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Characteristics of technological base, pace of technological development, and growth of young technology-based firms

Joachim Tischler

ABSTRACT

Young technology ventures are strongly affected by technological environmental conditions. In the light of opportunity theory, this study focuses on the interaction of a young firm's technological base and the pace of technological development in its field. It distinguishes three technological characteristics: radicalness, scope, and the degree of collaborative development. Empirical results support the hypothesis that young technology-based firms commercializing radical technologies grow faster in rapidly developing technology fields. By contrast, young firms commercializing technologies that are developed through research collaborations with established firms outperform others when the pace of technological progress is relatively slow. This study provides empirical evidence of a beneficial interplay between technological characteristics and technological environment and offers a modified patent-citation-based criterion for measuring the pace of technological development in different technology fields.

EXECUTIVE SUMMARY

Technological progress is neither straightforward nor predictable. Technologies develop cumulatively along evolutionary paths on which new or enhanced technological development proceeds with discontinuities. The frequency of technological developments differs among technology fields and changes over time, of course; periods of rapid progress alternate with ponderous development. Technology-based firms and high-tech industries are both strongly affected by technological environmental conditions. Especially young ventures are governed by progress in their technological field, as they have often concentrated their efforts on a single technology and are competing with financially strong incumbent firms. Rapid progress in the field can be profitable for them, enabling them to prevail against established firms and enter existing industries. On the other hand, they face serious obstacles when their technological base becomes obsolete.

All of a firm's products and services are rooted in its technological base. This study focuses on the pace of technological progress as the key environmental factor interacting with the technological base. This environmental condition assesses the velocity of introduction of new or enhanced technological developments along their evolutionary paths in a given technological field. The present study identifies those characteristics of firms' technological bases that appear particularly beneficial given different paces of development in that field.

Building on opportunity theory, I argue that two counteracting effects derive from pace of technology field development, both of which favor young technology-based firms with a radical base. Likewise, young ventures with a broad technological base are expected to profit from rapid progress. Young ventures commercializing radical and broad technologies are supposed to profit from rapidly progressing fields, because it lets them enter existing industries with their exclusive technology and keep imitators at bay easily. In contrast, young ventures with technologies developed in collaboration with incumbent firms ought to outperform in slowly or ponderously developing technological environments, as they can profit from the incumbent's assets, expertise, and heuristics as well as from comparatively long-lasting opportunities. The pace of progress in technological fields is measured objectively and in a more nuanced and more accurate way through a patent citation-based approach using the concept of technology cycle time. Evaluating the technological base and early performance (sales growth) of 122 German academic spin-off firms across industries, I found empirical support for two of three hypotheses. The results provide evidence that young firms commercializing radical technologies grow faster in rapidly developing technology fields, while a collaboratively developed technological base fares better in relatively stable technological environments. The effect of technological scope could not be confirmed empirically from sample, neither in rapid nor in ponderous environments.

This study contributes to the entrepreneurship literature in two respects. First, it underpins recent theoretical considerations by showing empirically that dynamic fit between a firm's technological base and its environment is a source of entrepreneurial success, while dynamic mismatch in the strategy-opportunity-environment relationship causes young technology-based firms to underperform. From these results recommendations are developed that can help technology transfer offices evaluate the most promising commercialization channel (e.g. firm formation vs. licensing), and in the event of firm formation, the entry timing options for spin-offs based on particular academic inventions. Second, this article makes a substantial methodological contribution in light of recent literature emphasizing the need for fine-grained, precise ways to measure firms' environmental conditions. In light of this, I develop a modified patent-based technology indicator (technological cycle time) as an objective, fine-grained, and time-varying patent-citation-based criterion that can more accurately capture the pace of development in a field of technology.

1 INTRODUCTION

Performance and growth of young technology-based firms (YTBFs) are greatly affected by the technological environment. It influences YTBFs' formation (Shane 2001b), commercialization achievements (Agarwal & Bayus 2002), and opportunity exploitation success (Plummer, Haynie, & Godesiabois 2007). Technologies often develop along evolutionary paths interrupted by discontinuities (Dosi 1982; Foster 1985), where periods of rapid progress alternate with comparatively slow developmental periods (Anderson & Tushman 1990; Ayres 1994; Sood & Tellis 2005). In regimes of technological progress, new technological developments enhance or replace existing technological paradigms (Dosi 1982; Henderson & Clark 1990). This study focuses on the pace of technological progress as a key technological environmental condition (McCarthy, Lawrence, Wixted, & Gordon 2010), since it indicates how fast new or enhanced technological developments get introduced into a specific technological field. The rate of technological progress has several implications for young ventures and established firms.

Rapid technological progress can bring widespread change to established organizational and industrial structures (Tushman & Anderson 1986; Rosenbloom & Christensen 1994). It may make existing structures obsolete, destroy the value of existing expertise and knowledge bases, and create new markets and customer requirements (Abernathy & Clark 1985; Abernathy & Utterback 1978). In a regime of rapid technological progress, young ventures have a chance to prevail against established firms and enter existing industries, whereas incumbents face growing selection pressure as their technological base and organizational structures become increasingly obsolete (Rosenbloom & Christensen 1994; Schumpeter 1934). Hence, technological development provides entrepreneurial opportunities conducive to varying

degrees to young firms commercializing their technologies, and it varies over time and from one technological field to another (Companys & McMullen 2007).

Although dynamic environmental conditions are a central complicating factor in the opportunity exploitation process (Plummer *et al.* 2007), how they moderate the relationship between technology characteristics and young firms' success has received limited attention in the entrepreneurship literature (Nerkar & Shane 2003; Song, Podoyntsyna, van der Bij, & Halman 2008). This study contributes to this literature in two respects. First, it underscores the pace of technological progress as a crucial environmental factor in Teece's (1986) appropriability regime model of innovating firms. Recent theoretical considerations, underpinned by empirical evidence, hold that entrepreneurial success flows in part from the dynamic fit between a firm's technological base and its environmental conditions (Kor, Mahoney, & Michael 2007). Others hold that a mismatch in the strategy-opportunity-environment relationship can cause YTBFs to underperform (Plummer *et al.* 2007). The hypotheses are reasoned both through an opportunity discovery and creation theory lens, respectively. In this vein, I found some YTBFs managing to discover and create opportunities even in comparatively stable technological fields as a consequence of their technological base, a phenomenon largely neglected in the literature (Companys & McMullen 2007). Second, there have been calls recently for more fine-grained, precise measurements of firms' environmental conditions (McCarthy *et al.* 2010). The methodological contributions of this article are a modification of the technological cycle time indicator and the development of an objective, fine-grained, time-varying, and patent-citation-based criterion for measuring the pace of technological field development more accurately.

Generally, YTBFs want to commercialize products and services that are essentially rooted in their technological base (Vohora, Wright, & Lockett 2004). This study distinguishes three intrinsic characteristics of young-ventures technological bases to investigate firms' commercial potential and success operating in developing technological environmental conditions. A firm's technological base is characterized by means of its (1) technological radicalness, (2) technological scope, and (3) degree of collaborative development. These characteristics reflect major attributes of innovation diffusion theory (Rogers 2003). Basically, YTBFs commercializing radical technologies can generate predominant product and service characteristics (Dahlin & Behrens 2005). Moreover, YTBFs whose technological base has broad possible market applications and who are well protected against imitation ought to outperform firms with a narrow technological base (Lerner 1994). Young ventures are likely to commercialize technologies in a comparatively embryonic nature and early stage of market maturity (Jensen & Thursby 2001). Collaborations with incumbent firms increase their complementary assets, know-how, and heuristics (Baum, Calabrese, & Silverman 2000), which help them achieving commercial success.

This study builds on opportunity discovery and creation theory (Alvarez & Barney 2007; Zahra 2008) to develop three hypotheses. First, I argue that two counteracting effects derive from the level of technology field development pace, which paradoxically both favor YTBFs with radical technological bases. Likewise, young ventures possessing a broad technological base are expected to profit from a rapid technological progress. YTBFs commercializing radical or broad technologies are supposed to benefit in rapidly developing technology environments, because they have the chance to enter existing industries with their exclusive technology and prevent others from imitation easier. Third, young ventures that have developed their technological base collaboratively with incumbent firms ought to outperform in slowly or ponderously developing technological environments, because they can profit from established heuristics, faster entry, and comparatively long-lasting opportunities.

Empirical studies of technological environmental conditions are challenged to accurately measure the pace of development in the pertinent fields. So far, researchers have conceptualized pace (1) by categorizing technological fields as fast or slowly developing (e.g. Gruber 2007), (2) by identifying stages of the technology life-cycle in the field (e.g. Haupt, Kloyer, & Lange 2007), or (3) by surveying technology experts' estimates (e.g. Jaworski & Kohli 1993). Others have looked into a field's perceived degree of competition (e.g. Schmidt, Walter, & Walter 2013), which more likely pertains between different technology fields than within one. These measures either lack of sophistication or objectivity or both to expose the time-varying pace of technological progress in a delimited technological field (Shane 2001b). To measure the pace of technological progress more accurately and with nuance and objectivity, I apply a modified patent-based measure based on technology cycle time (Kayal & Waters 1999).

Evaluating the technological base and sales performance (growth) of 122 young German academic spin-off firms across industries, I found empirical support for two of the hypotheses. These firms were an adequate population, as the characteristics of their technological bases are highly relevant to their success at commercialization (Jensen & Thursby 2001; Shane 2001a; Vohora *et al.* 2004). The empirical results attest that YTBFs commercializing a radical technological base grow faster when technological progress is rapid. On the other hand, a technological base which is collaboratively developed with incumbent firms profits, all things being equal, in more stable technological environments. The influence of a broad technological base on a young venture's sales growth could be confirmed empirically neither in rapid nor stable technological progress regimes.

The following section derives three hypotheses from the bodies of opportunity-discovery and creation theory. Section three and four discuss the empirical investigation and the results. Certain technological characteristics prove beneficial in rapid technological progress regimes and others in more stable regimes to those firms commercializing the respective kinds of technology. Section five explores the study's implications for entrepreneurship theory, future research, and for management of young ventures.

2 DEVELOPMENT FROM THEORY

2.1 *Conceptual Background*

Entrepreneurship research often uses the concept entrepreneurial opportunities (Eckhardt & Shane 2003; Shane & Venkataraman 2000), commonly defined as “situations in which new goods, services, raw materials, markets and organizing methods can be introduced through the formation of means, ends, or means-ends relationships” (Eckhardt & Shane 2003, p. 336). They “can be treated as a latent concept underlying the [...] entrepreneurial action” (Klein 2008, p. 176). Among others, two prominent perspectives have been developed (Alvarez & Barney 2007). Entrepreneurial opportunities are viewed either as objective (i.e., entrepreneurs discover or recognize them) or subjective (i.e., entrepreneurs create or construct them) phenomena, or as both, interacting in a virtuous cycle (Buenstorf 2007; Companys & McMullen 2007; Kor *et al.* 2007; Vaghely & Julien 2010; Zahra 2008). Opportunities arise from (1) the firm’s own internal capabilities, resources, and skills, or from (2) environmental conditions (Plummer *et al.* 2007; Zahra 2008), but they remain profitable for a limited period of time only (Eckhardt & Shane 2003).

With respect to internal resources, a YTFB’s technology base is a cornerstone in opportunity theory (Companys & McMullen 2007). It is a key resource and integral factor in opportunity discovery, creation, and eventually, exploitation (Shane 2001a; Short, Ketchen, Shook, & Ireland 2010; Ardichvili, Cardozo, & Ray 2003). A young venture’s technology base is the foundation upon which products and services are commercialized to create wealth, and it determines the range of opportunities a firm can pursue in different markets (Shane 2000; Vohora *et al.* 2004). The technological base can be characterized by distinguishing (1) its technological radicalness, (2) its technological scope (Nerkar & Shane 2007), and (3) its degree of collaborative development. This third characteristic captures the fruitfulness of research collaboration as a source of external knowledge and heuristics (Baum *et al.* 2000). In innovation diffusion theory, these characteristics are major attributes behind innovation success (Rogers 2003). Item for item, these technological base characteristics do not line up easily with Rogers’ innovation attributes¹, but all three speak to the most relevant ones “compatibility”, “relative advantage”, and “complexity” (Tornatzky & Klein 1982).

The emergence, types and characteristics of entrepreneurial opportunities depend on environmental conditions (Eckhardt & Shane 2003; Eddleston, Kellermanns, & Sarathy 2008), as do the success of entrepreneurial strategies (Plummer *et al.* 2007; Vaghely & Julien 2010) and young venture performance (Hmieleski & Baron 2008; Wiklund & Shepherd 2003). In particular, young ventures’ commercialization success and their ability to serve a market depend on them (Nerkar & Shane 2003; Eckhardt & Shane

¹ For example, products based on radical technologies can provide a relative advantage on technological performance or time-saving issues but may be more difficult to use and less compatible at the same time.

2011). The *technological environment* is highly relevant for consideration by YTBFs because of the potential for market structures to shift or fall apart (Buenstorf 2007; Murmann & Frenken 2006), and because niche markets with new or specialized customer requirements evolve (Abernathy & Clark 1985). Thus, technological progress in the immediate technology field directly affects the commercialization of a young venture's technological base (Gruber 2007; Shane 2001b) and can trigger successful opportunity exploitation (Kor *et al.* 2007; Plummer *et al.* 2007). As the key environmental condition, technological progress provokes the existence of opportunities and fosters or requires the need to construct those (Abernathy & Clark 1985; Christensen & Bower 1996; Companys & McMullen 2007). Consequently, the pace of progress in the technology field – as the indicator of the velocity of introducing new, distinct, or enhanced technological developments – promotes the emergence and creation of entrepreneurial opportunities (Tushman & Anderson 1986).

Of course, whether discovered or created, entrepreneurial opportunities only remain profitable for a limited time (Eckhardt & Shane 2003; Plummer *et al.* 2007), depending on imitation by competitors (Companys & McMullen 2007), shelf life (Zahra 2008), or replacement by superior ones. In stable environments, opportunities generally stay commercially attractive for longer (Eckhardt & Shane 2003), so timing is critical to discovering, creating, and exploiting opportunities (Hjorth 2007; Choi, Lévesque, & Shepherd 2008). An empirical example of how crucial timing is lies in the restricted supportive timeframe from a study of the rigid disk drive industry (Christensen, Suárez, & Utterback 1998).

In the following, three hypotheses are developed about how young ventures fare in terms of growth performance, given the characteristics of their technological base and the pace of technological progress in their field. All three are argued both from an opportunity-discovery and from a creation theory perspective.

2.2 Hypotheses

2.2.1 Technological Base Radicalness and Sales Growth

Technological radicalness means the degree to which a technology differs from the state of the art (Gatignon, Tushman, Smith, & Anderson 2002). A radical technology combines different technological paradigms and skills and thus promotes the possibility of creating new, distinguishable, and beneficial products and services or lowering the cost of existing ones (Shane 2001a; Dahlin & Behrens 2005). In particular, a radical technology can spawn entrepreneurial opportunities (Alvarez & Barney 2007) because of its potential to undermine the advantages established firms have (Shane 2001a). For this reason, radicalness has been one of the key characteristics of YTBF technology bases investigated in the entrepreneurship literature. Recent literature attests a positive impact of technological radicalness on firm formation (Shane 2001a), but its impact on a firm's growth and survival depends on the firms' competitive

environment (Nerkar & Shane 2003; Schmidt *et al.* 2013). I argue that two counteracting effects will both favor YTBFs with a radical technological base in fast developing technological environments:

(1) First, from an opportunity discovery theory perspective, a high pace of technology field development ought to render obsolete the technological base of any firm that cannot discover new opportunities. Rapid technological progress is competence destroying particularly for incumbent firms and established industries; but for YTBFs it lowers entry barriers and brings new opportunities (Capon & Glazer 1987; Tushman & Anderson 1986). YTBFs “see the world through different lenses” and discover promising opportunities more easily (Kaplan & Tripsas 2008, p. 800). This allows them to enter an evolving niche market with specialized customer requirements or compete with established firms and industries (Adner 2002; Dosi 1982; Henderson 1993). Their radical technology and organizational flexibility let them serve these market needs with exclusive products and services or with cost advantages (Christensen & Bower 1996). Incumbents, on the other hand, face growing selection pressure (Schumpeter 1934) even as their technological base and organizational structure become more and more obsolete (Abernathy & Clark 1985; Rosenbloom & Christensen 1994). They may eschew investments in radical technologies as well, especially when it could risk cannibalizing their own technological base (Chandy & Tellis 1998; Shane 2001a).

(2) Alternatively, opportunity-creation theory suggests that a radical technology base creates ways to reconfigure and redefine prior knowledge such that opportunities actually arise from it. The technological base comprises different technological paradigms and skills and is a promising foundation for superior and distinguishable products and services. Moreover, in a rapidly progressing technological environment, a radical technological base can gain YTBFs easier access to complementary resources (e.g., venture capital) that allow it to experiment, learn, and adapt (Kor *et al.* 2007; Zahra 2008). Firms tend to establish new procedures and structures in a rapid development environment (Abernathy & Clark 1985), and it is unlikely for any one firm to possess all the resources to exploit opportunities single-handedly (Powell, Koput, & Smith-Doerr 1996). In a nutshell, firms become more interested in building alliances and creating value cooperatively (Afuah 2001; Hill & Rothaermel 2003). For example, either individual or in a collective, entrepreneurs can construct a niche in which to commercialize their radical technological bases (Luksha 2008). This results in the hypothesis:

H1: The pace of technological progress positively moderates the relationship between the radicalness of the technological base and sales growth of YTBFs. Young firms with radical technologies grow faster – c. p. – in rapidly developing technological environments.

2.2.2 *Technological Base Scope and Sales Growth*

A broad technological base benefits opportunity discovery and creation in two respects. First, it signals technological diversification and provides a wider range of applications, products, and ways to serve different market needs than a narrower base does (Khoury & Pleggenkuhle-Miles 2011; Shane 2004; Teece 1996), making it a key resource in opportunity discovery and creation (Zahra 2008). Broad technologies are more likely to be commercialized through the formation of a firm (Shane 2001a), and young firms possessing broader technologies are more likely to survive in fragmented industries (Nerkar & Shane 2007). Second, a technological base broadly protected by patents prevents competitors from imitating and circumventing the technology more effectively (Merges & Nelson 1990), perhaps keeping entrepreneurial opportunities commercially attractive for longer and generating more profits (Eckhardt & Shane 2003; Teece 1986). In fact, empirical evidence has confirmed the positive effect of broad patent protection regarding firm value (Lerner 1994). Particularly in a rapidly progressing technological environment YTBFs commercializing a technology with broad patent protection should profit from this both in the discovery and creation of entrepreneurial opportunities and thus outperform others.

(1) Opportunity-discovery theory holds that rapid technological progress comes with uncertainty about future market needs (Teece 1996), new niche markets (Abernathy & Clark 1985; Dosi 1982), and upcoming opportunities that allow YTBFs to enter both new markets and established industries (Companys & McMullen 2007). A technological base characterized by a broad range of possible applications will be compatible with a broader set of opportunities, so firms that have one can exploit the most commercially attractive opportunities as they are discovered. Simply, more avenues are open to such firms, and this bolsters their future market success (Gruber, MacMillan, & Thompson 2008). Apart from that, the broader the scope of patent protection in the firm's portfolio, the more applications it covers (Merges & Nelson 1990; Shane 2004). In rapidly progressing technological environments established firms are forced to extend and enhance their existing technological base, even as it gets increasingly obsolete (Hill & Rothaermel 2003). Broad patent protection lets YTBFs prevent imitation and circumvention of their technologies by competitors more effectively than do narrowly drawn patents (Merges & Nelson 1990).

(2) From the opportunity-creation perspective, a broad technological base increases the probability that a venture's efforts in experimenting, learning, and adaptations will result in products and services that correspond to commercially attractive opportunities. It allows different developmental areas or designs to be pursued concurrently, and the risks of setbacks or dead ends (Fleming 2001) or of customer uncertainty (Clark 1985) incurred in creating opportunities can be diversified. Uncertainty about customer requirements arises especially in fast-developing technological environments, and this gives YTBFs with a broad technological base an edge (Clark 1985). Furthermore, a broad technological base makes a firm

attractive to others interested in collaborating in order to diversify their own technological bases (Zahra 2008). Finally, YTBFs with a broad, protected technological base tend to attract venture capital, needed to build up complementary assets, more easily (Lerner 1994); in rapidly developing environments, this is crucial (Teece 1986). Formally stated:

H2: The pace of technological progress positively moderates the relationship between the scope of the technological base and sales growth of YTBFs. Young firms with broad technologies grow faster – c. p. – in rapidly developing technological environments.

2.2.3 Collaboratively Developed Technological Base and Sales Growth

In terms of their applicability and utility in serving concrete market needs and customer requirements, YTBF technological bases vary widely. Often, young ventures commercialize their technological base at a comparatively early stage of market maturity, so they must adapt and further improve their initial products and services, which usually consumes time and money (Jensen & Thursby 2001). R&D collaborations between YTBFs and incumbent firms enhance both the young venture's assets and capabilities as well as stakeholder perceptions of them (Baum *et al.* 2000; Teece 1986). Young ventures profit from complementary assets, external resources, strategic know-how, and competences (Ahuja 2000; Powell *et al.* 1996; Teece 1992), which require mostly time to establish. For example, crucial in discovering and creating opportunities, incumbent firms assist young ventures with their knowledge of solving customer needs (Shepherd & DeTienne 2005) and they extend the YTBFs' experiences and heuristics (Bingham, Eisenhardt, & Furr 2007). This knowledge and competence lets entrepreneurs commercializing a collaboratively developed technological base benefit both in discovering and creating opportunities as well as in exploiting ones; they are, briefly put, better prepared for commerce. Consequently, their technological base is considered more "exploitation-favored" (Khoury & Pleggenkuhle-Miles 2011, p. 946). I hypothesize that a technological base promotes the performance of YTBFs when the pace of technology field progress is comparatively slow and ponderous, backed by these theoretical considerations:

(1) When entrepreneurs discover promising opportunities, *a priori* strategic planning is more likely to be fruitful in slower-developing technological environments (Alvarez & Barney 2007; Gruber 2007). To reiterate, young firms whose technological base has been developed collaboratively to a high degree can develop products and services that fit concrete market needs and require fewer adaptations and improvements, and can do so easily and quickly (Vohora *et al.* 2004). They also benefit from opportunities discovered among incumbents' prior knowledge of solving customer problems (Shepherd & DeTienne 2005). In particular, when the pace of technology field progress is comparatively slow, entrepreneurs are able to create products and services better tailored to concrete market needs. This makes early strategic planning more promising, and YTBFs can outperform ventures whose technological base is

more embryonic. For example, they can establish entry barriers, exploit their own opportunities faster and with less financial commitment, and reap first-mover advantages (Patterson 1993). Their opportunities stay profitable longer in slowly developing technology fields, unlike those pursued at times of rapid technological progress, when established applications and customer needs become obsolete faster, which leads to under-exploitation and underperformance (Plummer *et al.* 2007).

(2) Entrepreneurial opportunities are created in a context of uncertainty, and entrepreneurs must grapple with time- and resource-consuming alterations and learn by doing (Alvarez & Barney 2007). The key here is that technologies developed collaboratively with established firms tend to be more mature and ready for commercial exploitation as a result of the incumbent's experience, know-how, and heuristics (Baum *et al.* 2000; Bingham *et al.* 2007). Entrepreneurs in this kind of situation need less time and financing to experiment, test, and learn, so they can create opportunities more accurately when future market needs becomes clearer; the same opportunities also remain profitable longer in slowly developing technological environments. Second, the experiences and heuristics the young venture gains are more fruitful in stable environments (Abernathy & Clark 1985; Song, Wang, & Parry 2010), and YTBFs can profit from them for a longer period. Third, R&D collaborations more easily attract external resources later on, because they indicate to venture capitalists and other potential partners that the venture's technological base is legitimate and stands a chance of being accepted in the market (Baum *et al.* 2000; Powell *et al.* 1996). Summing up:

H3: The pace of technological progress negatively moderates the relationship between the degree of collaborative development behind the technological base and sales growth of YTBFs. Young firms with collaboratively developed technologies grow faster – c. p. – in slowly developing technological environments.

3 EMPIRICAL STUDY

3.1 Method

This study combines survey and patent data from 122 YTBFs operating on patents and founded by scientists at German public research organizations (academic spin-off firms). The entrepreneurs have begun exploiting at least one entrepreneurial opportunity by founding a company commercializing academic technologies and know-how. Academic spin-offs are an adequate population for the present study because, one, they are commercializing technologies at a comparatively early stage of technological development under strong intellectual property protection, and two, their technological base is crucial to their eventual commercialization success (Jensen & Thursby 2001; Shane 2004). This study is part of a

larger research project on the early development of academic spin-off firms². The level of analysis is set at the individual young firm, allowing evaluation of venture performance determinants.

Data acquisition proceeded as follows: more than one thousand potential academic spin-offs, across industries, were contacted between 2005 and 2010; these were identified from directories of (1) public research organizations, (2) technology transfer offices, and (3) fairs, as well as from (4) internet searches using various search strings. Of these, 446 met the common definition of an academic spin-off firm (which were confirmed over the phone) and agreed to participate in a face-to-face interview using standardized questionnaires. In age and location, they did not differ substantially from non-responding firms in a mean-difference test. Information about individual- and founding-team-related factors, firm-level characteristics, and firm performance patterns was obtained during face-to-face interviews with a founder of each spin-off.

Despite several limitations, patent data is viewed as an objective source of information about a firm's technological base (Dahlin & Behrens 2005). Patent data for this study came from the PATSTAT database (version 10/2010) provided by the European Patent Office. All relevant patent families were gathered in a stepwise approach. First, promising patents were culled as those on which a spin-off name or a founder's name appeared as the inventor or applicant; this would locate patents applied for by founders, often before firm formation. Second, each patent application was checked manually to ensure its technological content fit the firms' technological base; this would certify that each patent application actually was a part of the spin-offs' technological base. Third, every application in the corresponding DOCDB patent families was collected to minimize the probability of overlooking data due to spelling mistakes in the database. Fourth, the patent application data was grouped into patent families; this aggregation procedure avoids double-counting the same technological invention. Finally, each firm's technology base characteristic is the averaged patent indicator of the corresponding patent families, if their priority application date was within three around firm formation, respectively.

In all, patent applications by 291 of the interviewed firms were identified in the database. Firms older than 13 years at observation date were excluded (6 ventures) as not being young ventures. And because this study makes use of patent-based measures to expose the technological base, young firms who did not apply for patents within three years around founding (19) were dropped. Further ventures were excluded if they were younger than four years (73) or had not reported at least four years of sales history (58), because their sales growth would be impossible to determine. Missing values for the explanatory variables reduced the final sample to 122, which applied 1220 patent families, altogether.

² The dissertations by Dickel (2008), Gupte (2007), Riesenhuber (2008), Schillo (2010), and Schmidt (2010) resulted from this project and used subsets of the project database. Dickel, Gupte, Riesenhuber, and Schillo did not examine radicalness, scope or degree of collaboration as predictor variables of sales growth. An exception is Schmidt et al. (2013) (earlier version in: Schmidt (2010)) who examined the radicalness-performance relationship moderated by technological competition and product diversity. I thank Petra Dickel, Manoj Gupte, Felix Riesenhuber, and Arne Schmidt for their help in collecting data.

3.2 Measures

3.2.1 Dependent Variable

New venture growth is an adequate indicator of opportunity outcomes (Davidsson 1991). In this study, sales revenue growth serves as the dependent variable. This is a well-established performance measure in entrepreneurship research (Brush & Vanderwerf 1992; Murphy, Trailer, & Hill 1996). It indicates the degree to which a YTBF achieves market acceptance and depicts technology transfer success (Walter, Auer, & Ritter 2006). Four years' growth (base year: four years before observation) is applied as a comparatively long-term measure of commercial success; this avoids short-term distortions, and a natural log transformation is employed to normalize the skew distribution. This is also a common procedure in entrepreneurship research (e.g. Chandler, McKelvie, & Davidsson 2009).

3.2.2 Explanatory Variables

Radicalness of technological base: In order to determine the degree of technological radicalness of firms' technological bases, a measure of patent radicalness is adopted that grades the degree of combination of different technological paradigms outside the patents' own technology fields. Following Shane (2001a), the radicalness of a patent family is measured by the number of 4-digit IPC technology classes assigned in the backward citations, minus those to which the focal patent family is assigned. The radicalness of a firm's patent portfolio, consequently, is the arithmetic mean of the patent radicalness of all firm's patent families three years before to three years after its formation.

Scope of technological base: Similar to radicalness, the technological scope of a firm's technological base is the arithmetic mean of the patent scope of all patent families filed three years before and after founding. Following Lerner (1994), the patent scope derives from the count of 4-digit IPC technology classes assigned in each firm's patent family. This measure captures the range of patent protection of the firm's technological base, its diversification, and the scope of possible applications.

Collaboratively developed technological base: The degree of collaboration is quantified as the proportion of a firm's patents filed with an incumbent co-applicant three years before and after founding. This is to indicate how intensely a young firm has collaborated with incumbent firms to develop its technological base (Khoury & Pleggenkuhle-Miles 2011; Sapsalis & van Pottelsberghe de la Potterie 2007). To ensure that any collaboration partner is really incumbent, only those firms are considered that had at least five years patenting history.

Pace of technological progress: Besides the firm's technological base, patent data are also a promising way to evaluate technological environmental conditions because they are classified into technology fields independently of market applications and boundaries and the cumulative path of technological progress is reflected in patent citations (e.g. von Wartburg, Teichert, & Rost 2005). The pace of technological

progress is measured using an objective, fine-grained, and time-varying patent-citation-based criterion. It leans on the concept of *technological cycle time* (*TCT*) aggregated at the 4-digit IPC technology field level (Narin 1994). This approach is considered suitable to determine the pace of progress in a technological field (Kayal & Waters 1999; Martino 2003). The relationship is inverse: when the *TCT* indicator in a definite technology field is comparatively low, the pace of technological progress is high. The original *TCT* measure of course captures variations both *between and within* fields because there are other differences in patenting and citation behavior among them. In fact, it differs considerably from one technology field to another (Narin 1994). I modified this measure by constructing the relative technological cycle time ($rTCT_{ij} = TCT_{ij} / \overline{TCT_i}$) such that it measures variations in the pace of technological progress in a specific and well-delimited technology field every year. This way, it excludes differences in development pace and in patenting and citation behavior between technology fields. For the numerator (TCT_{ij}), the averaged median age of all backward citations in every patent family is computed with priority in year j assigned in the 4-digit IPC technology field i ; this is similar to the *TCT* indicator in Kayal & Waters (1999) aggregated on the 4-digit IPC technology field level. In the denominator ($\overline{TCT_i}$) a patent-family-counts-weighted mean of the technology cycle time is calculated for each technology field i for the period 1980-2008 to reduce the field-specific mean TCT. This mean value is restricted to patent families between 1980 and 2008, since only young ventures founded after 1990 are considered, and the PATSTAT database version of 10/2010 lacked sufficient patents after 2008. Finally, the 3-years moving average is computed to smooth the data and eliminate short-term fluctuations and outlier effects (e.g. Haupt *et al.* 2007).

3.2.3 Control Variables

Industry sectors and technology field size: YTBFs often have options with respect to what markets and industries to serve with their technological base (Gruber *et al.* 2008). Since entrepreneurial opportunities, and thus the possibility to grow and earn profits, differ between industries (Buenstorf 2007), four dummy variables are included to capture the different *industry sectors* (electrical engineering; chemistry; pharmaceuticals; machinery engineering; software and others (reference sector)) the firms were operating in. Moreover, the *size of the technology field* is measured by computing the number of patent families (in 100,000s) in the firm's technology field in the year of firm formation.

Firm-level characteristics: To account for differences in growth patterns due to *firms' age* and *size*, the venture's age and number of employees in the year of observation are included in the regression model (Walter *et al.* 2006). Resources from *venture capital* allow young ventures to experiment and pursue different opportunities (Wiklund & Shepherd 2003). It is incorporated as a dummy variable appended according to whether venture capitalists were participating in each YTBF's equity (1) or not (0). Moreover, the *size of patent portfolio* for each firm varies broadly; it is added into the regression model to

assess for its potential explanatory power. Furthermore, *patent family size* is included as an indicator of the value of patent rights, since it reflects efforts to protect the invention abroad and correlates with the decision to renew, as renewal is costly (e.g. Harhoff, Scherer, & Vopel 2003).

Founding team characteristics: A stock of prior knowledge is essential for discovering and creating opportunities (Gruber *et al.* 2008). The *size of the founding team* serves to gauge its stock of prior knowledge (Song *et al.* 2008). Also the combination of different knowledge domains plays a major role in entrepreneurship and opportunities theory (Comanys & McMullen 2007; Kor *et al.* 2007), so the regression model incorporates *heterogeneity of the founding team*, captured as the number of distinct academic disciplines among the founding members (business administration; economics; natural science; computer science; engineering; medicine; physics; law). Furthermore, particularly in opportunity-creation theory (cultural cognitive school (Comanys & McMullen 2007)), social interaction between the entrepreneur and her environment is one of the factors that produce fruitful opportunities (Vaghely & Julien 2010). Therefore, the founders' *network capabilities* are considered in the regression model³ (Walter *et al.* 2006). Experience and heuristics are also critical for their effect on opportunity discovery and creation (Bingham *et al.* 2007; Gruber *et al.* 2008), so a dummy is included according as one of the founders had prior *founding experience* (1) or not (0).

4 RESULTS

4.1 Analytical Procedures

Descriptive statistics and bivariate correlations of all variables are shown in Table 1. The predictions are examined with hierarchical moderated regression techniques on firm level, using a longitudinal design to better justify causal inferences. To predict young ventures' performance with respect to initial technology base and environment characteristics, the firms' sales growth measure at observation is regressed on the explanatory variables from the firms' formation stage. Multicollinearity is reduced by centering all explanatory variables (Aiken & West 1991). The variance inflation factors (VIF) are below 2.8 with the highest values for industry dummies in all models, and the highest conditional index (CI) is 4.13; together with the relatively low correlation coefficients in Table 1, these values diminish concerns about multicollinearity. The Breusch-Pagan test of homoscedasticity, however, reveals that heteroscedasticity could be problematic ($\chi^2(1) = 6.45, p < 5\%$). Therefore, a heteroscedasticity-robust regression routine is conducted, estimating the regression standard errors using the Huber-White sandwich estimator in STATA 11 (Greene 2003; Tabachnick & Fidell 2007).

³ Network capabilities items are surveyed at the date of observation, as I expect those have not changed substantially since firm formation.

Table 1: Descriptive statistics and bivariate correlations ^a

Variable	Correlations																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1 Sales growth	1																		
2 Eletrical engineering	-.16	1																	
3 Chemistry	-.04	-.16	1																
4 Pharmaceuticals	.03	-.34	-.26	1															
5 Maschinery engineering	.02	-.24	-.18	-.40	1														
6 Size of technology field	.14	.03	-.14	.06	-.14	1													
7 Firm age	-.40	.07	.07	.00	-.03	-.33	1												
8 Firm size	.02	.07	-.02	.18	-.14	-.11	.31	1											
9 Venture capital ^b	.18	.07	-.02	.18	-.10	.12	-.02	.27	1										
10 Size of patent portfolio	.07	-.03	.04	.18	-.09	-.05	.04	.54	.31	1									
11 Mean Patent family size	.07	-.12	.00	.28	-.07	.08	-.11	.18	.19	.15	1								
12 Size of founding team	.27	-.14	.13	.08	-.08	.13	-.26	.10	.10	.22	.05	1							
13 Heterogeneity of founding team	.19	-.09	.02	.12	-.07	.06	-.17	.07	.06	.20	.08	.41	1						
14 Network capabilities	.23	.03	-.01	.04	-.09	.11	.09	.28	.12	.08	.08	-.02	-.03	1					
15 Founding experience ^b	.05	-.02	.06	-.01	-.01	.09	-.02	.15	.11	.15	.12	.21	.13	.13	1				
16 Technological radicalness	-.01	-.05	.16	-.09	.12	-.17	.04	.09	.02	.16	.21	.01	.14	.14	-.10	1			
17 Technological scope	.06	-.20	.08	.14	.09	-.12	-.15	.09	.21	.12	.30	.29	.23	.05	.06	.13	1		
18 Degree of collaborative development	.12	.12	-.03	-.09	-.03	-.12	-.15	.09	-.03	-.04	.16	.00	-.18	.10	-.07	.00	-.01	1	
19 Rel. technological cycle time (rTCT)	-.21	.00	-.11	-.10	.32	-.35	.28	-.04	-.09	-.09	.02	-.23	-.05	.06	.04	.22	.06	-.11	1
Mean	1.03	0.17	0.11	0.36	0.22	0.15	6.89	17.83	0.18	10.00	3.28	3.12	1.58	22.84	0.30	4.60	2.19	6.24	0.96
Standard Deviation	0.93	0.38	0.31	0.48	0.42	0.15	2.24	22.62	0.39	16.91	2.11	1.49	0.75	2.44	0.46	2.58	0.87	15.37	0.05
Min	-0.85	0	0	0	0	0	4	1	0	1	1	1	1	15	0	0.0	1.0	0	0.83
Max	3.98	1	1	1	1	1	13	146	1	134	18	8	4	28	1	12.8	5.4	78	1.11

^a $p < 0.05$ for $r > |0.18|$; $p < 0.01$ for $r > |0.23|$. Two-tailed tests. ^b Coding: 1 = YES, 0 = NO.

4.2 Regression Results

All six regression models explain a considerable amount of variance in sales revenue growth (adjusted R^2 : 0.23 – 0.32). First, the above mentioned control variables enter the model (Table 2, Model 1). The expected relationship of the firm age, network capability, and venture capital engagement is confirmed. The second step adds the main effects of the technological base characteristics (Model 2). No direct effect of the focused characteristics can be observed. Models 3 to 6 depict the interaction effects successively. The regression analyses provide empirical evidence that technological environmental conditions and the characteristics of a firm's technology play an influential role. The results show that the pace of technological development in the field of operation significantly moderates the relationships of technological radicalness and degree of collaborative development on firms' performance. Simple slope analyses, as recommended by Aiken and West (1991), bolster the significance of the interaction effects for technological radicalness (Figure 1) and collaborative base development (Figure 2). It appears that a radical technological base, per se, does not guarantee outstanding young venture performance. Moreover, firms focused on commercializing radical technologies outperform others when they were founded in a fast-developing technological environment rather than in a stable one. On the other hand, if the pace of technological progress is slow (indicated by a high $rTCT$ value), YTBFs with a less radical technological base edge out those with a more radical base (Figure 1; low moderator: $b = 0.12, t = 2.47, p < 0.05$; high: $b = -0.08, t = -2.66, p < 0.01$). In contrast, firms commercializing a highly collaboratively developed technological base perform better in more stable technological environments (Figure 2; low: $b = -0.01, t = -1.15, n.s.$; high: $b = 0.01, t = 1.86, p < 0.1$). Again, the degree of collaborative development has no direct effect on sales growth. These results support hypotheses 1 ($p < 0.001$) and 3 ($p < 0.01$), but hypothesis 2 is not supported in the sample: neither directly nor in interaction with the pace of technological development, does the scope of a YTBF's technological base seem to impact its early sales growth substantially.

Table 2: Regression results on sales growth

	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6	
	b	rob.S.E.	b	rob.S.E.	b	rob.S.E.	b	rob.S.E.	b	rob.S.E.	b	rob.S.E.
<i>Control variables</i>												
constant	1,03 ***	0,07	1,03 ***	0,07	1,08 ***	0,07	1,03 ***	0,07	1,05 ***	0,07	1,10 ***	0,07
Electrical engineering	-0,60 *	0,26	-0,59 *	0,26	-0,45	0,27	-0,59 *	0,26	-0,59 *	0,25	-0,46 ^t	0,26
Chemistry	-0,44	0,29	-0,39	0,31	-0,44	0,31	-0,39	0,31	-0,36	0,31	-0,43	0,31
Pharmaceuticals	-0,37	0,25	-0,34	0,27	-0,33	0,26	-0,34	0,26	-0,33	0,26	-0,33	0,26
Machinery engineering	-0,24	0,30	-0,09	0,34	0,01	0,35	-0,09	0,35	-0,09	0,34	0,01	0,35
Size of technology field	-0,43	0,57	-0,81	0,60	-0,54	0,63	-0,81	0,61	-0,82	0,60	-0,55	0,63
Firm age	-0,16 ***	0,04	-0,16 ***	0,04	-0,16 ***	0,04	-0,16 ***	0,04	-0,15 ***	0,04	-0,15 ***	0,04
Firm size	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Venture capital ^b	0,40 ^t	0,23	0,45 *	0,22	0,40 ^t	0,22	0,46 *	0,22	0,46 *	0,22	0,41 ^t	0,22
Size of patent portfolio	0,00	0,01	0,00	0,01	0,00	0,01	0,00	0,01	0,00	0,01	0,00	0,01
Mean patent family size	-0,01	0,05	0,02	0,05	0,03	0,04	0,02	0,05	0,01	0,05	0,02	0,05
Size of founding team	0,09	0,06	0,10	0,07	0,09	0,06	0,10	0,07	0,11	0,07	0,10 ^t	0,06
Heterogeneity of founding team	0,09	0,11	0,14	0,12	0,17	0,12	0,14	0,12	0,14	0,12	0,17	0,12
Network capabilities	0,10 **	0,03	0,11 ***	0,03	0,12 ***	0,03	0,11 ***	0,03	0,11 ***	0,03	0,12 ***	0,03
Founding experience ^b	-0,09	0,18	-0,10	0,19	-0,11	0,18	-0,10	0,20	-0,09	0,19	-0,09	0,19
<i>Main effects</i>												
Rel. technological cycle time (rTCT)			-1,68	1,65	-1,25	1,42	-1,72	1,68	-1,13	1,56	-0,72	1,37
Technological radicalness			-0,02	0,04	0,02	0,03	-0,02	0,03	-0,02	0,03	0,02	0,03
Technological scope			-0,15	0,10	-0,15 ^t	0,09	-0,15	0,10	-0,17 ^t	0,10	-0,17 ^t	0,09
Degree of collaborative development			0,00	0,01	0,00	0,01	0,00	0,01	0,00	0,01	0,00	0,01
<i>Interaction effects</i>												
Technological Radicalness x rTCT					-1,86 ***	0,45					-1,89 ***	0,45
Technological Scope x rTCT							-0,19	1,78			-0,33	1,35
Degree of collaborative development x rTCT									0,18 *	0,07	0,19 **	0,07
F-value	3,91 ***		4,11 ***		5,00 ***		3,83 ***		4,63 ***		5,29 ***	
R ²	0,32		0,35		0,42		0,35		0,36		0,44	
adj. R ²	0,24		0,24		0,32		0,23		0,25		0,32	

^a n = 122. ^b Coding: 1 = YES, 0 = NO.; ^t p < .10; * p < .05; ** p < .01; *** p < .001 (two-tailed test).

Figure 1: Interaction effect of technological radicalness and pace of technological progress

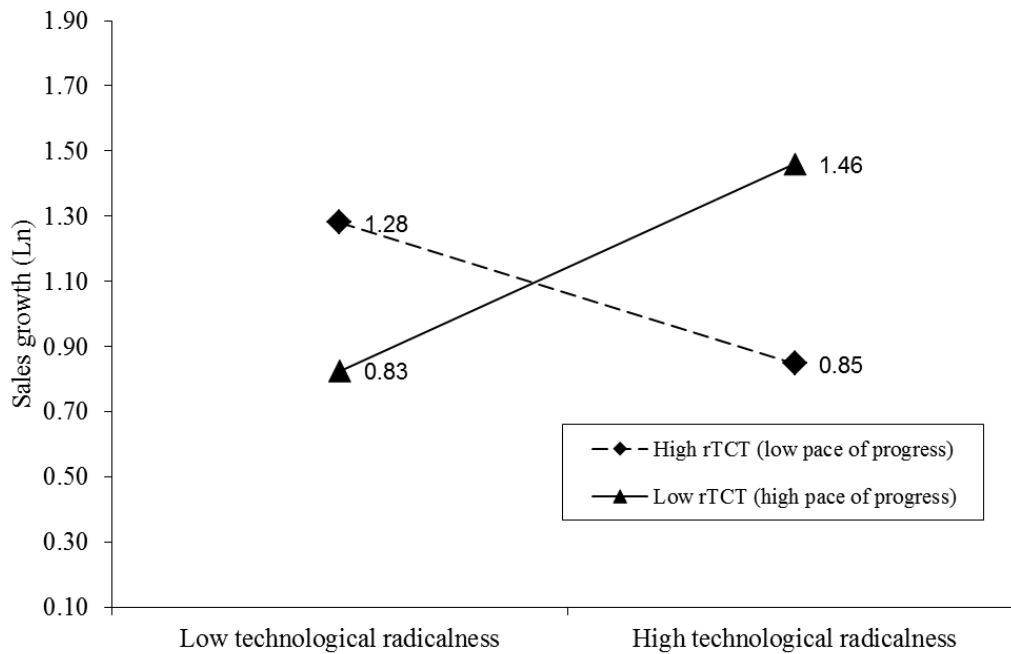
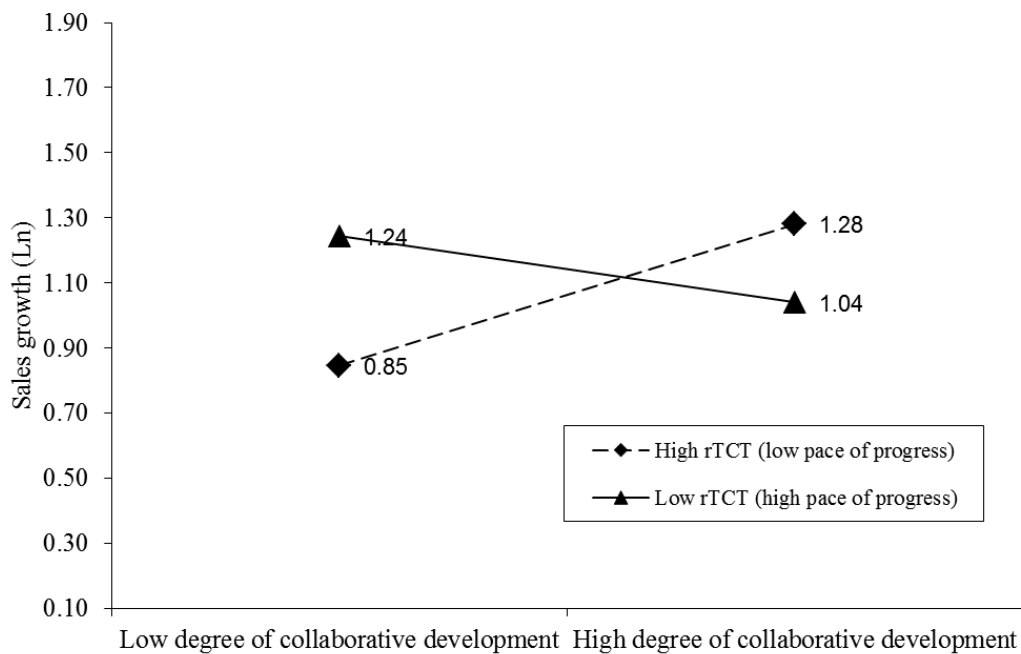


Figure 2: Interaction effect of degree of collaborative development and pace of technological progress



The results were subject to several tests for robustness and alternative variable operationalization. First, Kayal & Waters' (1999) original technological cycle time indicator was considered instead of the modified pace-of-technological-progress measure, yielding the same direction for all interaction effects but markedly lowering their significance. I believe that measure indicates differences *between* technology

fields rather than *within* one, and therefore that it captures the specific and time-varying development velocity much less appropriately (see discussion for further remarks). Next, I included the two variables perceived degree of technological competition and product diversity as moderators of the radicalness growth relationship (Schmidt *et al.* 2013), yielding the results stable. The following steps were taken in addition: (1) different degrees of technological classification aggregation (3- and 4-digit IPC level) were considered both for the explanatory and the moderating variables; (2) collaborating firms were allowed into the collaborative development variable regardless of their patenting history; (3) all control variables were dropped; (4) venture origin, base-year sales, industry experience, and entrepreneurial orientation of the founding team were added separately; (5) the range of considered patents was expanded from three to five years before and after firm formation; (6) firms younger than five or older than ten years were excluded; last, (7) outlier-robust weighted regression procedures were performed without correcting standard errors due to heteroskedasticity. All additional estimations yield nearly the same results, sometimes with slightly weaker significance (not exceeding $p < 0.08$).

5 DISCUSSION AND IMPLICATIONS

This study contributes to entrepreneurship research in at least two respects. As Kor *et al.*'s (2007) theoretical considerations suggest, the dynamic ties between entrepreneurial opportunity and the firms' environment is one of the major entrepreneurial success factors. Furthermore, Plummer *et al.* (2007) argue that mismatch between opportunity exploitation strategy and the opportunity-environment is likely to occur in rapidly progressing environments that will result in underperformance. Empirical results from the present study provide evidence that the interaction between the technological base and the pace of progress in the technology field, both sources of opportunity in literature, affect young venture's growth and commercial success. This enhances our understanding, for it appears that the effects of either technological characteristics or the environment alone are of secondary significance; it is primary their interaction from which promising opportunities arise. This study thus underscores both the importance of the technological environment for theoretical considerations in opportunities theory as well as its actual moderating role in new venture performance. I have found YTBFs successfully discovering and creating opportunities in comparatively stable technology fields given certain characteristics of their technological base, which is also a novelty in entrepreneurship research (Companys & McMullen 2007). This study's findings reveal the relevance of the pace of technological progress for innovating firms, contributing to empirical verifications of Teece's (1986) appropriability regime. Teece differentiates between legal and technological environmental effects on the profitability of technological innovations (Teece 1986). I believe this study contributes to his framework evidence of how influential the pace of technological progress is. Also, it appears that technology experts cannot well evaluate environmental conditions for a lack of accuracy and objectivity (Shane 2001b). In this connection, the modified measure of relative

technological cycle time this study uses proves an objective, fine-grained, and time-varying patent-citation-based criterion that can measure the pace of progress in a technology field and do so at different precision levels, a welcome step up from more bias-prone measures. Additional testing for validity was done by correlation analyses of the modified measure (*rTCT*) against established measurements. It showed a moderately significant correlation between the original *TCT* indicator and both technological turbulence (Jaworski & Kohli 1993) and technological competition (Schmidt *et al.* 2013) (both judged by the spin-off founders), but none between *rTCT* and either of the subjective indicators. It seems reasonable to suppose that founders can easily rate differences between technology fields, but apparently they are bad at tracking how the pace of progress within technology fields change over time. Yet understanding the pace of progress is key to discovering or creating entrepreneurial opportunities.

This study has a number of implications for young venture management and technology transfer. First, it provides empirical evidence pertaining to entry timing, which is shown to be sensitive to the pace of technological progress, and leads to recommendations for how to time the entry of a YTBF based on an academic invention. For example, a radical technology ought to be commercialized through spin-off formation – *ceteris paribus* – at a time of fast-paced progress in the field. Second, transfer offices must sometimes decide whether to support spin-off formation or license a technological invention to existing firms. The insight this study gives should be valuable to them. Although we do not understand under which circumstances academic inventions are most fruitfully exploited by established firms, recommendations for young ventures still emerge. This study suggests radical technologies should be commercialized by firm formation in rapidly progressing technological environments, whereas collaboratively developed technologies are more promising in stable environments, as judged by early sales growth numbers in the respective cases. Future research is invited to take the same line (i.e., look at different technology characteristics and the pace of technological progress) but focus on how incumbent firms fare exploiting the inventions. Third, the modified pace of technological progress indicator proves a practical measurement for use by young venture management and technology experts. This study provides them an easily-computable, objective, and fine-grained indicator of the pace of technological progress they can deploy in evaluating this crucial aspect of the technological environment, approximating future development in a technology field, and choosing suitable entrepreneurial strategies.

This study is not without limitations. First, its empirical purview is limited to German academic spin-off firms whose technological base builds on patents. Although nothing indicates that the results are peculiar to German spin-offs, the arguments and hypotheses ostensibly pertain to young ventures, regardless of origin or nationality and so generalize in a way not backed by empirical evidence. Future research should therefore investigate the moderating role of developmental pace in light of national differences and of different firm types. Second, since the performance measure is sales growth, only such firms are

investigated as manage to achieve years of sales revenue commercializing their technological base. This brings up the possibility of sample selection bias, for which reason truncation-correction and Heckman's sample selection techniques have been incorporated⁴ (Greene 2003). Since no substantial influence is found for firms that have not made sales yet, all results remain stable. A third limitation lies in the impossibility of making statements about YTBFs that fail in few years after founding. Relatively few of the interviewed spin-off firms have failed since the survey (approx. 10%). Nevertheless, some research has shown that technological characteristics and environmental conditions do affect new venture survival (Nerkar & Shane 2003), so it is important to note that this study refers to surviving YTBFs. Last, one consequence of a singular focus on pace to characterize the technological environment is that any conclusions must be made with *ceteris paribus* restrictions on other aspects such as complexity or munificence (McCarthy *et al.* 2010). Further research needs to be done to objectively measure these aspects of the technological environment.

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⁴ As an additional instrumental variable the link to scientific literature is considered in the selection equation. It is significantly (negatively) correlated with appearance of sales growth and measured by the share of non-patent-literature in the firm patents' backward citations.

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