.280)	(0.183)	(0.524)	(0.185)
Prominent VC					0.155**	0.211***	0.253***	-0.334**
					(0.070)	(0.057)	(0.059)	(0.139)
Seed Stage						1.186***	1.549***	1.268***
						(0.151)	(0.125)	(0.133)
Early Stage						1.217***	1.978***	1.668***
						(0.146)	(0.122)	(0.126)
Late Stage						1.454***	1.648***	1.370***
						(0.150)	(0.120)	(0.126)
Board Interlock x Seed						0.067***		
						(0.021)		
Board Interlock x Early						0.146***		
						(0.017)		
Board Interlock x Late						0.056***		
						(0.020)		
VC Cross-Pollination x Seed							1.514**	
							(0.620)	
VC Cross-Pollination x Early							1.791***	
							(0.561)	
VC Cross-Pollination x Late							1.372***	
							(0.531)	
Prominent VC x Seed								0.843***
								(0.177)
Prominent VC x Early								0.855***
								(0.161)
Prominent VC x Late								0.756***
								(0.168)
<u>*Controls*</u>								
Financing (ln)	0.105***	0.123***	0.114***	0.115***	0.115***	-0.026*	-0.017	-0.021
	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.013)	(0.014)	(0.013)
Knowledge Base Size (ln)	0.062	0.023	0.112**	0.117**	0.109**	0.217***	0.231***	0.231***
	(0.043)	(0.042)	(0.047)	(0.047)	(0.047)	(0.035)	(0.036)	(0.036)
Technological Fertility	0.349***	0.451***	0.421***	0.410***	0.413***	0.156***	0.131***	0.125***
	(0.028)	(0.035)	(0.035)	(0.035)	(0.035)	(0.034)	(0.035)	(0.035)
Technological Diversity	1.281***	1.136***	0.826***	0.798***	0.791***	0.666***	0.661***	0.675***
	(0.082)	(0.086)	(0.099)	(0.099)	(0.098)	(0.076)	(0.083)	(0.082)
Technology Generality	0.401	-0.424	-0.159	-0.181	-0.277	0.814*	0.626	0.618
	(0.550)	(0.527)	(0.515)	(0.514)	(0.518)	(0.417)	(0.418)	(0.410)
Portfolio Size (ln)	0.102*	-0.024	-0.023	-0.024	-0.021	0.079*	0.089**	0.095**
	(0.055)	(0.063)	(0.061)	(0.061)	(0.061)	(0.043)	(0.044)	(0.042)
Firm Age	0.006	0.002	0.003	0.005	0.005	0.008*	0.009*	0.008*
	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.005)	(0.005)	(0.005)
U.S. Firm	0.088	0.017	-0.009	-0.006	-0.020	-0.062	-0.036	-0.014
	(0.084)	(0.085)	(0.084)	(0.084)	(0.084)	(0.067)	(0.068)	(0.066)
Inverse Mills Ratio		1.307	-0.352	0.855	0.233	-0.718	-2.233	-2.362
		(5.342)	(6.699)	(6.615)	(6.628)	(4.592)	(3.960)	(3.372)
Intercept	-1.524***	-2.350	-1.117	-2.092	-1.572	-0.624	0.345	0.694
	(0.293)	(4.300)	(5.380)	(5.314)	(5.321)	(3.691)	(3.191)	(2.723)
N	1,100	1,100	1,100	1,100	1,100	1,100	1,100	1,100
R^2	0.500	0.504	0.532	0.540	0.542	0.697	0.678	0.691
Condition Number	2.879	3.053	3.259	3.273	3.351	7.695	8.341	6.732
Mean VIF	1.44	1.45	1.53	1.49	1.48	2.83	2.94	2.41

* p < .10; ** p < .05; *** p < .01

Robust standard errors reported in parentheses.

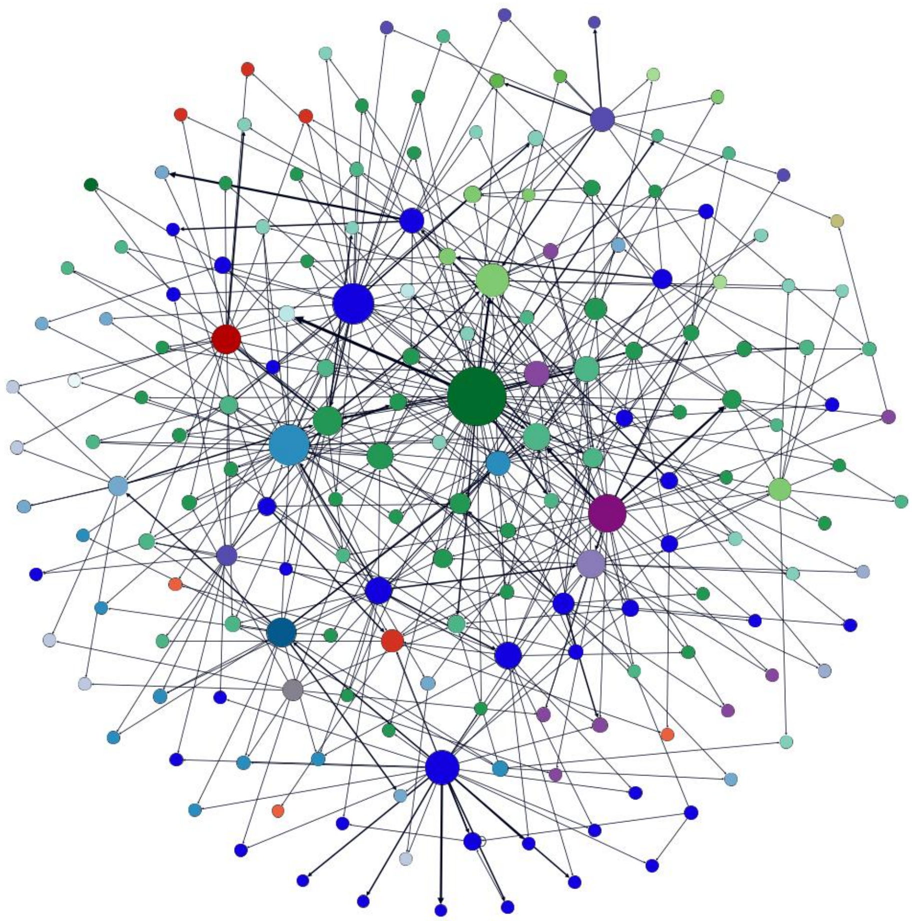

Figure 1: Visualization of VC Co-investment Networks

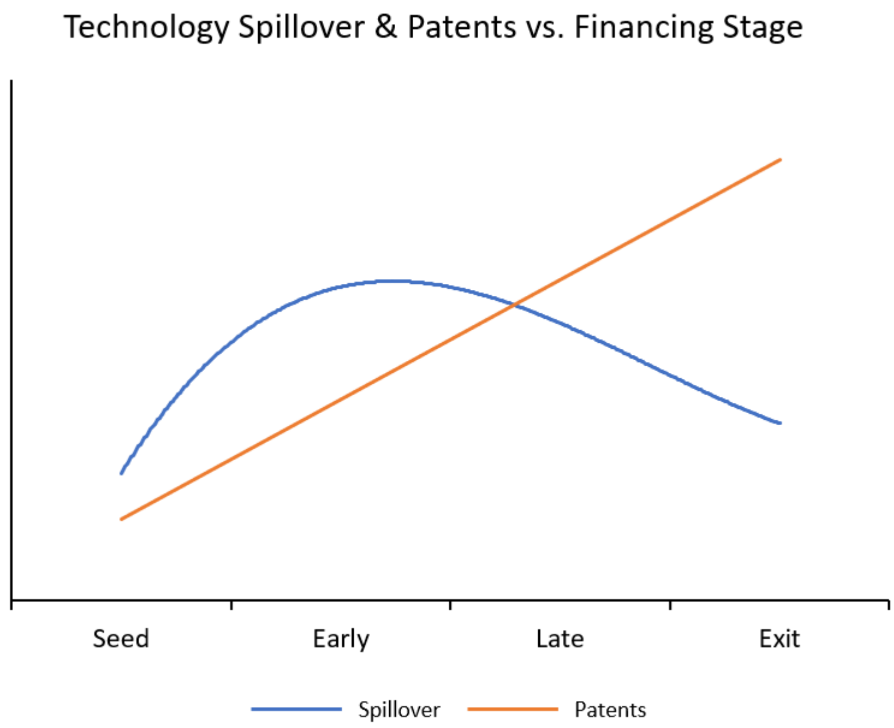

Figure 2: Technology Spillover & Patents vs. Financing Stage