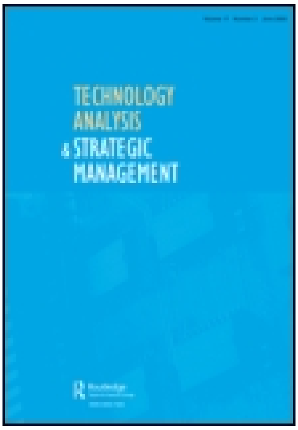

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Shifting grounds: how industry emergence changes the effectiveness of knowledge creation strategies – the case of the US automotive airbag industry

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This paper investigates the effect industry life cycle phase shifts have on the effectiveness of firms' knowledge creation strategies. Building on literature streams on strategic knowledge management and industry life cycles, we develop theoretical arguments for why the best knowledge search strategy should be different before the emergence of an industry compared to afterwards. Testing our hypotheses empirically in the emerging US automotive airbag industry confirms the powerful forces of industry emergence: the best knowledge search strategy is initially one that looks inward into the organisation but outside of the technology area, and later shifts to one that is looking outward from the organisation and the technology. As practical implication we derive that R&D managers should (i) adjust their teams' knowledge search strategies depending on the industry life cycle phase in which they find themselves, and (ii) especially look for new applications of their firm's existing knowledge in related fields.

Keywords: industry life cycle; knowledge management; search processes; R&D; patents

Introduction

Knowledge is increasingly considered a critical valuable resource, particularly for companies developing high-technology products and systems. Recent research has placed an emphasis on the capability of knowledge creation as an important explanatory variable of firm performance (Argote, McEvily, and Reagans 2003). Early research on organisational learning has established the cumulative nature of knowledge creation (Cohen and Levinthal 1990). In other words, knowledge creation has been conceptualised as a repeated experience exercise along a path, a path that can either explore local knowledge neighborhoods or bridge more distant knowledge areas. More recent research has shown that this distance contains multiple dimensions, including both

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technological and organisational aspects (Ahuja and Lampert 2001; Katila and Ahuja 2002; Rosenkopf and Nerkar 2001).

Most of the existing research has studied the phenomenon of knowledge creation in relatively mature industries. What is less known is whether the same knowledge building strategies are effective in emerging industries, i.e. in situations in which firms, knowledge and industries co-evolve. This question is increasingly relevant given that technological change is accelerating and time frames of continuing industry leadership are shortening. For example, almost 50% of the companies on the 1999 Fortune 500 list were no longer on that list in 2009. This paper aims to contribute to filling this gap by exploring the effect of industry emergence on the most effective knowledge building strategy.

The remainder of the paper is organised as follows. In the next section we discuss the relevant literature and formulate our hypotheses. Section 3 presents an overview of our data and methods. The empirical results are presented in Section 4, Section 5 provides the corresponding discussion of the findings including theoretical and practical implications, and Section 6 concludes.

Theoretical background and hypotheses

Characteristics of knowledge creation as cumulative search process

If knowledge creation is interpreted as a cumulative process, i.e. newly created knowledge searches for, and builds on, existing knowledge, the question of path dependence of this process arises. Early research on knowledge creation has emphasised the importance of a firm's existing knowledge. Knowledge which is familiar to the firm yields more immediate and likely returns (Levinthal and March 1981), and creates an 'absorptive capacity' enabling the firm to recognise the value of new and external information (Cohen and Levinthal 1990).

However, building only on closely related knowledge has its limitations built-in. While this type of local search leads to the formation of 'core capabilities', it also increases the risk for firms to develop 'core rigidities' (Leonard-Barton 1992). This tension between the pros and cons of narrow but deep and shallow but wide searches for knowledge creation strategies has led researchers to suggest that over the long run organisations need to develop 'ambidexterity' (Tushman and Oreilly 1996), 'combinative capabilities' (Kogut and Zander 1992), or 'dynamic capabilities' (Teece, Pisano, and Shuen 1997) to overcome these challenges.

More recently, research has begun to unpack what it means for knowledge to be closely related, i.e. what constitutes local vs distant searches. Various dimensions along which to study knowledge relatedness have been suggested, e.g. knowledge characteristics such as proximity, commonality and complementarity (Breschi, Lissoni, and Malerba 2003), knowledge subjects such as product, customer, or management (Tanriverdi and Venkatraman 2005), or knowledge sources such as customers, competitors, suppliers and universities (Laursen and Salter 2006; Paananen 2009).

On the technology level, Ahuja and Lampert (2001) consider both firm boundaries and industry boundaries to distinguish various levels of distance, i.e. technology newness, which they label novel, emerging, and pioneering technologies. On the firm level, Katila and Ahuja (2002) define search depth by the frequency with which a firm reuses old knowledge and search breadth by how widely a firm explores new knowledge territory. Finally, Rosenkopf and Nerkar (2001) combine both technological and organisational dimensions to define four types of knowledge exploration a firm can engage in, and their measure for distance assesses whether or not the search processes crosses a technological boundary, or an organisational boundary, or both.

Industry emergence

In a separate stream researchers have been searching for regularities with which industries evolve and change over time (Fine 1998; Foster 1986; Klepper 1997; McGahan 2004; Schumpeter 1942). One widely used theory to explain how industries evolve has been the industry life cycle (or product life cycle (because particularly early on many industries are defined by a single product, e.g. typewriter, automobile, computer (Abernathy and Utterback 1978; Utterback 1994)). The core idea of this theory is that industries go through a sequence of recognisable phases. It suggests that industries start from a fluid phase in which an increasing number of firms enters the industry and competes with a broad variety of solutions. In the subsequent transitional phase the market grows and firms' foci begin to shift from product to process innovation. Finally, in the specific phase the industry matures and competition is driven by cost considerations and the number of participating firms declines (Klepper 1996, 1997; Utterback 1994).

The crucial consequence of industries evolving through phases is that for firms in those industries the competitive environment changes from one phase to another. Several aspects such as dominant designs, timing patterns of firm entry and exit, and sales take-offs have been identified as playing key roles in shaping the competition in an emerging industry. Because of its standardising effect, the dominant design – once it is established – makes competing very difficult for firms who previously bet on a contending design. For the disk-drive industry it has been empirically shown that firms who enter an industry immediately prior to the emergence of a dominant design increase their survival chances (Christensen, Suarez, and Utterback 1998). Broad entry timing differences seem to be more relevant than smaller variances: Agarwal and Bayus (2004) find in their study across a broad range of innovations that what matters is the timing difference between cohorts, not within cohorts. The ultimate confirmation of a design's dominance occurs when it becomes accepted by the market participants (Rosa et al. 1999), i.e. with significant sales take-off. In most industries, there is a substantial incubation period of several years between product invention, market launch, and sales take-off (Agarwal and Bayus 2002; Golder and Tellis 1997; Kohli, Lehmann, and Pae 1999).

Hypotheses

Following recent research that conceptualises knowledge creation as search and recombination processes, we build on Rosenkopf and Nerkar's (2001) typology of four types of exploration to capture both technological and organisational boundary-spanning of these processes. Rosenkopf and Nerkar propose that knowledge search activities can cross organisational boundaries (external boundary spanning), technological boundaries (internal boundary spanning), neither boundary (local), or both boundaries simultaneously (radical) (Figure 1). However, in contrast to Rosenkopf and Nerkar, we do not investigate the knowledge search processes during an industry's mature phase, but rather during the period of the industry's emergence. For the purpose of this study we define industry emergence as the period when meaningful sales begin to materialise. Consequently, we formulate separate hypotheses for the industry pre-take-off incubation stage and for the industry post-take-off growth stage.

The theory on the industry life cycle suggests that technological discontinuities trigger the start of a fluid phase in which many firms enter an industry and compete for dominance with alternative products.[1] In such an industry pre-take-off stage, neither a consolidated industry structure nor substantial industry-wide product knowledge exist yet, while alternative technologies compete for dominance (Abernathy and Utterback 1978). In environments characterised by high levels of

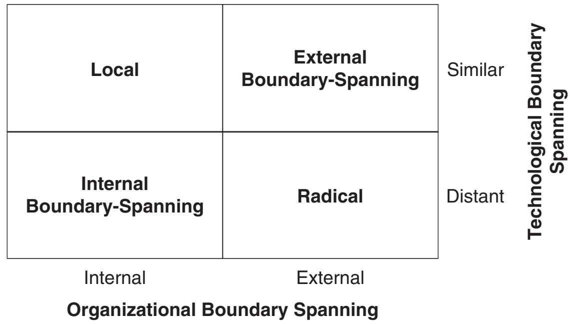

Figure 1. Four types of exploration (adapted from Rosenkopf and Nerkar 2001).

technological uncertainty, firms tend to prefer familiar knowledge over unfamiliar and can build specialised competencies by refining their internal knowledge (Levinthal and March 1981; Nelson and Winter 1982). In addition, to develop the capacity to understand and evaluate the potential of outside knowledge requires first the development of an own knowledge base (Cohen and Levinthal 1990). Notice that the arguments above favour *de alio* firms who can build on knowledge that is internal to the firm but external to the new product technology over *de novo* firms. Thus, we formulate our first hypothesis as follows.

Hypothesis 1A: In the industry pre-take-off stage, a firm exploring knowledge within its organisational boundary is more likely to develop high impact technological solutions than a firm exploring across its organisational boundary.

In addition to the organisational boundary we consider the product technology boundary as the second dimension of knowledge search processes. In the industry pre-take-off stage where substantial industry-wide knowledge is limited by definition, a firm searching for new solutions only within the new industry limits itself. In contrast, prior to the existence of a dominant design firms compete with various technical solutions, originating from or inspired by other technologies. Thus, in case of an emerging industry it is not so much the knowledge exhaustion effect that can be observed when firms search only within the existing focal product technology space that leads firms to look elsewhere for superior solutions (Fleming 2001), but rather the lack of a sizable knowledge stock in this new industry in the first place. In addition, searching a broader technology space in the industry pre-take-off phase may also reduce the high risk of choosing a wrong technology in this early phase of the industry (Christensen, Suarez, and Utterback 1998).

Hypothesis 1B: In the industry pre-take-off stage, a firm exploring within its organisational boundary but across the product technology boundary (internal boundary-spanning) is most likely to develop high impact technological solutions.

For the development of the next two hypotheses we shift our focus to the industry post-take-off stage. In this industry stage, the technological path solidifies after the dominant design has been accepted in the industry and its associated market through experimentation and communication between suppliers and their customers (Rosa et al. 1999; Utterback 1994). Firms who have set initially on another design either exit the industry (Anderson and Tushman 1990; Suarez and

Utterback 1995) or adapt their technology to meet the technological path defined by the dominant design (Tegarden, Hatfield, and Echols 1999). With an industry maturing, firms also become increasingly aware of their mutual dependence on knowledge and place more emphasis on being a part of larger technological communities (Gittelman and Kogut 2003; Powell, Koput, and Smith-Doerr 1996). For these reasons, firms need to watch the technological developments of other firms in the industry. In addition, tapping into external knowledge can help reducing the risk of organisational rigidity (Leonard-Barton 1992) in the industry growth phase.

Hypothesis 2A: In the industry post-take-off stage, a firm exploring across its organisational boundary is more likely to develop high impact technological solutions than a firm exploring within its organisational boundary.

As for the pre-industry take-off phase, we now consider the product boundary simultaneously with the organisational boundary. The dominant design shapes a technological path in an emerging industry. Once such a path is created, a firm may be locked out of the market if a solution other than its own has become the dominant design and the firm is unable to develop products compatible with the accepted technology (Schilling 1998). In this stage, firms are more likely to succeed by choosing and refining the accepted technological path rather than creating a new one as the industry evolves. Moreover, if knowledge is new not only to the industry but also to the firm it can cause information overload and assimilation problems (Ahuja and Lampert 2001; Kogut and Zander 1992).

Hypothesis 2B: In the industry post-take-off stage, a firm exploring across its organisational boundary but within the product boundary (external boundary-spanning) is most likely to develop high impact technological solutions.

Data and methods

Industry and product

We choose as our setting the emerging US automotive airbag industry because the airbag is a multi-technology device whose design and manufacture requires diverse technologies such as mechanical, electrical and electronic, computing, chemical, and textile technologies. In addition, the airbag industry grew from being almost non-existing to a multi-billion dollar industry in less than 15 years, and its emergence in the early 1990s lends itself to proper analysis without creating censored data problems. While some technical development activity on automotive airbags occurred in the 1960s, legal challenges between the automotive industry and US governmental agencies delayed the large-scale market introduction of airbags by 20 years. Then, in the 1980s, a combination of a National Highway Traffic and Safety Administration (NHTSA) ruling requiring automobile manufacturers to introduce passive restraint systems in their vehicles, several Supreme Court rulings, changes in management in some of the car companies, and pressure from the Insurance industry resulted in all new passenger cars being equipped with first driver and subsequently passenger front airbags in the late 1980s and early 1990s (Figure 2).

A typical automotive airbag system consists of four main components: a sensor that senses a vehicle's deceleration rate, a diagnostic and control unit whose algorithms determine whether a crash has actually occurred, an inflator that in case of a crash rapidly inflates the bag, and the bag itself as the protective device.

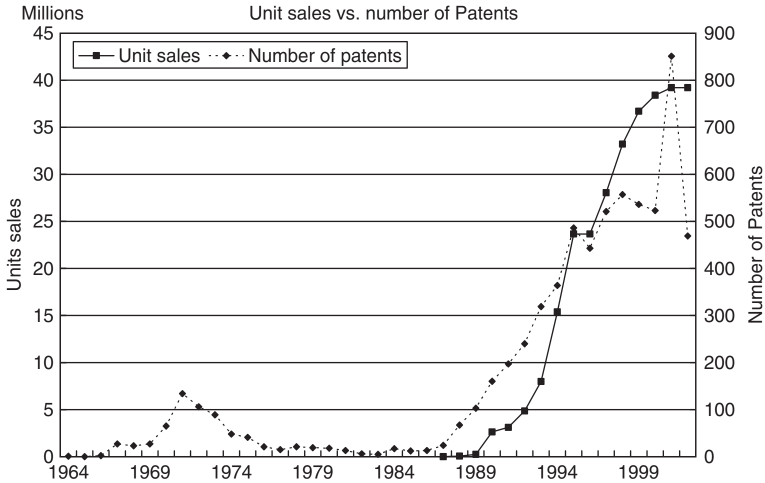

Figure 2. US automotive airbag patents and market growth (1969–2002).

Data

We test the proposed hypotheses using patent data and patent citation data from the US patent and trademark office (USPTO). Given that not all inventions are patented and that the economic value of patents that are granted is highly skewed, there is substantial noise in using patents as economic indicators (Griliches 1990). However, researchers have argued that with careful analysis design and conservative interpretation patent data can be used to learn about innovative activities (Hall, Jaffe, and Trajtenberg 2002; Pavitt 1985). Focusing on one product technology in one industry in one country, our research design follows this advice.

Because we measure knowledge creation strategies along two dimensions, product technology boundary-spanning and organisational boundary-spanning, these boundaries require careful definition. To define the product technology boundary, following prior research on individual industries (Giarrantana 2004; Rosenkopf and Nerkar 2001), we reviewed the manual of the US patent classification system (USPCS) and selected sub-class level patent classification numbers that are relevant to the automotive airbag technology, and cross-referenced them with the manual of the International Patent Classification (IPC). Additional keyword searches and cross-checks with USPTO employees increased the confidence that our sample neither excluded relevant patents nor included non-relevant patents. As a result, our airbag product technology boundary comprises all patents with classification numbers that fall in one of the categories between USPC 280/728.1 and USPC 280/743.2 (Table 1).

To be able to recognise knowledge creation as a search that can cross organisational boundaries requires dynamically identifying the location of an organisation's boundary, i.e. to take into account changes over time through mergers and acquisitions (M&A) or divestments. To do this, we categorised organisational boundary changes into four types (subsidiaries, joint ventures, M&As, and divestitures) and developed rules to decide when a knowledge search process crosses an organisational boundary (Figure 3).

First, a search process between subsidiaries is considered as not crossing an organisational boundary. Second, a search process between a joint venture and its parents is also considered being within the organisational boundary (Oxley and Wada 2009). Third, a search process between

Table 1. US patents class/subclass numbers and titles related to automotive airbags.

Level 1	Level 2	Level 3	Title
280/728.1			Inflatable passenger restraint or confinement (e.g. air bag) or attachment
	280/728.2		With specific mounting feature
	280/728.3		Deployment door
	280/729		Plural compartment confinement (e.g. 'bag within a bag')
	280/730.1		Inflated confinement specially positioned relative to occupant
		280/730.2	Mounted in vehicle and positioned laterally of occupant
	280/731		Deflated confinement located within or on steering column
	280/732		Deflated confinement located within or on instrument panel
	280/733		In the form of or used in conjunction with a belt or strap
	280/734		Responsive to vehicle condition
		280/735	Electric control and/or sensor means
	280/736		With source of inflation fluid and flow control means thereof
		280/737	With means to rupture or open fluid source
		280/738	With means to aspirate ambient air
		280/739	With confinement deflation means
		280/740	With means to diffuse inflation fluid
	280/741		Inflation fluid source
	280/742		Flow control means
	280/743.1		Specific confinement structure
		280/243.2	With confinement expansion regulating tether or strap

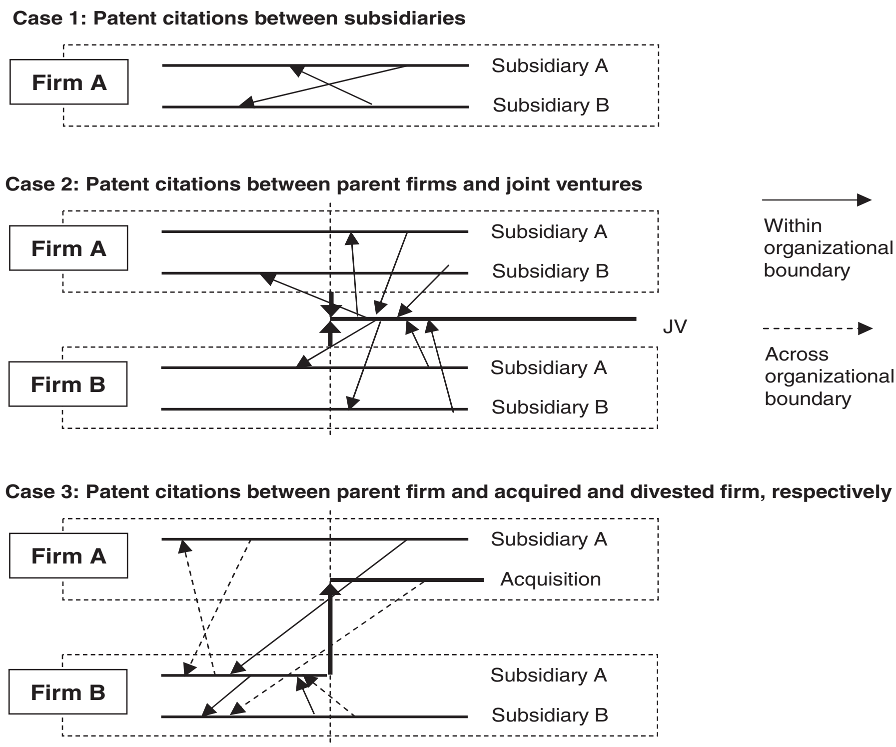

Figure 3. Decision rules for deciding whether a knowledge search crosses organisational boundaries.

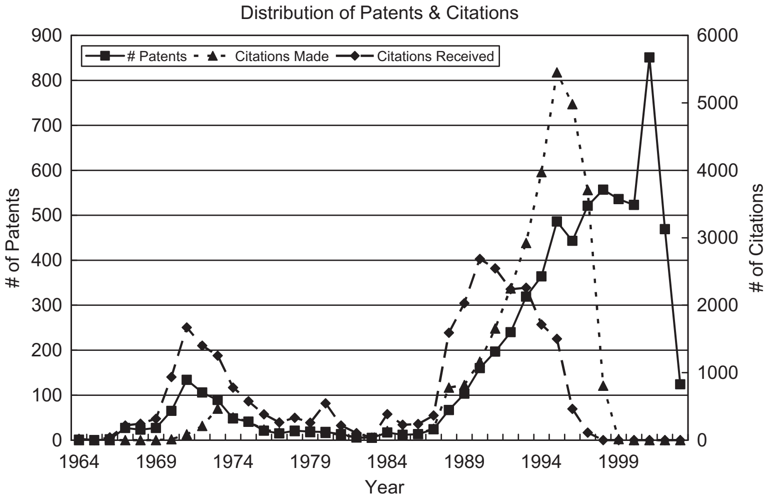

Figure 4. Distribution of US airbag-related patents and patent citations (1964–2002).

acquired firm and acquiring firm is considered as occurring within the organisational boundary if the search occurs after the acquisition, but across the organisational boundary if the search was conducted before the acquisition. These three definitions are based on the empirical finding that tie strength and trust are positively correlated with inter-organisational knowledge transfer (Van Wijk, Jansen, and Lyles 2008). Fourth, we consider a knowledge search process between divested part and firm parent as crossing the organisational boundary if a search is made after the divestiture, but within the organisational boundary if a search is made before the divestiture.

We explore knowledge search processes and their impact using prior art citations which a patent makes and future citations which a patent receives, respectively. The citations data we extract from the National Bureau of Economic Research (NBER) US patent citations data file that includes citation data from 1975 to 1999 (Hall, Jaffe, and Trajtenberg 2002) and link it to the detailed patent data using corresponding patent numbers. Figure 4 presents the distributions of patent and citation data for the airbag technology patents.

Because only customers ultimately purchasing an industry's products and services allow an industry to exist, we focus in determining the point of industry emergence on the recognisable beginning of the sales take-off. Following Agarwal and Bayus (2002) we define as the sales take-off year the year that exhibits the largest year-on-year sales increase, measured in per cent. In our data set, this year is 1990 with annual sales growth of 985%. Based on this definition, we use the year switch 1989/1990 to separate the industry pre-take-off incubation stage from the industry post-take-off growth stage. Next, we expand each stage to include 6 years each, i.e. 1984–1989 and 1990–1995, to cover all major portions of the growth of both knowledge creation activity and product sales.

During our focus time frame from 1984 to 1995, a total of 1938 patents were filed in this product technology (industry) and of those, 1825 patents were owned by 180 firms based on adjusted assignee codes (113 patents did not have any assignee code). Those 1825 airbag patents made 19,518 prior art citations and received 17,781 future citations during our analysis timeframe. Because in our data set 17 firms account for about 70% of the total patents and for more than 70% of the total citations received, we focus our analysis on these 17 firms (Table 2).

Table 2. Top 17 firms and their distribution of patents and firm-years.

Firm	No. of patents	Cumulative percentage	No. of years
TRW	325	16.2	10
Morton Thiokol	262	29.3	12
Takata-Petri	180	38.3	8
General Motors	116	44.1	9
Daimler-Benz	70	47.6	10
Toyota Motor	63	50.7	9
Textron	60	53.7	7
Ford Motor	53	56.4	8
Robert Bosch	46	58.7	11
Allied Signals	45	60.9	7
Tokai Rika	41	63.0	9
Honda Motor	37	64.8	10
Breed	35	66.6	11
Nissan Motor	30	68.1	9
Denso	25	69.3	6
Dynamit Nobel	17	70.2	7
Autoliv ASP	17	71	3
Sum	1422		146
Total	2002		831

Variables

Dependent variable: invention performance

We measure firms' invention performance using the number of patent citations that the patents of a focal firm receive. Researchers have interpreted the number of citations that a patent receives from subsequent patents as an indicator of the relative importance of the focal patent (Ahuja and Lampert 2001; Fleming 2001; Gay and Le Bas 2005; Rosenkopf and Nerkar 2001; Trajtenberg 1990). The correlation between citations received and technological importance is seldom challenged; the correlation between citations received and economic value is less significant as this relationship contains substantially more noise. Thus, we limit our findings conservatively to technological impact. We define impact of a firm *i* in year *t* as the number of citations which firm *i*'s patents in year *t* receive from subsequent patents. A look at the top performing patents shows that the system architecture of automotive airbags was established in the early 1980s, after which the influential work shifted to the component level, first to inflators, then to bags, and then to electronic sensors (Figure 5).

Independent variable: knowledge creation

Because in the USA each patent must cite prior patents to recognise relevant existing technology, previous research has frequently used patent citations also as a proxy of knowledge flow (Katila and Ahuja 2002; Rosenkopf and Nerkar 2001). However, recent research has cautioned the overly optimistic use of patent citations as a proxy of knowledge flow. For example, in a study of patents from 2001 to 2003 Alcacer, Gittelman, and Sampat (2009) find that between 41% and 60% of all citations have been added by patent examiners. At the same time, while acknowledging substantial noise in patent citation data, Jaffe, Trajtenberg, and Fogarty (2002) find in their survey-based study significant evidence for knowledge spillover related to patent citations, and – employing carefully constructed research designs – recent research continues to use patent citations to study

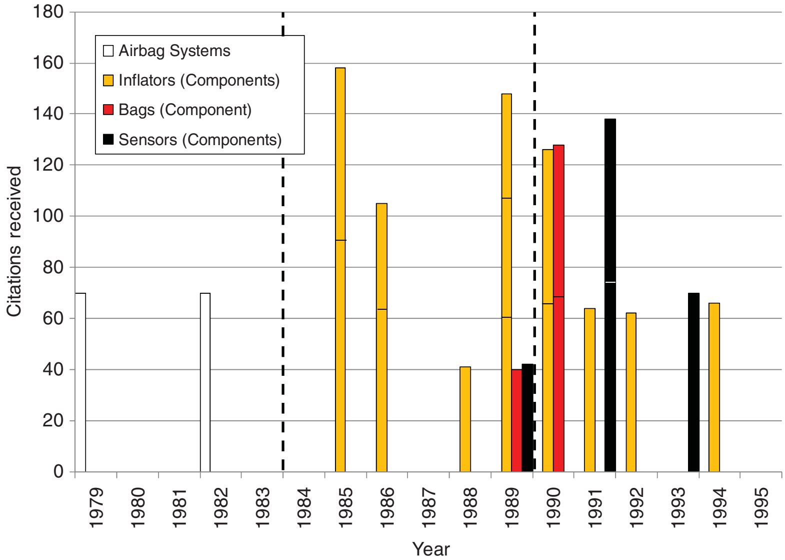

Figure 5. Impact of top 10 patents for 1984–1989 and 1990–1995, and top two patents prior to 1984.

knowledge flow (Jang, Lo, and Chang 2009; Oda, Gemba, and Matsushima 2008; Oxley and Wada 2009).

Applying our boundary definitions introduced above, and building on Rosenkopf and Nerkar (2001) we define four variables to map a firm's knowledge building activity during the focal timeframe into one of four exploration sub-areas: local, internal boundary-spanning, external boundary-spanning and radical. *Local exploration* is measured by the number of prior art citations that do not cross either the product boundary or the organisational boundary, made by a firm i in year t. *Internal boundary-spanning exploration* is measured by the number of prior art citations that cross the product boundary but do not cross the organisational boundary, made by a firm i in year t. *External boundary-spanning exploration* is measured by the number of prior art citations that do not cross the product boundary but do cross the organisational boundary, made by a firm i in year t. *Radical exploration* is measured by the number of prior art citations that cross both the product boundary and the organisational boundary, made by a firm i in year t.

We also measure the extent of knowledge search with respect to organisational boundary and product boundary independently. The extent of knowledge search with respect to organisational boundary is measured by the number of self citations made by a firm i in year t, and the extent of knowledge search regarding the product boundary we measure by the number of airbag technology-related citations made by a firm i in year t.

Figure 6 provides a view on the shifts of the top five patenting firms from 1984–1989 to 1990–1995. Note that all firms increase the fraction of within-product technology citations between pre- and post-sales take-off, a sign of a maturing technology. The firms differ, however, in the way they build on existing internal knowledge, especially in the pre-sales take-off phase. The two automobile manufacturers, GM and Daimler-Benz, and the explosives company, Morton Thiokol, bring in substantial own knowledge in the pre-sales take-off phase, but decrease this internal reliance in the post-sales take-off phase. In contrast, the two automotive suppliers, Takata

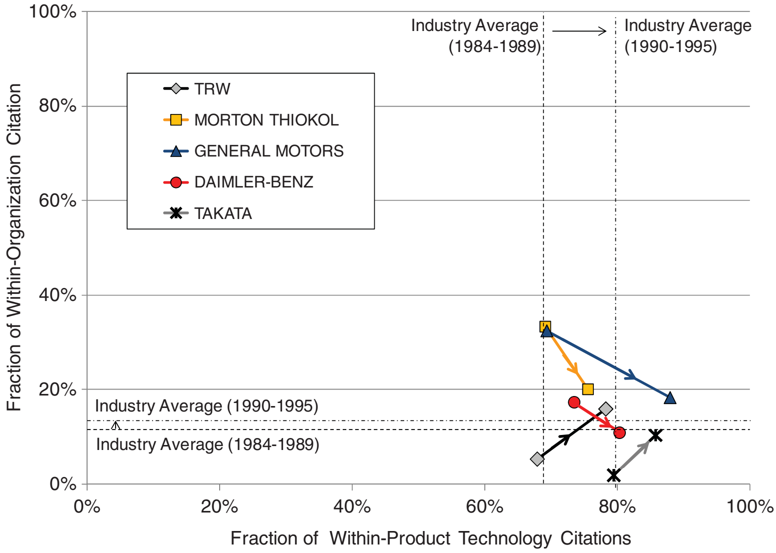

Figure 6. Shift in knowledge creation strategies of top five firms (comparing averages 1984–1989 and 1990–1995).

and TRW, who enter this niche industry without much prior knowledge in airbag technology increase their reliance on internal knowledge between pre- and post-sales take-off.

Control variables

Number of patents. Since the number of citations that a firm receives can be affected by the sheer size of a firm's patent portfolio, we include number of patents to control for this effect.

Other citations. In cases where patents do not contain assignee codes, we cannot decide whether a citation crosses an organisational boundary. We count the number of citations which cannot be assigned to any of the four types of knowledge exploration as 'other citations'.

Patent age. Since patents granted in earlier years are on average more likely to have received more citations only because they have been exposed over a longer time period we include patent age from application to year 1995 as a control.

Number of acquisitions. Acquisitions can be beneficial if the knowledge base of the acquired can be utilised (Ahuja and Katila 2001) and detrimental if managerial energy is absorbed by the integration process instead of by R&D (Hitt et al. 1991). To control for these effects we include the number of acquisitions on the subsidiary level.

Region. Knowledge may flow more effectively within national borders than across them as a result of geographic proximity, cultural similarity, or inventors' mobility (Birkinshaw and Hood 1998; Krugman 1991; Stolpe 2002). We include region dummies that are determined by the geographic location of a firm's head-quarter to account for this potential bias.

Position in supply chain. Although we focus on one industry, its players are not all identical. Research on the automobile industry has shown that the type of relationship between an original equipment manufacturer (OEM) and its suppliers impacts the performance of both OEM and supplier, and of the overall supply chain (Helper 1991). To account for this effect we include dummies to distinguish between OEMs (0) and suppliers (1).

Model specification

Since our dependent variable, invention impact as measured by the number of citations received, is an over-dispersed count variable, we specify a negative binomial distribution to allow the variance to be greater than the mean (Cameron and Trivedi 1998; Hausman, Hall, and Griliches 1984), and employ the generalised estimating equations (GEEs) regression method to account for repeated observations for the same firms over time (Dobson 2002; Hoffmann 2004).

Estimation results

Tables 3 and 4 present descriptive statistics and correlations for all variables, separately for the two timeframes of 1984–1989 and 1990–1995. Because of the additive nature of the four types of exploration variables, we control for total citations and report partial correlations with respect to total citations. Table 5 presents the estimated coefficients for the GEE regression models (Model 1 and 2) for each timeframe. We also report confidence intervals ($p < 0.05$) for the four types of exploration in Model 2 to investigate if they are significantly different from each other.

The industry pre-take-off stage (1984–1989)

In Model 1, we consider each dimension independently. As shown in Table 5, the coefficients for both self citation and airbag citation are significant and positive. This result demonstrates that in the industry pre-take-off stage developing a solution from a firm's own prior knowledge has a greater impact than searching for a solution across the organisational boundary. This finding supports Hypothesis 1A.

Model 2 presents the results considering both dimensions of knowledge relatedness simultaneously and examines the relative impact of the four different types of exploration. We find that internal boundary-spanning exploration and radical exploration obtain significant coefficients, and that the coefficient of internal boundary-spanning is significantly higher than that of radical exploration ($p < 0.05$). This result suggests a firm building on its own prior knowledge but outside of the product technology is most likely to develop high impact technological solutions in the industry pre-take-off stage, fully supporting Hypothesis 1B.

The industry post-take-off stage (1990–1995)

We hypothesised that as an industry shifts from the early incubation stage to a steep growth stage, different capabilities will be required to succeed in this new environment. Our results demonstrate that the impact of different types of knowledge searches indeed changes as the industry emerges. In Model 1, the coefficients for both self citation and airbag citation are significant and negative, which demonstrates that in the industry post-take-off stage a firm searching for a new solution outside of the firm is more likely to develop high impact technological solutions than a firm building on its own prior knowledge, providing support for our Hypothesis 2A.

In Model 2, while we hypothesised that external boundary-spanning has the highest impact in the industry post-take-off stage, we find that the coefficient of external boundary-spanning exploration is significantly higher than that of local exploration ($p < 0.05$) but significantly lower than that of radical exploration ($p < 0.05$) and insignificantly different from that of the internal boundary-spanning exploration. This result does not support Hypothesis 2B. We will return to this result in the discussion section.

Table 3. Descriptive statistics for the timeframe 1984–1989.

				Partial correlation coefficeints, $N = 49$										
		Mean	S.D.	1	2	3	4	5	6	7	8	9	10	11
1	Total impact	61.41	72.85	1.00										
2	Self citations	2.86	4.67	0.28†	1.00									
3	Airbag citations	14.98	15.65	0.31*	−0.29*	1.00								
4	Local	1.98	3.03	0.19	0.92***	−0.21	1.00							
5	Internal	0.88	2.01	0.32*	0.82***	−0.32*	0.53***	1.00						
6	External	13.00	14.24	0.17	−0.63***	0.91***	−0.60***	−0.49***	1.00					
7	Radical	5.37	8.46	−0.36*	−0.11	−0.69***	−0.10	−0.09	−0.53***	1.00				
8	Others	1.92	4.08	−0.27†	0.14	−0.65***	0.16	0.07	−0.60***	0.03	1.00			
9	No. of patents	2.88	2.60	0.54***	−0.11	0.38**	−0.14	−0.04	0.37**	−0.42**	−0.11	1.00		
10	Patent age	8.59	1.54	0.09	0.06	−0.20	−0.06	0.22	−0.14	0.19	−0.03	−0.13	1.00	
11	No. of acquisitions	1.18	1.59	0.14	−0.26†	0.20	−0.15	−0.34*	0.22	−0.08	−0.03	0.02	0.04	1.00
12	Total citations	23.14	26.94											

Note: ***,**,*,† denote significance at 0.001, 0.01, 0.05 and 0.1 levels respectively. S.D. = standard deviation.

Table 4. Descriptive statistics for the timeframe 1990–1995.

				Partial correlation coefficeints, $N = 97$										
		Mean	S.D.	1	2	3	4	5	6	7	8	9	10	11
1	Total impact	95.06	124.21	1.00										
2	Self citations	19.21	44.65	−0.52***	1.00									
3	Airbag citations	99.01	188.72	−0.11	0.01	1.00								
4	Local	17.30	40.52	−0.45***	0.96***	0.19†	1.00							
5	Internal	1.91	5.12	−0.33**	0.23*	−0.66***	−0.03	1.00						
6	External	81.71	150.00	0.20†	−0.63***	0.76***	−0.49***	−0.56***	1.00					
7	Radical	19.01	38.09	0.01	0.06	−0.93***	−0.11	0.63***	−0.75***	1.00				
8	Others	4.75	10.22	0.48***	−0.26**	−0.53***	−0.27**	0.00	−0.29**	0.23*	1.00			
9	No. of patents	1.97	1.03	0.50***	−0.33**	0.15	−0.26**	−0.28**	0.31**	−0.16	0.06	1.00		
10	Patent age	3.45	1.70	0.45***	−0.03	−0.14	−0.03	0.02	−0.10	0.07	0.23*	−0.04	1.00	
11	No. of acquisitions	0.43	0.71	−0.08	0.10	0.02	0.08	0.07	−0.04	−0.04	−0.02	0.11	−0.03	1.00
12	Total citations	124.68	237.78											

Note: ***,**,*,† denote significance at 0.001, 0.01, 0.05 and 0.1 levels respectively. S.D. = standarddeviation.

Table 5. GEE regression coefficients for pre-take-off and post-take-off timeframes.

	Industry pre-take-off stage (1984–1989)		Industry post-take-off stage (1990–1995)	
Variables	Model 1	Model 2	Model 1	Model 2
Self citations	0.0770**		−0.0059***	
Airbag citations	0.0440		−0.0221***	
Total citations	−0.0373†		0.0134***	
Other	0.0169	−0.0053	0.0061	0.00196***
Local[a]		0.0384		−0.0143***
		(−0.0452, 0.1220)		(−0.0183, −0.0104)
Internal[a]		0.1101***		−0.0010
		(0.0470, 0.1732)		(0.0339, 0.0318)
External[a]		0.0127		−0.0085***
		(−0.0164, 0.0417)		(−0.0120, −0.0049)
Radical[a]		−0.0448*		0.0146**
		(−0.0869, −0.0027)		(0.0042, 0.0250)
Number of patents	0.1922***	0.1597***	0.0959***	0.0936***
Patent age	−0.0013	−0.0710	0.2630***	0.2617***
Number of acquisitions	0.1008	0.1068	−0.0412	−0.0271
Region 0 (USA)	0	0	0	0
Region 1 (Europe	−0.5803†	−0.6350†	−0.5556*	−0.5393*
Region 2 (Japan)	−0.2152	−0.3658	−0.5922*	−0.5568†
Supply position 0	0	0	0	0
Supply position 1	−0.0358	−0.0824	−0.0045	−0.0121
Intercept	3.3024***	4.0268***	2.9273***	2.9200***
N	49	49	97	97
Overdispersion parameter	5.3559	5.2880	5.1675	5.1870
Scaled deviance	35.3714	34.6462	85.1873	84.4778
Log likelihood	365.91	376.18	1404.17	1393.70

Note: ***,**,*,† denote significance at 0.001, 0.01, 0.05 and 0.1 levels respectively.
[a]We report 95% confidence interval for estimated coefficients of four types of knowledge exploration to compare if the differences are significant.

Of our control variables, number of patents obtains significant and positive coefficients for both Model 1 and Model 2 and for both timeframes. Patent age obtains significant and positive coefficients for both models in the industry post-take-off stage but insignificant and negative coefficients for both models in the pre-take-off stage. While patents granted in earlier years are likely to have more citations because they have been available for a longer time period, the value of patents also depreciates over time. Number of acquisitions does not obtain significant coefficient in either stage. Significant (except for region 'Japan' in pre-take-off stage) and negative coefficients of region dummies suggest there is a discernable disadvantage for foreign firms. Finally, our results do not indicate that the position in the supply chain makes any difference for the firms' technological performance.

Discussion

We hypothesised that the moment of industry emergence changes the relative effectiveness of various knowledge building strategies. Testing our hypotheses empirically with data from the US automotive airbag industry, we find that this change indeed occurs. In the industry pre-take-off stage knowledge exploration within the organisational boundary has a greater impact on subsequently developed technological solutions than exploration across the organisational boundary. Moreover, the finding of an organisation inward focus but an technological outward focus is consistent with earlier research emphasising firms' absorptive capacity (Cohen and Levinthal 1990) and adaptive search (Levinthal and March 1981).

With the shift to the industry post-take-off stage of the airbag industry the higher impact on subsequent technological solutions now shifts to explorations across the organisational boundary. This result suggests that once the industry sales take-off and many fundamental questions have been answered, a focus that is too strong on the firm's own knowledge can result in core rigidities. This finding is in line with other results for mature industries (Rosenkopf and Nerkar 2001). In addition, we find that in this post-take-off stage knowledge from outside the product technology has a higher impact than more closely related knowledge. This result cannot confirm our hypothesis 2B, but might be caused by our impact measure measuring overall impact; it is possible that the product technology impact would be influenced more through a knowledge search within the product technology category.[2]

Beyond the detailed results for individual phases, this study produced two important findings. The first insight is that the grounds indeed shift when an industry emerges. This shift in relevance of various knowledge exploration patterns at the birth of the industry signals that a shift in search strategy is required, which, in turn, has implications for R&D management. It has been suggested that firms need to find the balance at the intersection of exploration and exploitation (Lavie, Stettner, and Tushman 2010) and that they need to account for different dimensions even within the exploration dimension (Rosenkopf and Nerkar 2001). To complement this body of knowledge we add that these exploration decisions should be different at very early industry life cycle stages.

The second insight carries another lesson for R&D management, and more broadly, for corporate entrepreneurship. The results explain why firms with simple, i.e. internal, access to knowledge that is somewhat distant to the original business (e.g. explosives to automobiles) but relevant in a new application (e.g. airbag inflators) have an advantage over *de novo* firms. Consequently, it is a task for company leaders to identify promising areas to which existing knowledge can be transferred and built upon.

Conclusion

The main contribution of our study is the investigation of the dynamic nature of effective knowledge creation strategies in a technology-intensive industry. We develop the idea and provide supporting empirical evidence that knowledge search is not only a multi-dimensional but also a dynamic and context-dependent concept, and that a major shift occurs as the industry moves from an embryonic stage into a growth stage, a change that needs to be actively managed.

There are at least two limitations to our study. First, patent data can only track successful inventions that are patentable. Many process inventions that are not patented are not accounted for in our data set, and, while not patented, these inventions still require active attention of the R&D management. Second, the single-industry context, while allowing to build rich datasets to unearth and analyse interesting relationships and mechanisms (Fixson and Park 2008; Lee et al. 2010), simultaneously requires caution when extrapolating the results to other settings.

A direction for future research could address this limitation and take our results and tests them in other industries. A second direction could be a study of *de novo* vs *de alio* firms. Such a study could follow Khessina and Carroll (2008) who find in their study of the optical disk drive industry that *de novo* firms experience a stronger identity imprint through activities in the focal industry compared to *de alio* firms who experienced their identity formation in other industries. These identity imprints might lead to additional variations in knowledge exploration behaviour.

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Notes

1. Because we will define an industry by using technological knowledge categories, our use of the 'product technology' dimension becomes identical to what the industry life cycle theory (Utterback 1994) has labelled 'industry' or 'product'.
2. We were unable to use a product-technology impact measure for comparison across the pre- and post-sales take-off phases as the dataset is too small in the pre-take-off period.

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References

Abernathy, W.J., and J.M. Utterback. 1978. Patterns of Industrial Innovation. *Technology Review, MIT* 80, no. 7: 40–7.

Agarwal, R., and B.L. Bayus. 2002. The market evolution and sales takeoff of product innovations. *Management Science* 48: 1024–41.

Agarwal, R., and B.L. Bayus. 2004. Creating and surviving in new industries. In *Advances in strategic management*, Vol. 21: *Business strategy over the industry life cycle*, ed. J.A.C. Baum and A. McGahan, 107–30. Amsterdam: Elsevier.

Ahuja, G., and R. Katila. 2001. Technological acquisitions and the innovation performance of acquiring firms: A longitudinal study. *Strategic Management Journal* 22: 197–220.

Ahuja, G., and C.M. Lampert. 2001. Entrepreneurship in the large corporation: A longitudinal study of how established firms create breakthrough inventions. *Strategic Management Journal* 22: 521–43.

Alcacer, J., M. Gittelman, and B. Sampat. 2009. Applicant and examiner citations in U.S. patents: An overview and analysis. *Research Policy* 38: 415–27.

Anderson, P., and M.L. Tushman. 1990. Technological discontinuities and dominant designs: A cyclical model of technological change. *Administrative Science Quarterly* 35: 604–33.

Argote, L., B. McEvily, and R. Reagans. 2003. Managing knowledge in organizations: An integrative framework and review of emerging themes. *Management Science* 49: 571–82.

Birkinshaw, J., and N. Hood. 1998. Multinational subsidiary evolution: Capability and charter change in foreign-owned subsidiary companies. *Academy of Management Review* 23: 773–95.

Breschi, S., F. Lissoni, and F. Malerba. 2003. Knowledge-relatedness in firm technological diversification. *Research Policy* 32: 69–87.

Cameron, A.C., and P.K. Trivedi. 1998. *Regression analysis of count data*. New York: Cambridge University Press.

Christensen, C.M., F.F. Suarez, and J.M. Utterback. 1998. Strategies for survival in fast-changing industries. *Management Science* 44: S207–S220.

Cohen, W.M., and D.A. Levinthal. 1990. Absorptive capacity: A new perspective on learning and innovation. *Administrative Science Quarterly* 35: 128–52.

Dobson, A.J. 2002. *An introdution to generalized linear models*, 2nd ed. Boca Raton, FL: Chapman and Hall/CRC.

Fine, C.H. 1998. *Clockspeed – winning industry control in the age of temporary advantage*. Reading, MA: Perseus Books.

Fixson, S.K., and J.-K. Park. 2008. The power of integrality: Linkages between product architecture, innovation, and industry structure. *Research Policy* 37: 1296–316.

Fleming, L. 2001. Recombinant uncertainty in technological search. *Management Science* 47: 117–32.

Foster, R. 1986. *The attacker's advantage*. New York: Summit Books.

Gay, C., and C. Le Bas. 2005. Uses without too many abuses of patent citations or simple economics of patent citations as a measure of value and flows of knowledge. *Economics of Innovation and New Technology* 14: 333–38.

Giarrantana, M.S. 2004. The birth of a new industry: Entry by start-ups and the drivers of firm growth – the case of encryption software. *Research Policy* 33: 787–806.

Gittelman, M., and B. Kogut. 2003. Does good science lead to valuable knowledge? Biotechnology firms and the evolutionary logic of citation patterns. *Management Science* 49: 366–82.

Golder, P.N., and G.J. Tellis. 1997. Will it ever fly? Modeling the takeoff of really new consumer durables. *Marketing Science* 16: 256–70.

Griliches, Z. 1990. Patent statistics as economic indicators – a survey. *Journal of Economic Literature* 28: 1661–707.

Hall, B.H., A.B. Jaffe, and M. Trajtenberg. 2002. The NBER patent-citations data file: Lessons, insights, and methodological tools. In *Patents, citations and innovations – A window on the knowledge economy*, ed. A.B. Jaffe and M. Trajtenberg, 403–59. Cambridge, MA: MIT Press.

Hausman, J., B.H. Hall, and Z. Griliches. 1984. Econometric models for count data with an application to the patents R&D relationship. *Econometrica* 52: 909–38.

Helper, S. 1991. Strategy and irreversibility in supplier relations: The case of the U.S. automobile industry. *Business History Review* 65: 781–824.

Hitt, M.A., R.E. Hoskisson, R.D. Ireland, and J.S. Harrison. 1991. Effects of acquisitions on research-and-development inputs and outputs. *Academy of Management Journal* 34: 693–706.

Hoffmann, J.P. 2004. *Generalized linear models: An applied approach*. Boston, MA: Pearson Education.

Jaffe, A.B., M. Trajtenberg, and M.S. Fogarty. 2002. The meaning of patent citations: Report on the NBER/Case-Western Reserve survey of patentees. In *Patents, citations and innovations – A window on the knowledge economy*, ed. A.B. Jaffe and M. Trajtenberg, 379–401. Cambridge, MA: MIT Press.

Jang, S.-L., S. Lo, and W.H. Chang. 2009. How do latecomers catch up with forerunners? Analysis of patents and patent citations in the field of flat panel display technologies. *Scientometrics* 79: 563–91.

Katila, R., and G. Ahuja. 2002. Something old, something new: A longitudinal study of search behavior and new product introduction. *Academy of Management Journal* 45: 1183–94.

Khessina, O.M., and G.R. Carroll. 2008. Product demography of *de novo* and *de alio* firms in the optical disk drive industry, 1983–1999. *Organization Science* 19: 25–38.

Klepper, S. 1996. Entry, exit, growth, and innovation over the product life cycle. *American Economic Review* 86: 562–83.

Klepper, S. 1997. Industry life cycles. *Industrial and Corporate Change* 6: 145–81.

Kogut, B., and U. Zander. 1992. Knowledge of the firm, combinative capabilities, and the replication of technology. *Organization Science* 3: 383–97.

Kohli, R., D.R. Lehmann, and J. Pae. 1999. Extent and impact of incubation time in new product diffusion. *Journal of Product Innovation Management* 16: 134–44.

Krugman, P. 1991. Increasing returns and economic-geography. *Journal of Political Economy* 99: 483–99.

Laursen, K., and A. Salter. 2006. Open for innovation: The role of openness in explaining innovation performance among U.K. manufacturing firms. *Strategic Management Journal* 27: 131–50.

Lavie, D., U. Stettner, and M.L. Tushman. 2010. Exploration and exploration within and across organizations. *Academy of Management Annals* 4: 109–55.

Lee, J., F.M. Veloso, D.A. Hounshell, and E.S. Rubin. 2010. Forcing technological change: A case of automobile emissions control technology development in the US. *Technovation* 30: 249–64.

Leonard-Barton, D. 1992. Core capabilities and core rigidities: A paradox in managing new product development. *Strategic Management Journal* 13: 111–25.

Levinthal, D.A., and J.G. March. 1981. A model of adaptive organizational search. *Journal of Economic Behavior & Organization* 2: 307–33.

McGahan, A. 2004. How industries change. *Harvard Business Review* (October): 87–94.

Nelson, R.R., and S.G. Winter. 1982. *An evolutionary theory of economic change*. Cambridge, MA: Harvard University Press.

Oda, T., K. Gemba, and K. Matsushima. 2008. Enhanced co-citation analysis using frameworks. *Technology Analysis & Strategic Management* 20: 217–29.

Oxley, J., and T. Wada. 2009. Alliance structure and the scope of knowledge transfer: Evidence from U.S.–Japan agreements. *Management Science* 55: 635–49.

Paananen, M. 2009. Exploring the relationships between knowledge sources in the innovation process: Evidence from Finnish innovators. *Technology Analysis & Strategic Management* 21: 711–25.

Pavitt, K. 1985. Patent statistics as indicators of innovative activities: Possibilities and problems. *Scientometrics* 7: 77–99.

Powell, W.W., K.W. Koput, and L. SmithDoerr. 1996. Interorganizational collaboration and the locus of innovation: Networks of learning in biotechnology. *Administrative Science Quarterly* 41: 116–45.

Rosa, J.A., J.F. Porac, J. Runser-Spanjol, and M.S. Saxon. 1999. Sociocognitive dynamics in a product market. *Journal of Marketing* 63(Special Issue): 64–77.

Rosenkopf, L., and A. Nerkar. 2001. Beyond local search: Boundary-spanning, exploration, and impact in the optical disk industry. *Strategic Management Journal* 22: 287–306.

Schilling, M.A. 1998. Technological lockout: An integrative model of the economic and strategic factors driving technology success and failure. *Academy of Management Review* 23: 267–84.

Schumpeter, J.A. 1942. *Capitalism, socialism, and democracy*. New York: Harper.

Stolpe, M. 2002. Determinants of knowledge diffusion as evidenced in patent data: The case of liquid crystal display technology. *Research Policy* 31: 1181–98.

Suarez, F.F., and J.M. Utterback. 1995. Dominant designs and the survival of firms. *Strategic Management Journal* 16: 415–30.

Tanriverdi, H., and N. Venkatraman. 2005. Knowledge relatedness and the performance of multibusiness firms. *Strategic Management Journal* 26: 97–119.

Teece, D.J., G. Pisano, and A. Shuen. 1997. Dynamic capabilities and strategic management. *Strategic Management Journal* 18: 509–33.

Tegarden, L.F., D.E. Hatfield, and A.E. Echols. 1999. Doomed from the start: What is the value of selecting a future dominant design? *Strategic Management Journal* 20: 495–518.

Trajtenberg, M. 1990. A penny for your quotes – Patent citations and the value of innovations. *Rand Journal of Economics* 21: 172–87.

Tushman, M.L., and C.A. Oreilly. 1996. The ambidextrous organization: Managing evolutionary and revolutionary change. *California Management Review* 38: 1–23.

Utterback, J.M. 1994. *Mastering the dynamics of innovation*. Boston, MA: Harvard Business School Press.

Van Wijk, R., J.J.P. Jansen, and M.A. Lyles. 2008. Inter- and intra-organizational knowledge transfer: A meta-analytic review and assessment of its antecedents and consequences. *Journal of Management Studies* 45: 830–53.