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Antecedents of cooperative commercialisation strategies of nanotechnology firms

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ABSTRACT

We examine the antecedents for cooperative behaviour in the commercialisation of nanotechnology for both small/medium and large firms. For small and medium firms (SMEs) our results confirm the influence of complementary assets and transaction costs, but surprisingly do not support any influence of intellectual property rights protection on cooperative behaviour. For large firms the results show a negative relationship for both intellectual property rights protection and ownership of complementary resources with cooperative behaviour. Overall, collaboration-based commercialisation in nanotechnology for both small/medium as well as large firms seems to follow antecedents previously identified in earlier studies. In addition, we find that in the current stage of the nanotechnology commercialisation environment, intellectual property rights protection for small/medium-sized enterprises is associated with the acquisition of other firms.

1. Introduction

Understanding how scientific knowledge translates into commercially viable products in the marketplace is an important research issue (Arora et al., 2001; Gans and Stern, 2003; Goldfarb and Henrekson, 2003; Sobrero and Roberts, 2002) and it is a common mistake for inventors to underestimate the difficulty in commercialising science and technology (Hung and Chu, 2006; Waitz and Bokhari, 2003). Nanotechnology is emerging from recent scientific advances to which marketers and investors attribute enormous commercial potential (e.g. Bozeman et al., 2007). For example, estimates about the total worldwide market size add up to over US$ 1 trillion in 10–15 years (National Science Foundation, 2001). Today already, articles on topics related to nanotechnology account for 2.5% of scientific articles and 0.7% of patents, which can be seen as an indication that the commercial potential of nanotechnology will have at least the same magnitude as biotechnology (Wonglimpiyarat, 2005; Zucker and Darby, 2005). However, according to research by Meyer (2001), nano-patents tend to cite only other patents and to a much smaller degree scientific research papers. This is remarkable in view of the fact that nanotechnology is very much a science-based discipline. According to Lemley (2005) the very building blocks of a technology are being patented in nanotechnology. As nanotechnology is an emerging technology, in situations such as technological change there is a certain risk that too broad patents are being granted. This has also been the case in biotechnology where patents have been granted on upstream research results (Heller and Eisenberg, 1998; Zekos, 2006).

According to the United States National Nanotechnology Initiative, nanotechnology can be defined as (i) research and technology at the atomic, molecular or macromolecular levels, i.e. a length scale below 100 nm; (ii) creating and employing structures, devices and systems with novel properties and functions which are due to their small and/or intermediate size; (iii) the possibility to control and manipulate on the atomic scale (Bonaccorsi and Thoma, 2005, 2007; www.nano.gov). Another remarkable characteristic of nanotechnology is its complex industrial structure, in which funders (public and private), large firms, subsidiaries, joint ventures, universities, research organisations, small companies and start-ups interact in non-traditional ways (Cientifica, 2003). Also, since nanoscience is rooted in a number of sciences (physics, chemistry, biology, and engineering), nanotechnology at the industrial level covers a number of different industries such as energy, aeronautics, telecommunication, information technology and bio-technologies (Kahane et al., 2008).

Research so far has studied the economic potential and market applications of nanotechnology in a variety of different fields, e.g. electrical and chemical engineering (Kenney and Goe, 2004; Mowery and Rosenberg, 2000), medical instruments (Trajitenberg, 1989) and biotechnology (Owen-Smith et al., 2002; Zucker and Darby, 1996).

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Despite the fact that the relevance of nanotechnology commercialisation is widely acknowledged by researchers and industry experts alike, previous studies to our knowledge have not yet examined the commercialisation strategies of nanotechnology firms. Prior studies show that the commercialisation of an invention can be pursued by either following a competitive product market strategy, which requires that the innovator offers an integrated value proposition and avoids detection and a competitive reaction from established market players, or by cooperating with others (Gans and Stern, 2003; Gans et al., 2002; Wilson and Appiah-Kubi, 2002). Gans et al. (2002) show that cooperation is more efficient than an independent entry on the market when the supplier of ideas has strong intellectual property rights (IPR), the search and bargaining costs for finding a cooperation partner are low, and the potential partner owns important complementary resources. In order to understand the commercialisation dynamics in the emerging nanotechnology context, we examine the antecedents of cooperation.

Consequently, we pose the following research question: To what extent do intellectual property rights, low search and bargaining costs, and the importance of complementary assets have an influence on the decision to pursue a cooperative as opposed to a stand-alone commercialisation strategy of nanotechnology inventions?

We derive hypotheses that link intellectual property rights, search and bargaining costs for finding a cooperation partner, the ownership and importance of complementary resources to cooperative commercialisation strategies. We test our hypotheses using samples of both small/medium and large nanotechnology firms since previous studies show that in the nanotechnology context small and large firms innovate and commercialise (Bhat, 2005).

Two of our four hypotheses are confirmed for small/medium as well as large firms. With regard to commercialisation preferences, firms in both samples prefer competitive market entry over cooperative strategies. Furthermore, contrary to the assumption that intellectual property protection fosters cooperative strategies and licensing, we find strong evidence, that intellectual property rights holders prefer acquisition of other firms over a commercialisation strategy.

The reminder of the paper is organised as follows. The next section develops hypotheses about the relationship between commercialisation environment and commercialisation strategy. Following the data and methodology section, we present the empirical results. The final section concludes with a discussion and suggestions for future research.

2. Theory and hypotheses

We examine whether a cooperative commercialisation strategy used by nanotechnology innovators is associated with intellectual property rights protection, the cost of searching for and bargaining with a cooperation partner and the ownership of complementary assets. The appropriability regime refers to the institutional factors that govern an innovator's ability to capture the profits generated by an innovation (e.g. Katz and Shapiro, 1985; Teece, 1986). According to Teece (1986) the most important specifications of such a regime are the nature of the technology and the efficacy of legal mechanisms of protection. Intellectual property protection has been discussed many times as being crucial to nanotechnology companies (Harris et al., 2004; Luther et al., 2004).

Nanotechnology is considered a new technological paradigm; therefore, there is a lot of uncertainty involved. Patenting at the molecular level raises questions about ownership of matter at the molecular level. Thus, the appropriability regime is of central importance. With a strong patent position (tight appropriability) a firm can access complementary resources solely by means of a contract, which can be a licensing or an outsourcing agreement. Stronger patents can encourage licensing because they make it more difficult for the licensee to invent around the patent. More generally, since licensing implies lower control on the diffusion of the technology, the strength of patent protection makes it more difficult for anyone to free ride on the right to use or produce the technology. Gans et al. (2002) found evidence that innovators who control intellectual property rights are more likely to pursue a cooperative strategy for commercialising their invention than a competitive market entry.

However, given the unique nature of nanotechnology, large firms play an important role in innovation. We argue that for large firms the relationship between intellectual property protection and cooperation can actually be reversed. Large firms usually have expertise and own complementary assets necessary for commercialisation. Thus, for them there might be no need to cooperate since they can commercialise their innovation with their own resources.

Hence,

H1a. There is a positive relationship between intellectual property rights protection of SMEs and a cooperative commercialisation strategy.

H1b. There is a negative relationship between intellectual property rights protection of large firms and a cooperative commercialisation strategy.

A key argument in transaction cost economics is that transactions should be aligned with governance structures in an efficient way (Oxley, 1997, Williamson, 1991). According to transaction cost theory, firms as integrated constructs only have a right to exist if they are able to solve the coordination and motivation problems more efficiently internally than through interaction with external partners on the market. According to Williamson (1991), particularly heavy transaction problems arise when economic subjects, endowed with bounded rationality and acting in an opportunistic way, enter transaction relations with a high degree of uncertainty, and when information and knowledge is asymmetrically distributed among the transaction partners (Williamson, 1991). In these cases, pure market forms of exchange, coordinated over the price mechanism, have too many transaction costs. Consequently, there is a large variety of arrangements for the exchange of technologies or technological services, ranging from joint ventures, partnerships, or strategic alliances to licensing and cross-licensing agreements (Arora et al., 2001; Sobrero and Roberts, 2002).

However, even if intellectual property rights are well defined, there may still be uncertainty and ambiguity about potential cooperation partners as well as the value or the characteristics of the new technology. Recently, many areas of nanotechnology have witnessed a sharp increase in the number of patents filed (Koppikar et al., 2004). European Patents are granted by the European Patent Office. However, it is the national courts that have the final say as to the validity of such patents in their respective countries. The national courts sometimes contradict the European Patent Office. As a consequence, nanotechnology patentees can find themselves in the unfortunate situation of being granted a European Patent which may not be enforceable in Europe's largest national market (Germany). Patentees should thus be aware of both the European and German patentability criteria when drafting their European claims and, if necessary, introduce additional claims specifically designed for enforcement in Germany. In summary, the increasing number of patents in this field means that those seeking to commercialise products must look out for patents of others. Patents in the area of nanotechnology may be so broad in scope of the claims and enablement issues. Nanotechnology brings together many scientific disciplines. As a result of the characteristics of nanotechnology, unique legal issues will arise. Currently it is unclear how well nanotechnology patents could be enforced. Especially tricky is the “doctrine of inherency”, under which a prior reference may “inherently” anticipate a claimed invention, even if the reference does not expressly disclose the later invention. There is a great deal of uncertainty regarding the validity and scope of nanotechnology patents. Furthermore, there is a backlog of unexamined patent applications and increasingly long periods for patent pendency. The number of judicial opinions on nanotechnology patents is still limited, there is a lack of standardised terminology; the definitions used in the patent applications are often unclear, conflicting terminology sets patent holder up for patent litigation suits or cross-licensing agreements. As a result, many nanotechnology patent holders live with the uncertainty as to whether someone will dispute their claim at some point down the road.

This uncertainty may induce search costs and necessitate detailed bargaining between the parties about royalty rates and other contingent contracting provisions (Gans et al., 2002). Thus, the lower the level of search and bargaining costs associated with following a cooperation strategy are, the more probable is it to follow this strategy for commercialising an innovation. This applies equally to small, medium and large firms.

H2. There is a negative relationship between the search and bargaining costs and establishing a cooperative commercialisation strategy

Successful commercialisation of an innovation generally requires that the know-how in question be utilised in conjunction with other capabilities or assets (Avenel et al., 2007; Greis et al., 1995; Luukkonen, 2005), such as marketing, competitive manufacturing, and after-sales support. Cooperation allows innovators to exploit complementary assets controlled by other firms (Autio and Yli-Renko, 1998; Gans et al., 2002; Gans and Stern, 2003). Both large and small firms might differ in their assessment of necessary complementary assets but will both have incentives to cooperate if they perceive that the cooperation partner owns valuable resources.

Nanotechnology is a generic and radical technology that is of high interest due to its potential for value creation across a broad range of industries and applications. As a generic technology, nanotechnology offers the potential for value creation across a broad range of industries and applications, which will yield benefits for a wide range of sectors of the economy and/or society (Keenan, 2003). Generic technology may face high barriers to commercialisation despite its potential for value creation. Nanotechnology has the potential to lead to radical innovations downstream in several industry value chains (Klevorick et al., 1995). Nanotechnology has divergent dynamics and within the overall field of nanotechnology several subfields can be identified, such as ionic channels, molecular motors, nano-instrumentation, nanofabrication, and nano-electronics materials and nano-materials. However, the aforementioned fields account for the majority of publications and patents (Bonaccorsi and Thoma, 2007).

Biotechnology and nanotechnology share many characteristics but differ in others as studied by Rothaermel and Thursby (2007). They examined whether the adaptation of incumbent firms to new methods of inventing follow similar industry patterns across industries and inventions and they compare the biotechnology and nanotechnology industry. In the biotechnology industry, the new biotechnology firms, alliances with pharmaceutical companies provided complementary assets for commercialisation of products; and for the pharmaceutical firms, the new enterprises provided the critical expertise in new technology for discovery as well as manufacturing and process development, bolstering their fledging product pipelines (Galambos and Stuchio, 1998; Henderson et al., 1999). Similar arguments can be made for R&D sourcing by pharmaceutical firms through acquisition of research-intensive small biotechnology firms. By drawing on the expertise of the new biotech firms, incumbents companies were able to adapt to the revolutionary changes in molecular biology. Although the sources of the enabling inventions in nanotechnology and biotechnology differ, with the latter coming from university labs, both were revolutionary in that they were entirely new methods of inventing (Darby and Zucker, 2005).

Rothaermel and Thursby (2007) argue that because the scientific discoveries underlying both nanotechnology and biotechnology represent inventions of methods of inventing one might expect to observe similar development patterns in the strategies of incumbent firms when attempting to build an innovative presence in nanotechnology. Darby and Zucker’s work which compares biotechnology and nanotechnology shows similar publishing, patenting, and the entry of academic start-ups near academic centres as was the case in the biotechnology revolution. However, Rothaermel and Thursby (2007) argue that differences between nano- and biotechnology exist, because the enabling technology of nanotechnology was commercially available much faster than biotechnology which took over two decades. Thus, they suggest that incumbents firms in biotechnology would rely on alliances and acquisitions much longer than would incumbents firms in nanotechnology. They examine whether bio- and nanotechnology exhibit similar evolutionary patterns. They argue that one might expect similar evolutionary patterns because both biotechnology and nanotechnology represent new methods of inventing, but that the period of excludability might have been longer in biotechnology than in nanotechnololgy. They also state that differences in bio and nanotechnology may be a reflection of the different degrees of maturity in the two technology cycles. While nanotechnology catches up fast with biotechnology it is a younger technology, thus external knowledge stocks might be more important in future stages of development and maturity.

While avoiding duplication of sunk assets is important in some environments, complementary assets confer minimal value in settings where innovation makes the existing complementary assets obsolete (Gans et al., 2002; Henderson, 1993). As the sunk costs of a competitive product market entry increase, the gains from trade between innovators and complementary asset holders increase and so innovators will be more likely to forego a competitive product-market entry (Gans et al., 2002). However, if the innovator is already owner of the complementary assets necessary for commercialising their innovation, the probability for choosing a cooperation strategy decreases. Thus,

H3a. There is a positive relationship between the importance of complementary assets for the commercialisation of a given innovation and a cooperative commercialisation strategy.

H3b. There is a negative relationship between the degree of ownership of complementary assets for a given innovation and a cooperative commercialisation strategy.

3. Data and method

3.1. Sample, survey design and data collection

We obtained data through two pre-tested surveys of small/medium and large nanotechnology firms in Germany from November 2005 through January 2006. According to European Union classification for firm sizes, small and medium firms are those with less than 250 employees whereas the number of employees in large firms exceeds this threshold (European Commission, 2004). The survey approach is appropriate because publicly available financial information does not provide the level of detail that we needed for this study, including fine-grained information concerning the strategy and characteristics of these firms.

Therefore all data were self-reported, but previous research supports to the reliability and validity of self-reported measures in this field (Brush and Vanderwerf, 1992; Gans et al., 2002; Orpen, 1993), especially if other sources are unavailable, as in the study of young and privately held small firms (Dess and Robinson, 1984). Furthermore, managerial judgment provides the opportunity to gather information concerning multiple dimensions of firm characteristics and development. To ensure that a high proportion of the answers were valid, the questionnaires were sent personally addressed to the CEOs and/or founders of the firms (Brush and Vanderwerf, 1992; Huber and Power, 1985). CEOs and founders are considered the single most knowledgeable and valid information sources, especially regarding strategic information (Glick et al., 1990), such as a firm's commercialisation strategy. We are, of course, aware of the trade-off between objective data collected from secondary sources at several different times and data richness derived from primary sources; given the unavailability of sufficient data, we therefore had to opt for a survey approach of self-report data (Lyon et al., 2000).

We are also aware that all questionnaire data is susceptible to Common Method Bias which can result in misleading conclusions (Campbell and Fiske, 1959) and we took several procedural techniques as suggested by Podsakoff et al. (2003) to control method bias. First, we separated the measurement of criterion and predictor variable proximally and psychologically. Second, we guaranteed the protection of respondent anonymity and thus reduced evaluation apprehension. Third, we paid special attention to the wording of the items to avoid ambiguity or complicated syntax, and kept it simple, specific and concise. In addition, we examined both the individual variables as well as the relationships among them prior to the statistical analyses, following the procedure recommended by Hair et al. (1998). In particular, we paid attention to missing data and the identification of outliers, and tested the assumptions for the use of multivariate data (Hair et al., 1998).

In our empirical investigation, we surveyed 96 large and 336 small and medium-sized firms in nanotechnology, thereby addressing the total population of such companies at the time of the survey in Germany. We made an effort to identify *all* relevant nanotechnology firms in the aforementioned countries. Our survey of the existing nanotechnology firms is based on the European nanotechnology gateway "nanoforum.org", which includes a comprehensive database of all firms in Europe. Nanoforum.org is a pan-European nanotechnology network founded by the European Union under the Fifth Framework Programme (FP5) to provide information on European nanotechnology efforts and support to the European nanotechnology community. Several sources recommend the nanoforum database as a reliable source for identifying firms active in nanotechnology, among them the Federal Ministry for Education and Research (www.bmbf.de/en/index.php) and the VDI—The Association of German Engineers (www.vdi.de/vdi/english/index.php). The Nanoforum website (www.nanoforum.org) provides all users with access to a comprehensive database of European nanoscience and nanotechnology organisations. From the Nanoforum database, we selected all firms registered in Germany. In a second step, we validated the information in the nanoforum database by contacting the firms, which reduced our sample to 432 firms, as some firms had gone out of business or did not consider themselves as active in nanotechnology. Finally, we also collaborated with other researchers who had identified firms in the area of nanotechnology. We estimate that our database is sufficiently representative (Hair et al., 1998) since to the best of our knowledge it does not contain any systematic omissions of firms.

For the mailing process, we used the total design method as it was suggested by Dillman (1978). The final number of completed surveys for the large firms was 36, which constitutes a response rate of 38%, and the final number of completed surveys for the small and medium-sized firms was 98, translating into a response rate of 29%.

3.2. Imputation

When data is collected by questionnaire, subjects may be unwilling or unable to respond to some items or may fail to complete sections of the questionnaire due to a lack of time or interest (Schafer and Olsen, 1998). These types of lapses, though inevitable, are unintended by and uncontrollable to the researcher. Traditional approaches to dealing with missing data include listwise deletion, pairwise deletion, mean substitution and inclusion of an indicator variable. But none of these constitutes an optimal solution for missing values except under specialised circumstances (Acock, 2005), as all of them can result in biases in a positive or negative direction, increase Type II errors, reduce the efficiency of estimates, and neglect correlations and β weights and thus jeopardise the validity of a study (Allison, 2002; Little and Rubin, 1987; Schafer, 1999). Many of the data sets used in articles appearing in management journals have serious problems with missing values, and often do not report how the researchers have dealt with them. Over the past decades, numerous strategies were introduced that are innovative improvements over traditional approaches. The most common alternative is to impute values for missing data (Schafer and Graham, 2002). To impute complete data for our sample, we used the EM algorithm of NORM (Little and Rubin, 1987; Schafer, 1999), a software program designed to assist researchers in following multiple imputation guidelines outlined by Rubin (1987) and Schafer (1999), and followed the procedures outlined by Schafer and Olsen (1998). The reader is referred to Acock (2005) for a detailed description of the advantages of this approach and the EM algorithm.

3.3. Small and medium-sized firms

3.3.1. Variables

Table 1 reports the summary statistics for the variables that we used in the SME study.

3.3.2. Dependent variable

3.3.2.1. Cooperation measure. We asked respondents to rate, on a 7-point Likert scale, the extent to which they pursue an alliance or joint venture with another firm in order to commercialise their innovation. For firms with more than one cooperation partner, we asked respondents in the survey to focus on the most important cooperation partner. The mean value for this measure is 4.56.

3.3.3. Independent variables

3.3.3.1. Intellectual property protection. Intellectual property rights protection is composed of the answers of respondents regarding the number of patents, petty patents and trademarks, which they own.

3.3.3.2. Search and bargaining costs. In their study, Gans et al. (2002) used venture capital funding as a proxy for the search and bargaining costs start-ups have in trying to find and bargaining with a cooperation partner. We used a more direct measure for the costs and effort associated with finding and bargaining with a cooperation partner to commercialise the innovation by asking respondents to indicate them on a 7-point Likert scale.

3.3.3.3. Complementary assets: importance. In their study Gans et al. (2002) combined the importance and ownership of complementary assets into one variable, whereas we include them as two separate dimensions of complementary assets. We asked respondents on a 7-point Likert scale to indicate how important access to a number of complementary assets has been for their commercial success. Our questions addressed capital/financial means, intermediate inputs, know-how, manufacturing equip-

Table 1
Summary statistics[a] for small and medium firms.

Variables		Mean	σ[#]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Cooperation		4.56	(1.89)	−0.03	−0.29**	0.27**	0.12	0.04	−0.07	0.02	−0.15	−0.19†	−0.03	−0.05	−0.00	−0.06	0.01	0.10
Intellectual property rights	1	8.27	(10.79)	X	0.04	0.08	−0.06	0.23*	0.19	0.00	−0.13	0.08	−0.01	0.01	−0.07	−0.03	−0.05	0.07
Search and bargaining costs	2	4.43	(1.93)		X	0.18†	−0.07	0.08	0.23*	−0.28**	0.21*	0.21*	0.07	−0.11	0.13	−0.08	−0.16	−0.06
Complementary assets: importance	3	30.29	(6.63)			X	0.30**	0.09	0.11	−0.15	0.12	0.03	0.17†	−0.03	0.02	−0.10	−0.01	−0.03
Complementary assets: ownership	4	29.84	(7.27)				X	−0.17†	0.09	−0.16	0.38***	0.04	0.14	0.16	0.11	−0.07	−0.12	−0.08
VC-funded	5	1.24	(0.43)					X	−0.03	−0.01	−0.20†	−0.20†	−0.15	0.02	−0.10	0.03	0.08	0.24*
Product innovation	6	0.57	(0.50)						X	−0.16	0.04	0.15	0.14	−0.03	−0.08	0.24*	−0.12	0.06
University spin-off	7	0.26	(0.44)							X	−0.14	−0.05	−0.05	0.01	−0.19†	−0.11	0.11	0.03
Company age	8	19.87	(24.95)								X	0.21*	−0.06	−0.08	−0.07	−0.05	0.07	−0.14
Nanotechnology experience	9	7.79	(6.41)									X	−0.09	−0.01	0.16	0.16	−0.08	−0.07
Industry segment: automotive	10	0.06	(0.24)										X	−0.11	−0.08	−0.07	−0.20*	−0.10
Industry segment: chemicals/materials	11	0.15	(0.36)											X	−0.14	−0.12	0.53***	−0.17†
Industry segment: electronics/IT	12	0.09	(0.29)												X	−0.09	−0.25*	−0.13
Industry segment: energy/env. tech.	13	0.07	(0.26)													X	−0.22*	−0.11
Industry segment: optics/analytics/fine mechanics	14	0.39	(0.49)														X	−0.33***
Industry segment: medicine/life science	15	0.14	(0.35)															X

[a] **Note:** The numbers on the first column are of means.
* $p \leq .05$.
** $p \leq .01$.
*** $p \leq .001$.
[#] Standard deviations of each variable. The number of responses used in the analyses is 98.
† $p \leq .1$.

ment, marketing/sales, after-sales-service, reputation/brand name, experience with regulation and legal regulation.

3.3.3.4. Complementary assets: ownership. The second dimension of complementary assets is the degree of ownership over complementary assets (see previous measure for a list of complementary assets) the firms in our sample had at the beginning of the commercialisation of their innovation.

3.3.4. Control variables

In order to focus on variations in the degree of cooperation solely from the factors specified in our model, we included funding source measures, firm-level controls, and project-level controls, which might affect the dependent variable.

3.3.4.1. Venture-capital funding. We controlled for venture capital funding because the transaction costs associated with finding a cooperation partner may be "lower in the presence of third-party "brokers" (such as venture capitalists) who have long-term reputations with rents" (Gans et al., 2002). Respondents indicated whether they had received venture capital funding. 24 of the firms were venture capital financed (24.5%).

3.3.4.2. Product innovation. Gans et al. (2002) point out that the type innovation may also influence the firm's cooperative behaviour. We therefore employed product innovation as a dummy variable.

3.3.4.3. University spin-off. In the sample, 25 firms were spin-offs from university (25.5%). Nanotechnology firms are very knowledge intensive (Wonglimpiyarat, 2005) and the successful commercialisation often depends on the presence of senior research personnel (Mazzola, 2003). We therefore included a dummy variable for university-spin off firms.

3.3.4.4. Company age. Respondents indicated the age of their firm. The small and medium-sized firms in our sample have an average age of 10 years (median) and the arithmetic mean is 20 years.

3.3.4.5. Nanotechnology experience. Since nanotechnology is a complex, emerging and cross-sectional industry, whose major impact on businesses and sectors remains yet to be seen (Cientifica, 2003; Knol, 2004), we included experience of firms with nanotechnology in the regression. Respondents indicated for how many years they have been doing business in the area of nanotechnology. The average value is 7.79 years (median).

3.3.4.6. Industry. We segmented the industries in our sample according to the segmentation used by Luther et al. (2004). Firms in this sample came from a wide range of industries, 23 from the fine mechanics/optics/analytics sector (39%), 15 from the chemical/materials sector (15.3%), 9 from IT and electronics sector (9.2%), 14 from the medical/Life Sciences sector (14.3%), 6 from the automotive sector (6.1%) 7 from the energy/environmental technology sector (7.1%) and 9 from other industries (9.0%). The literature on commercialisation productivity consistently indicates differences between industry sectors (e.g. Gans and Stern, 2003) in the commercial exploitation of inventions. To control for possible industry effects in our model, we included dummy variables for the industrial segments.

3.4. Large firms

3.4.1. Variables

Table 3 reports the summary statistics for the variables that we used in study 2.

3.4.2. Dependent variable

3.4.2.1. Cooperation measure. Cooperation in the large firm sample is a dummy variable consisting of two distinct measures, cooperation (e.g. strategic alliance, joint venture) and capital investment. For measuring whether firms had pursued a cooperative form of commercialisation we asked respondents to indicate on a dichotomous scale which commercialisation strategies they had chosen.

3.4.3. Independent variables

3.4.3.1. Intellectual property protection. Intellectual property rights protection was measured on a 7-point Likert scale, on which respondents indicated the degree to which their intellectual property was protected through legal protection mechanisms (number of patens, petty patents and trademarks).

3.4.3.2. Search and bargaining costs. Like in the SME study, we have a direct measure for the search and bargaining costs firms have by trying to find and negotiate with a cooperation partner. Respondents indicated the overall costs they had in order to find a cooperation partner on a 7-point Likert scale.

3.4.3.3. Complementary assets: importance. We asked respondents to indicate on a 7-point Likert scale how important access to complementary assets has been for the commercial success of their firms.

3.4.3.4. Complementary assets: ownership. Respondents indicated the degree of ownership of ownership of complementary assets which they had at the beginning of the commercialisation of the innovation on a 7-point Likert scale.

3.4.4. Control variables

3.4.4.1. Length of cooperation. Since the length of cooperation can affect the intensity of the chosen cooperation strategy, we controlled for how many years the firms in our sample and their partners had been cooperating.

3.4.4.2. Industry. We segmented the industries according to Luther et al. (2004). Firms in this sample came from a wide range of industries, 3 from the fine mechanics/optics/analytics sector (8.3%), 15 from the chemical/materials sector (41.7%), 4 from IT and electronics sector (11.1%), 4 from the medical/Life Sciences sector (11.1%), 1 from the automotive sector (2.81%), 1 from the energy/environmental technology sector (2.8%) and 4 from other industries (11.1%). In order to control for possible industry effects, we calculated a dummy variable for high-technology sectors which includes medical/life sciences, chemical/materials, IT and electronics sector in the regression.

4. Results

4.1. Descriptive results for small, medium and large firms

Since nanotechnology is a new and emerging field, no studies so far have looked explicitly at strategies firms choose for commercialising nanotechnology. We therefore find it interesting and useful to also report a number of basic results on the firm characteristics and their commercialisation activities in Germany, which is one of the larger players in the nanotechnology field (The European NanoBusiness Association, 2005). The following paragraphs focus on, (i) what makes nanotechnology commercially interesting for the responding firms, and (ii) which commercialisation strategies do they pursue and how do they evaluate complementary assets?

Asked what is commercially interesting about nanotechnology, the majority of companies from both samples mentioned that nanotechnology makes *miniaturisation* possible, which in turn offers new possibilities in the areas of (i) production processes such as in new ways for constructing IT/wafer structures, optics and surface coating (and thus less friction, abrasion and improved scratch resistance), (ii) new products and applications, based on new attributes of materials such as self-cleaning/easy-to-clean, catalysis, nanocomposites, nano imprint machines, in vivo marking, lithography, metrology, mono-structuring and new ways of drug delivery and (iii) improved possibilities for analytics and measurement in the nanometre scale and increased precision which paves the way for technological differentiation and new markets.

However, many respondents also made it clear that in the present stage of development, nanotechnology mostly offers opportunities to improve existing products and technologies in an incremental way. Radical innovations such as “nano-bots” were not mentioned by any of the responding firms and some respondents strongly suggested that such revolutionary innovations would not appear on the market within the next ten years. Additionally, we received feedback that a lot of the materials, tools and processes have been around for over thirty years as “microsystems” or “microtechnology” and are now regrouped under the term “nanotechnology”. Hence, many firms that commercialise nanotechnology are in fact firms with prior expertise in microsystems. This result is also interesting in terms of path dependency, since several studies point out that within the European nanotechnology activities, Germany is the most active part (Dietz, 2004). It would also be consistent with the fact that even though nanotechnology is a rather new phenomenon, more than 60 percent of all surveyed small, medium and large firms report the generation of revenue with one of their nanotechnology inventions.

Interestingly, we found only small differences between large and small/medium firms in the reported levels of importance of a successful commercialisation of their nanotechnology invention for their economic survival (Ø 5.51 for SMEs and Ø 5.21 for large firms), which indicates a generalised high importance of the economic success of the nanotechnology-based innovations. On average, SMEs reported a time of four years for developing nanotechnology inventions, of which the majority were product innovations (57.1%).

In retrospect, SMEs also reported that the most important resources for the commercial success of their nanotechnology innovation were production facilities, know-how, capital and marketing/sales. Large firms on the other hand considered know-how, qualified personnel and production facilities as the most important complementary resources for commercialising nanotechnology successfully. With regard to ownership of complementary resources SMEs reported the least ownership of marketing, after-sales and capital whereas large companies mostly lacked know-how.

The descriptive results of the commercialisation strategies of the SMEs (measured on a 1–7 Likert scale) chosen by nanotechnology innovators show that the SMEs in our sample most intensely pursue a competitive entry into the market (Ø 6.0) followed by cooperation in the form of strategic alliances and joint venture (Ø 4.6). To a lesser extent, they also license out their IPR (Ø 2.7), sell their company to another firm (Ø 2.7), acquire other firms themselves (Ø 2.7) and sell their IPR to another firm (Ø 2.1).

A big difference between large and small firms can be noticed in the degree to which a cooperation strategy is followed. Whereas only about one third of all SMEs follows a cooperative strategy for commercialising nanotechnology, almost 80 percent of the large companies pursue a cooperative strategy for commercialising their inventions. However, both SMEs and large firms evaluate the economic success of their most important cooperation as moderately high (SME: Ø 4.7; large firms: Ø 5.3). Asked about the intensity of their cooperation with small, medium and large firms, SMEs reported the highest cooperation intensity with small companies (i.e. up to 50 employees). SMEs also reported a significantly lower

Table 2
Hypotheses tests for small and medium firms[a].

Dependent variable	Hypothesis	Cooperation	
		1	2
Intellectual property rights	H1		0.01 n.s.
Search and bargaining costs	H2		−0.35**
Complementary assets: importance	H3a		0.30**
Complementary assets: ownership	H3b		0.10 n.s.
VC-funded		−0.03	−0.04
Product innovation		−0.03	0.05
University spin-off		0.00	−0.11
Company age		−0.10	−0.13
Nanotechnology experience		−0.17	−0.13
Industry segment: Automotive		−0.04	−0.08
industry segment: Chemicals/materials		0.06	−0.00
Industry segment: Electronics/IT		0.20	−0.03
Industry segment: energy/env. tech.		−0.04	0.01
Industry segment: optics/analytics/fine mechanics		0.02	−0.02
Industry segment: medicine/life science		0.08	0.07
F-value		0.50	1.89*
Change in R^2		0.06	0.20
R^2		0.06	0.26
Adjusted R^2		−0.06	0.12

[a] **Note:** standardised regression coefficients are shown. N = 98; † ≤ .1, * $p \leq .05$, ** $p \leq .01$, *** $p \leq .001$. Several robustness checks were conducted by the authors.

Table 3
Summary statistics for the large firms.

Variables		Mean[a]	σ[#]	1	2	3	4	5	6
Cooperation		0.25	(0.44)	−0.18	0.12	0.26	−0.50*	−0.17	−0.11
Intellectual property rights	1	5.58	(1.50)	X	0.28	0.26	0.05	0.51*	0.05
Search and bargaining costs	2	2.89	(1.12)		X	0.14	−0.05	0.30	−0.04*
Complementary assets: importance comp2	3	11.00	(6.16)			X	−0.28	0.01	−0.23
Complementary assets: ownership comp 1	4	15.52	(4.44)				X	0.07	−0.10
High-tech industry	5	0.74	(0.47)					X	−0.09
Duration of cooperation	6	5.00	(4.61)						X

[a] **Note:** The numbers on the first column are of means.
* $p \leq .05$, ** $p \leq .01$, *** $p \leq .001$.
[#] Standard deviations of each variable. The number of responses used in the analyses is 36. † ≤ .1.

absolute number of employees working in cooperation than large firms (Ø 20 versus Ø 67). Also cooperation with universities is considered very important by both SMEs and large firms.

4.2. Multivariate results for small and medium firms

An examination of the correlations in Table 2 indicates that relatively low levels of zero-order correlations exist across our independent variables. On a bivariate level, the relationship between cooperation and two of the independent variables is significant and in the hypothesised direction.

Table 2 presents the results of the tests of H1–H3b for the SME sample. Column 1 of Table 2 shows the results with only the control variables included and cooperation as the dependent variable. None of the control variables are significantly related to cooperation indicating a heterogeneous sample. Column 2 indicates that when the predictor variables are added to the equation, an additional 20% of the variance is explained (R^2 change = .20, $p < .001$). Contrary to our prediction, the regression results show that the intellectual property rights protection is not significantly related to cooperation, thus H1 is rejected. The regression results further show that search and bargaining costs are significantly ($p < .05$) and negatively related to cooperation, thus confirming H2. The importance of access to complementary resources is also positively and significantly ($p < .05$) related to cooperation. Thus H3a is supported. Finally, the ownership of complementary assets at the beginning of the commercialisation is not significantly related to cooperation, rejecting H3b.

4.3. Multivariate results of large firms

An examination of the correlations in Table 3 indicates that relatively low levels of zero-order correlations exist across our independent variables. On a bivariate level, the relationship between cooperation and one of the independent variables, complementary assets ownership is significant and in the hypothesised direction.

Table 4 presents the results of the tests of H1–H3b for the large firm sample. A logistic regression analysis yielded a significant negative relationship between intellectual property rights protec-

Table 4
Hypotheses tests for the large firms[a].

Dependent variable		Cooperation	
		1	2
Intellectual property rights	H1		−1.80*
Search and bargaining costs	H2		1.13 n.s.
Complementary assets: importance	H3a		0.11 n.s.
Complementary assets: ownership	H3b		−0.59*
High-tech industry		−0.74	0.50
Duration of cooperation		0.06	0.25
Nagelkerkes R^2		0.05	0.71
LL		30.40	13.77*

[a] **Note:** Regression coefficients are shown. N = 36.
* $p \leq .05$. The coefficients can be interpreted such that a one-unit change in the independent variable results in a one-unit change in the log-likelihood of a favoured outcome. Several robustness checks were conducted by the authors.

Table 5
Commercialisation strategies pursued by small and medium enterprises.

		Competitive market entry	Being acquired	Selling IPR of innovation	Acquisition	Licensing-in
IPR	*r*	.021	−.083	−.049	.409	−.065
	sig.	.835	.419	.633	.000	.525

Note: Pearson correlation coefficients are shown. $N = 98$; $^{\dagger} \leq .1$, $^{*}p \leq .05$, $^{**}p \leq .01$, $^{***}p \leq .001$.

tion and cooperative commercialisation strategy, thus confirming H1b, which had predicted a negative relationship. Contrary to our prediction in H2, search and bargaining costs are not related to cooperation, rejecting H2. Similarly, the importance of access to complementary resources is not significantly related to cooperation. Thus H3a is rejected. Finally, there is a significant negative relationship between ownership of complementary assets at the beginning of the commercialisation and cooperation, confirming H3b.

4.4. Post hoc analysis

A well-established result in the literature is the positive relationship between intellectual property rights protection of SMEs and licensing (Gans and Stern, 2000; Harris et al., 2004; Kollmer and Dowling, 2004) and other forms of cooperation (Goldfarb and Henrekson, 2003; Rodgers et al., 2002). Since previous research strongly supports the relationship between intellectual property protection and cooperative commercialisation, we were surprised to find no such relationship in our SME sample.

We therefore conducted a "post-hoc-analysis" investigating the relationship between intellectual property protection and commercialisation strategies, such as competitive market entry, being acquired, selling intellectual property rights of the innovation, acquisition of another firm, and licensing in. An examination of correlations in Table 5 indicates a relatively high level of zero-correlation between intellectual property rights and the acquisition of another company. On a bivariate level, the relationship between intellectual property rights and all other commercialisation strategies are non-significant.

To test the strength of this unexpected result, we also ran a hierarchical regression analysis with acquisition as dependent variable and all of the independent and control variables we used in the Hypotheses tests in the sample of SMEs (see Table 1 for the independent variables) and IPR are the only significant predictor variable ($p < 0.001$).

Since these results were rather surprising to us, we randomly picked 6 of the interviewed firms and contacted them again with open questions about their impression of the connection between intellectual property rights and commercialisation strategies (especially the seemingly missing link between the intellectual property rights protection and cooperation as well as licensing fees as commercialisation strategy). Most of the interviewees confirmed our results and explained them with the emerging nature of nanotechnology, which does not allow for adequate licensing fees in the current stage of development as well as the favourable conditions for acquiring other firms in the current market situation in Germany. In particular, they said that in the current development state of nanotechnology, it is rather difficult to find adequate cooperation partners and licensees due to the largely unknown market players, application potential and commercial markets. Furthermore, in the present German nanotechnology market SMEs with solid financial resources and the intention to strengthen their bargaining position for future nanotechnology stages meet other SMEs on the verge of bankruptcy. This situation creates a wide choice of potential acquisition candidates for potential buyers.

5. Discussion and conclusion

5.1. Contributions of the study

We set out to understand collaboration-based commercialisation of small, medium and large firms in the context of an emerging technology. In accordance with Gans et al. (2002) we find that for SMEs low search and bargaining costs as well as a high importance of complementary assets increase the intensity of cooperation. For large firms, both strong intellectual property rights protection and ownership of complementary resources are negatively associated with a cooperative strategy.

However, even though there is a vivid discussion about the influence of intellectual property protection on choosing a cooperation strategy for commercialising inventions, we find that for SMEs (i) there is no significant relationship between intellectual property protection and the pursuit of cooperation as exploitation strategy and, (ii) the actual dominant strategy for intellectual property rights holders is not cooperation but product market entry either by building up own resources or by acquiring other companies.

The results for SMEs are in contrast to the prediction of Gans et al. (2002) and support the traditional model of organising innovation, where R&D and the complementary assets required for innovation are integrated inside the firm (Arora et al., 2001).

We can think of several possible explanations for this result. First, the emerging nature of nanotechnology which still has undefined markets, unspecified applications and unknown players makes it difficult to find cooperation partners or licensees willing to pay appropriately. Second, despite the fact that by and large nanotechnology innovation can be fairly well protected by formal intellectual property mechanisms, the lack of expertise of patent offices with the interdisciplinary nature of nanotechnology has led to many patents with overlapping claims (Harris et al., 2004). The ample opportunities for patenting nanotechnology have inspired some to express fear for patent thickets length—many overlapping patents that make it difficult to navigate the nanotechnology landscape. For many nanotechnology start-ups, the intellectual patent portfolio represents the main asset to be exploited through business models based on the commercialisation of a new product through vertical integration or on licensing agreements (Munari and Toschi, 2008). The definition of what is a nanotechnology patent is not an easy task, given the newness of the field and the many scientific and technical areas involved. The characteristics of nanotechnology make it extremely difficult to adopt conventional Intellectual Property and Industry classification, leading to high uncertainty for patent examiners, inventors and prospective investors. Thus, firms in our sample may find it difficult to generate license fees at the present time because of the ambiguity of the current state of the market for nanotechnologies. This interpretation is also consistent with Teece (1986) and Pisano (1990) who argued that if a firm cannot obtain appropriate rents from innovation through licensing in order to profit from the technology, the firm should acquire assets that are co-specialised with the innovation.

Third, innovating firms may wish to strengthen their bargaining position instead of generating license fees or selling itself under value in the current phase, and thus try to build up a solid patent portfolio and necessary complementary assets, instead of licensing and thus sharing the profits with the licensee.

Fourth, favourable acquisition conditions may be present in the German nanotechnology market as indicated by the post hoc analysis, e.g. such as low prices and a wide choice of acquisition partners makes it attractive for firms to pursue commercialisation via the acquisition of complementary resources. Furthermore, firms which have a strong intellectual property rights position have usually heavily invested in R&D, which also enhances their ability to identify complementary assets within the market and absorb this information, making it rational for them, given financial power, to acquire other firms (Cohen and Levinthal, 1989).

Finally, the firms in our sample could have a preference for buying instead of cooperating because of the high amount of chemical firms in the area of nanotechnology. German chemical companies have pioneered the institutionalisation of in-house R&D early in the 20th century (Arora et al., 2001) and it might just be a case of path-dependency that firms seek integration instead of using the "market for technology".

Our non-result regarding complementary asset ownership in the SME sample might be explained by the fact that complementary assets are either closely held or freely available, depending on the industry in which the nanotechnology is commercialised. One possible explanation for our non-result regarding search and bargaining costs and cooperative commercialisation in the large firm sample could be the fact that the overall level of search and bargaining costs was low with little variance as can be seen in Table 3.

The fact that none of our industry variables are significant implies that based on the given sample size, potentially existing effects are too small to reach significance. Potentially existing industry effects may simply be not strong enough. However, given our sample size of 98 is sufficiently large to detect medium-sized effects. Thus, our results imply that potentially existing differences between industries are probably small. Another explanation for this result might be that we use dummy variables for operationalising industry. Perhaps a better proxy would be market structure to detect internal differences with respect to the impact of nanotechnology.

In sum, we believe that our study makes a number of contributions. First, we show that the influence of intellectual property protection in an emerging, cross-sectional technology with uncertainty and ambiguity about markets and players differs from the results of previous studies. Second, we contribute to the discussion in the management of innovation literature, by testing whether established findings apply in the context of an emerging technology and by showing that the antecedents of cooperative commercialisation differ between small and large firms. Third, our result regarding the influence of intellectual property rights on acquisitions answers the call for research on identifying which firms are responsible for acquisition in high technology industries (Blonigen and Taylor, 2000).

Furthermore, our study is one of the first to empirically examine the commercialisation strategies of firms in Germany, which is one of the major players in nanotechnology. Finally, we added another dimension of complementary assets (namely their importance) to the original model of Gans et al. (2002) for which we find a significant positive relationship with cooperation.

5.2. Limitations of the study

Like others, this study has some limitations that have to be taken into account with regard to the interpretation and generalisability of the results. Results from non-experimental and non-longitudinal research design can only be with great caution be interpreted causally (e.g. Biddle and Marlin, 1987; Cliff, 1983). Every time when questions are investigated for which there is no sufficient archived data available - as is the case in this study - researchers must resort to subjective measures of the involved persons (Kumar et al., 1993). A subjective evaluation was also required for this study, regardless of the availability of objective data, as - based on the question and the hypotheses - only the participants themselves offer an opportunity to gain information about the subjectively experienced and perceived commercialisation variables. Search and bargaining costs are the transactions costs involved in identifying a suitable commercialisation partner. Many scholars have already pointed out the difficulty of measuring transaction costs, which can hardly be measured 'objectively'.

When asking single respondents there is a specific danger of data distortion through retrospection when respondents are invited to evaluate the same construct, once in retrospect, and once currently (Huber and Power, 1985) because the retrospective evaluation influences the current evaluation. The risk of the answers' retrospective distortion is little in this study, as different constructs are queried in respect of the past and present (Morgenstern and Barrett, 1974). In keeping with Huber and Power's (1985) suggestions, those persons who had the greatest expertise with regard to the commercialisation strategy were selected for the survey: the top management team members themselves. Earlier studies on key informant distortion have pointed out the risk of a systematic distortion when only a single person is questioned per business (Kumar et al., 1993), as such distortion can constitute 30% of the total variance and jeopardise the construct validity.

The risk of respondent bias in this study is by the research design: A respondent bias develops specifically in respect of respondents' different functional and hierarchical positions in a company (Ernst, 2003). Top management team members, however, have similar hierarchical positions and functional tasks. Perception differences, which can arise between respondents due to different hierarchy levels, do not apply to context of this study.

Respondent bias also occurs whenever respondents draw on differing familiar and known information in their assessments (Ernst, 2003). Here, it is also true that in the context of this study respondents have equal access to similar information. A further influencing factor in respect of respondent bias is if the affiliation with companies differs. In the present study, it was verified that the respondents has been with their respective companies for a significant time.

Furthermore, our study only explains a small part of the variance in the dependent variables, which may be indicatory that we may have been missing relevant explanatory variables.[2] Finally, our sample of large firms only contains 36 respondents. Small sample size can impede generalisation of results and also lower the power of multivariate analyses (Cohen, 1988). However, at present only 432 firms are involved in nanotechnology in Germany. Thus, we have surveyed 31% of the total population of those firms at the time of the study. In addition, representativeness of samples is not a question of sample size but of randomness in sampling. The authors are unaware of any *systematic* omission of firms other than self-selection of the companies participating in our survey, which is known to be an unavoidable bias in social science research (Hair et al., 1998).

5.3. Potential avenues for future research

Overall, our results raise further questions about the dynamics of commercialisation in the context of an emerging technology. More research with similar samples is needed to assess the representativeness of the current findings. An especially fruitful avenue

[2] However, a small R^2 does not necessarily imply that estimates of simple regres-

for further research on the commercialisation of nanotechnology innovations seems to be the issue of regulation and the way such measures are implemented and enforced. In nano-electronics regulation takes place via the Semiconductor Roadmap and is basically self-managed by industry whereas in the medical sector, the FDA is working on several dossiers. In Europe, the coming into action of the registration, evaluation, authorisation, and restriction of chemicals (REACH) will probably strongly affect the regulatory environment of chemical products. In a similar vein, future research should aim at gaining an in-depth understanding of the issues of patentability of nano inventions and their related uncertainty.

It might also be of interest to re-examine our results regarding the influence of intellectual property protection on acquisitions, for example, by gathering comparative data in another emerging cross-sectional technology. Another area that would merit further investigation would be to examine the antecedents of alternative commercialisation strategies (e.g. licensing, acquisition, competitive market entry, etc.) pursued by nanotechnology inventors. Finally, given that none of our industry dummies are significant, future studies should look at a more granular level of internal and external firm characteristics. For example, future research may control for internal organisational differences or control for concentration of firms, market share of largest firms, and price/margins ratios in the respective industry contexts of their samples instead of using industry dummies.

In conclusion, our study has raised a number of questions regarding the commercialisation process of small and large firms. It has taken a first step to help both individuals and organisations to better understand the dynamics of nanotechnology commercialisation strategies. Right now, it seems important for nanotechnology innovators to carve out their claims by strengthening their patent portfolio as well as following a competitive product market strategy by building up own resources as well as acquiring other firms. We hope that future work will build on our results.

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sion models are biased. First, a small R^2 doesn't imply that the missing factors are correlated with explanatory variables that have been included. Second, choosing a set of explanatory variables based on the size of the R^2 can lead to misleading results as neither R-squared nor adjusted R-squared can be used for choosing between different functions forms for the dependent variable. When interpreting the variance explained through regression, one has to consider the number of independent variables included in the regression model. Furthermore, when interpreting the explained variance of any regression model, one has to pay attention to the variance explained by regression models of other studies looking at similar research questions. We are currently unaware of any other studies that look at the antecedents of nanotechnology commercialization in the same or similar regression models. Thus, a relative comparison of the variance explained with the variance explained by other studies is not possible. Similarly, we are unable to interpret the degree of explained variance in absolute terms and to make a judgment as to whether the total variance explained in our models is low or high. Also R^2 equals the explained variance and it reflects not only the quality of the regression, but also the distribution of the independent (conditioning) variables.

Also, we would like to add, that the variance explained is not only dependent on the quality of the regression models but also on the variance of the independent variables. When interpreting R^2s, researchers need to be careful because R^2 does not tell whether the independent variables are a true cause of the changes in the dependent variable, whether an omitted-variable bias exists, the correct regression was used, the most appropriate set of independent variables has been chosen, whether there is collinearity present in the data, and whether the model might be improved by using transformed versions of the existing set of independent variables. As R^2 is only a measure for the linear relationship between two variables, R^2 may be quite low in case a non-linear relationship between the two variables is present.

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