Innovation and firm performance: An assessment of patenting strategies of Chinese listed firms

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Abstract

We examine the impacts of explorative and collaborative innovations on firm performance within the potential-outcome framework using the patenting information of 1082 Chinese listed firms over 2009-2017. By identifying the firms' patenting strategies on the basis of their positioning in the matrix of exploitative-explorative and solitary-collaborative dichotomies, as opposed to at most the parallel dichotomies used in the existing studies, we obtain evidence for the impacts that are new to the literature. We find that the degree of exploration would not have positively impacted financial performance of the solitarily continual patenting firms until it reached 54.7%, while it is unrelated to the performance of the collaboratively continual patenting firms. Although the extent of collaboration does not affect market value of any patenting firm in the exploitation-exploration dichotomy, even the average treatment effect of the collaboratively explorative innovation is statistically significant and positive against the control group of no patenting activity in the matrix of the two dichotomies. However, while purely exploitative and purely explorative patenting firms benefit more from solitary than collaborative innovation, neither solitary nor collaborative effort adds any value to patenting firms that attempt both exploitative and explorative innovations. These results suggest that an innovation strategy of mixed exploration and exploitation allows patenting firms not to balance additionally between solitary and collaborative activities in the short run.

Key words: financial performance, patenting activity, average treatment effect, explorative-exploitative dichotomy, solitary-collaborative dichotomy

1. Introduction

As crucial as technological advance for economic growth, innovative activities lie at the core of wealth creation, contributing substantially to the financial performance of firms (Ernst, 2001; Hall et al., 2005). Furthermore, Montgomery (1995) predicts that profits from any single innovation might be transitory, but firm-level profits may persist if a firm could successfully and continually innovate. Apart from the distinction between the one-off and continual efforts, innovation can be explorative or exploitative by nature. March (1991) defines exploitation as the utilisation of existing capabilities through standardisation, upscaling and refinement and exploration as the creation of new capabilities by fundamental research, experimentation and search. It is considered more effective and profitable in the short term to exploit existing capacities within familiar areas of technology. However, Levinthal and March (1993) argue that solely relying on the exploitative focus could trigger a success trap in which exploitation drives out exploration, compromising firms' ability to adequately respond to forthcoming structural changes and thereby threatening the long-term survival of the firms. As exploring beyond familiar areas of technology entails greater uncertainty, overemphasis on exploration could reinforce a fruitless search cycle. Hence the literature, like O'Reilly and Tushman (2004) and Raisch et al. (2009), posits that firms must undertake balanced explorative and exploitative innovative activities in order to improve their survival chances and performance. On the other hand, Cassiman and Veugelers (2006) and Chesbrough (2003) suggest that firms must balance solitary and collaborative innovative activities. Collaborative research and development (R&D) opens up new technological possibilities by sharing resources and capabilities. However, association with external partners carries the risk of dissipating essential knowledge and incurs the costs of coordination (Faems et al, 2008; Gulati and Singh, 1998; Belderbos et al., 2010). Note that the literature, such as Baum and Oliver (1991) and Rothaermel and Deeds (2004), has mainly argued that the balance in the solitary-collaborative dichotomy could have a positive impact on the outcome of R&D investment instead of the financial performance of firms.

How firms position themselves in the exploitative-explorative and/or solitary-collaborative dichotomies is understandably crucial for firms' survival as well as the efficient allocation of resources. However, the seminal work by Belderbos et al. (2010) contributes greatly to our understanding of the complexity of balancing acts between exploration and exploitation or between collaborative and solitary innovative activities. Using the patenting information of 168 US, European and Japanese R&D-intensive firms active in five conventional high-tech sectors during 1996-2003, Belderbos et al. (2010) confirm the existence of an inverted U-shaped relationship between the share of explorative innovation and financial performance of firms and obtain the optimal share of explorative innovation at 39%. On the other hand, they find a direct negative relationship between collaboration and financial performance and an indirect positive performance effect of collaboration through increasing the share of exploration in technological activities.

The investigation of the roles of explorative and collaborative innovations has become relevant again, as the world is experiencing considerable changes and facing risks posed by the increased protectionism to global networks and innovation diffusion. As noted by the report of Global Innovation Index 2019[1] by World Intellectual Property Organisation (WIPO), innovation is no longer exclusive to firms of developed economies and both developed and developing economies promote innovation to achieve economic and social development. Innovation is taking place in all realms of the economy, not only in high-tech companies and technology sectors, and by 2019, medical technology has taken over pharmaceuticals as the most frequent patenting field. In this increasingly complex world, the evaluation of the

[1] https://www.wipo.int/edocs/pubdocs/en/wipo_pub_gii.2019, accessed in January 2020.

patenting strategies should be extended to firms of all industries and/or firms from developing economies.

Scientific and technological innovation by Chinese firms has gained considerable ground, since the explosive growth, at 32% per annum (see Chinese statistical yearbook 2018), of the number of domestic invention patent filings with the Chinese patent office during 1999-2013. The latest statistics reported by the Chinese National Intellectual Property Administration (CNIPA) show that the growth rate remains steady at 12.6% per annum during 2014-2018. Meanwhile, the WIPO Global Innovation Index 2019 reports that China is the only middle-income economy among the top 30 innovation nations (ranked 14th in 2019), maintaining top ranks in the categories of Patents by origin, High-tech net exports and Creative goods exports. Furthermore, China hosts the second largest number of science and technology clusters and Beijing is the top collaborating cluster for scientific co-authorships. It is confirmed by the CNIPA databases that most Chinese listed firms have attempted at least one invention patent application since the records started in 1994. The invention patents filed with CNIPA by the Chinese listed firms cover many industries and some of them have been achieved through collaboration with at least one external partner, either a firm, university or research institute, constituting a suitable context for verifying the propositions about the roles of explorative and collaborative innovations. From the policy perspective, it is of importance to observe how firms of an emerging economy like China position themselves in the spectrums of exploration and collaboration and evaluate the economic consequences of their patenting strategies. The findings from this study will have greater managerial implications for firms of developing economies in this increasingly complex world.

Motivated by Belderbos et al. (2010), we revisit the issues of optimising exploration and collaboration using Chinese patenting information. As opposed to the conventional regression analyses adopted in the literature of innovation, we will carry out multivalued treatment effect analyses of the various innovation strategies, as reflected in the invention patenting applications filed by the Chinese listed firms. We hand-collected the invention patenting information, such as submission dates, international patent classification codes, ownership and legal status of the invention patents, over the period of 2009–2017 from the China Stock Market and Accounting Research (CSMAR) database and the website of CNPIA. By contrasting the patenting information between the initiation period of 2009-2013 and the estimation period of 2014-2017, we distinguish first-time patenting firms from continual patenting ones and calculate the degree of exploration[2] for the continual patenting firms according to the definition of March (1991). Together with the extent of collaboration, we will identify the Chinese listed firms' innovation strategies through classifying the firms' invention patenting activities by time and the degree of exploration. We will estimate the causal effects on financial performance of the innovative strategies within the potential-outcome or counterfactual framework.

Our work differs from the existing studies further in several aspects. Firstly, we acknowledge that a firm's decision to adopt any innovation strategy is never random. Any assessment of the impact of corporate positioning in the exploitative-explorative and/or solitary-collaborative dichotomies, under the assumption of random assignment of the strategies, would be tempered by a self-selection bias. This self-selection bias differs from endogeneity caused by simultaneity or unobserved heterogeneity and cannot be adequately dealt with using the conventional lagged variables in a model evaluating financial performance of firms. Therefore, while estimating the causal effects of explorative and collaborative efforts on financial performance of firms in an outcome model, we will model the corporate patenting strategies simultaneously as treatment assignments to alleviate the self-selection bias. We assume that the corporate decisions depend on firms' financial ratios, including the R&D expenditures

[2] Following Belderbos et al. (2010), we use the number of new classes (International Patent Identification codes) awarded to a firm's patents in 2014-2017 relative to those awarded in 2009-2013, scaled by the firm's patent count in 2014-2017, to measure the degree of exploration.

standardised by sale revenues, and the economic conditions of the provinces where the firms locate. Note that we assume that R&D investment is directly related to innovation outcome instead of financial performance of firms.

Secondly, as opposed to the existing studies in the context of the exploitative-explorative or solitary-collaborative dichotomy, we will assess the innovation strategies in the matrix of the two dichotomies. When categorising the patenting firms by the dimensions of time, exploration or collaboration, we will estimate the relationships, respectively, between the degree of exploration and financial performance of firms pursuing solitary or collaborative innovation strategies and between the extent of collaboration and financial performance of firms implementing first-time or continual innovation strategies. The continual innovation strategies can be purely exploitative, purely explorative or mixed exploitative and explorative. When assigning the firms by time, exploration and collaboration, we will be able to contrast the average treatment effects of the solitary and collaborative innovation strategies over time and across the degrees of exploration. Note that we estimate the average treatment effects simultaneously across all possible innovation strategies instead of through multiple binary analyses as dictated by the very popular Propensity-Score Matching (PSM) technique. Repeating the estimation of the treatment effect in a binary setting as stipulated by the PSM technique will produce biased estimates in the presence of multiple treatment groups like our case where the number of patenting types is as high as eight. We anticipate verifying the optimal level of exploration observed by Belderbos et al. (2010) and detecting any positive impact of collaboration that may have been missed by Belderbos et al. (2010).

Belderbos et al. (2010) rightfully control for patent counts in the estimation of the relationships between the degree of exploration and extent of collaboration and financial performance of firms. The knowledge contained in patents can be immediately acted upon by firms to create value. However, the value-creation potential of patents also arises from their ability to allow patent-holding firms to choose the timing of their investment in the patented technologies when this involves sunk costs. Bloom and Van Reenen (2002) term the ability as patent real options. Hence, we will additionally verify the existence of the patenting real options, i.e., values that firms place on the exclusive rights to use their innovations until the patents expire, when estimating financial performance of firms within the potential-outcome framework.

The remaining of the paper is organised as follows. We review the literature in section 2 and describe the methodology in section 3. In section 4, we report the empirical results and discuss the implications for firm managers. Section 5 concludes.

2. Review of the literature and development of hypotheses

The concepts of exploration and exploitation were originally developed by March (1991) in the context of organisational learning. Since then, it has been widely applied to studies on strategic innovation management (e.g., Tushman and O'Reilly, 1996; He and Wong, 2004 and Jansen et al., 2006). The consensus is that focusing on exploitative activities is likely to improve effectiveness and efficiency of a firm's existing core capacities, thereby resulting in positive short-term effects. Levinthal and March (1993) warn, however, that an exploitative focus can trigger a success trap in which exploitation drives out exploration, compromising the ability of the firm to adequately respond to forthcoming industrial or technological changes and threatening the long-term survival of the firm. On the other hand, focusing solely on exploration entails greater risks and could be detrimental to firms' financial performance. For instance, Levinthal and March (1993) suggest that a cycle of search and failure could be reinforced, as an extensive search might not achieve any success but lead to more search and failure. It is therefore argued that companies able to establish a balance between exploration and exploitation are likely to outperform firms that focus solely on either exploration or exploitation. However, empirical evidence is rare and indirect on the right balance between the two. Testing the ambidexterity hypothesis of Tushman and O'Reilly (1996), He and Wong (2004) find a positive interaction effect between exploitation and exploration on a firm's sale growth. Uotila et al. (2009) and Belderbos et al. (2010) confirm the need to balance exploration and exploitation on the basis of an inverted U-shaped relationship between the relative share of the firm's exploration orientation and market valuation. But Belderbos et al. (2010) find that the optimal share of exploration is as low as 39% for the 168 US, European and Japanese R&D-intensive firms in five major high-tech sectors over 1996-2003.

Many studies have posited the relationship between collaboration and innovation outcome. For instance, technology collaboration facilitates the development of new skills or new ideas by decreasing technological risk (Dittrich and Duysters, 2007; Hagedoorn, 1993) and spreading the R&D cost (Harrigan, 1988; Veugelers, 1998). Teece (2002) suggests that working together encourages the transfer of knowledge, resulting in the creation and development of ideas that would be difficult to realise in isolation. Baum and Oliver (1991), Mitchell and Singh (1996) and Rothaermel and Deeds (2004) generalise that technological collaboration, in particular having a portfolio of strategic technological alliances, can have a positive impact on the innovative performance of companies. However, Belderbos et al. (2010) argue that collaboration with partners external to focal firms introduces relational risks and incurs coordination costs. In contrast to solitary technological activities, collaborated activities imply that firms also need to share the rewards with their partners. Lavie et al. (2007) acknowledge that collaboration might increase the probability of generating ideas successfully but may substantially restrict the ability of the focal firm to appropriate the value of such activities. Belderbos et al. (2010) even find a negative relationship between the share of collaboration and the market values of firms and interpret the negative relationship as collaboration's value appropriation complexities outweighing the value-enhancing potential.

Previous research also indicates that the preference for and the impact of solitary or collaborative approaches might be different in exploitative and explorative settings. Das and Teng (2000) and Hagedoorn and Duysters (2002) suggest that the more essential technological activities are for a firm's existing core business, the more the firm wishes to exert full control over such activities. Such full control can best be achieved by internalising technological activities. Ahuja (2000) concurs that firms have little inducement to engage in collaboration in fields where they already possess strength. Firms' preference for solitary activities may also be curbed by the concern that unintended spillover of their core technology through the collaborative arrangements could cause economic damages to the firms. In contrast, firms that have not acquired knowledge, skills or expertise in new technology domains are more likely to engage in explorative technological activities. Furthermore, the economic consequences of opportunistic behaviour in collaborative arrangements are likely to be lower in explorative than in exploitative settings. Hence, the value-generating properties of collaboration are considered to be higher for explorative technological activities than for exploitative technological activities (Belderbos et al., 2010). Belderbos et al. (2010) also find that whereas firms that are more intensively engaged in collaboration display higher levels of explorative innovation, the share of collaboration in explorative activities has a negative impact on the market value of the firms.

When developing hypotheses on the patenting behaviour of the Chinese patenting firms, we should also take into consideration the structural differences between firms of emerging economies and R&D-intensive firms of developed economies, the latter being the subject of most studies in the literature. The optimal share of exploration (39%) obtained in Belderbos et al. (2010) might be reasonable for the R&D-intensive firms of major high-tech sectors in developed economies, as the scope for further exploration is relatively limited for these firms. On the contrary, firms in developing countries may have smaller technological or high-tech capabilities. The degree of exploration on the high side or even above certain threshold might enable firms to open up innovation possibilities and thereby gain competitive advantages and increase firms' market values. Therefore, there more likely exists a U-shaped relationship between the degree of exploration and financial performance of ordinary patenting firms in developing economies. Furthermore, the threshold at which the rate of exploration would improve financial performance of firms that are confident with their own capabilities and pursuing solitary innovative activities should be lower than that for firms that are seeking technological breakthrough through collaboration with external partners. That is, the threshold rate of exploration for the solitarily innovative firms should be low enough to entice the firms to explore beyond their familiar domains of technology, as opposed to the threshold for the firms that engage in collaboration more intensively. Hence, we develop the following hypotheses.

Hypothesis 1a. There is a U-shaped relationship between the degree of exploration and financial performance of innovating firms.

Hypothesis 1b. The threshold at which the rate of exploration could improve financial performance of firms pursuing solitarily innovative activities is lower than that for firms engaging in collaboratively innovative activities.

Given that first-time patenting firms and continual patenting firms that explore beyond their familiar areas of technology might be more eager to strike any innovation breakthrough through collaboration with external partners than concerned about the relational risks and coordination costs associated with collaboration, these firms would be more likely to collaborate with external partners. The value-creation potential of collaboration should outweigh the relational risks and costs for these firms. Thus, we think it possible that there is a positive relationship between collaboration and financial performance of first-time patenting firms and continual patenting firms with a purely explorative focus. On the other hand, because continual patenting firms, especially those purely exploitative continual patenting ones, may be more concerned about the potential economic damages to be caused by the unintended spillover of technology in the process of collaboration with external partners, it is more likely for them to refrain from collaboration. That is, the value-creation potential of collaboration could be outweighed by the value-appropriation complexities for the purely exploitative continual patenting firms. Therefore, we do not think that there is any relationship between collaboration and financial performance of the continual patenting firms with a purely exploitative focus.

Hypothesis 2a. There is a positive relationship between collaboration and financial performance of the first-time patenting firms and the continual patenting firms with a purely explorative focus.

Hypothesis 2b. There is no relationship between collaboration and financial performance of the continual patenting firms with a purely exploitative focus.

Finally, the introduction of new products or process innovations can involve sizeable irreversible investments in additional plant and equipment, hiring and retraining workers, and advertising and marketing. Thus, when firms are facing uncertain market conditions, patents offer firms real options to choose the timing of its investment in their patented technologies involving sunk costs. Bloom and Van Reenen (2002) predict that higher market uncertainty will lead firms to be more cautious about their investments and develop the following hypotheses on the relationships between patents and uncertainty. Firstly, firm's valuation is clearly increasing in patent numbers, since even disembodied patents have an option value. Secondly, the market value will also increase with market uncertainty, since higher uncertainty will increase the option value of disembodied patents. Thirdly, the market value will rise due to the interacting effect between new patents and uncertainty, since higher uncertainty will increase the value of extra patents. We will take into account the patent real options in our outcome model and verify the three predictions of Bloom and Van Reenen (2002).

3. Methodology

We examine the impacts of exploration and collaboration through estimating the potential outcomes of the invention patenting strategies adopted by the Chinese listed firms during 2009 and 2017. Following Belderbos et al. (2010), we define the explorative innovation as the development of ideas, during 2014-2017, situated in technological domains where the firms have not patented in the past five years, i.e., during 2009-2013, while the exploitative innovation in 2014-2017 is the creation in technological domains where the firms have patented in the previous five years. In addition to the firms engaging in the above mentioned continual innovative activities throughout 2009-2017, there are firms that attempt innovation first-time during 2014-2017 without any patenting experience in the previous five years. Both the first-time patenting and continual patenting firms can engage in joint innovation with external partners. The extent of collaboration is measured by the percentage of patents that are co-owned by the focal firm and at least an external partner organisation, be it a firm, a research institute or a university. Hence, firms' innovation strategies can be categorised by the dimensions of time, degree of exploration and/or extent of collaboration.

3.1 The models

The following equation captures the determination of the financial performance of a firm.

$$Q_i = \alpha + \beta_1 EXT_i + \beta_2 EXT_i^2 + \gamma_1 PAT_i + \gamma_2 \sigma + \gamma_3 (\sigma \cdot PAT) + \lambda Q_{it-1} + \sum_{k=1}^{n} \phi_{1k} D_{ki} + \sum_{k=1}^{n} \sum_{l=1}^{n} \phi_{2k} (D_{ki} \cdot X_{li}) + \varepsilon_i \quad (1)$$

where Q is Tobin's q, calculated as a ratio of market value one year after the patenting year to total asset at the patenting year. In the case of non-patenting firms, the patenting year is replaced by the year when the firms started to invest in R&D over 2014-2017. β_1 and β_2 are the responses of Q with respect to changes in the degree of exploration and squared degree of exploration when patenting firms are categorised by the dimension of collaboration and with respect to changes in the extent of collaboration and squared extent of collaboration when patenting firms are categorised by the dimension of time or exploration. That is, we follow the literature and model the relationships between financial performance and exploration and collaboration as non-linear. γ_1, γ_2 and γ_3 are the elasticities of Q with respect to natural logarithm of number of invention patent count, stock volatility captured by the standard deviation of daily stock returns and the interaction between log patent count and stock volatility, addressing the direct and interacting effects of a patenting activity as specified by Bloom and Van Reenen (2002). Like the first order derivative of a firm's market value with respect to the patent count, the first order derivative of the market value with respect to uncertainty is expected to be positive, since higher uncertainty will increase the option value of disembodied patents. The cross derivative for the market value is again to be positive, since higher uncertainty will increase the value of extra patents. We further control for firm characteristics using the lagged Tobin's q.

In the equation, D is a treatment indicator that assigns a value between 1 to n if a firm attempts a particular type of innovation activity and zero to firms of the control group. For instance, when distinguishing patenting firms by time dimension, we assign k = 1 to first-time patenting firms and k=2 to continually patenting firms and let k=0 for non-patenting firms. When distinguishing among the continual patenting firms against the control group of first-time patenting firms, we assign k=1 to continual patenting firms that concentrate on the areas of technology in which they have patented in the previous five years (also known as exploitative firms), k=2 for continual patenting firms that explore beyond their familiar areas of technology (i.e., explorative patenting firms) and k=3 for continual patenting firms that attempt both exploitative and explorative activities (i.e., mixed patenting firms). When distinguishing patenting firms by the dimension of collaboration, k = 0 (solitary patenting firms) and k=1 (collaborative patenting firms). Finally, when distinguishing patenting firms by the dimensions of time, or exploration **and** collaboration simultaneously, k = 1, 2, …, 8 for the different kinds of technological activities: (1) solitary first-time patenting activity; (2) collaborative first-time activity; (3) solitary exploitative activity; (4) collaborative exploitative activity; (5) solitary explorative activity; (6) collaborative explorative activity; (7) solitary mixed exploitative and explorative activity and (8) collaborative mixed exploitative and explorative activity.

To successfully estimate this regression model in any case involving non-patenting firms, we must omit EXT and its squared term and PAT and its interaction term. The above equation in its complete form is applicable to cases where we focus on the behaviours of patenting firms, for instance, when contrasting behaviours between continual patenting firms and first-time patenting firms or between firms pursuing collaborative innovation and those attempting solitary innovation.

Finally, X is a vector of all the explanatory variables on the right-hand side of equation (1). The parameters, ϕ_{1k} and ϕ_{2k}, respectively, measure the differentials in the average Q and the slope coefficients of the included explanatory variables. However, if estimated by OLS, the estimates of equation (1) are confounded by a selection bias term. That is, the estimates are biased due to the fact that the patenting firms differ from the non-patenting firms for reasons other than the patenting status per se. Undoubtedly a firm's decision to patent in any form is never random, but self-selective. That is, firms decide whether to adopt a particular patenting strategy on the basis of their public and non-public information or observable and unobservable factors, such as expected revenue growth, unreported liabilities, corporate strategy, anticipated competitive pressures, corporate governance etc. Failure to account for the relationship between these factors and the corporate decision creates the self-selection bias that prevents the unbiased estimation of equation (1). To alleviate the selection bias, we model the decision to submit a particular patent application as follows.

$$D(k,i) = a_k + b_{1k}RD_i + b_{2k}RD_i^2 + c_{1k}AGE_i + c_{2k}SIZE_i + c_{3k}SOE_i + c_{4k}LIQ_i + c_{5k}LEV + d_iGDP + e_i$$
(2)

where b_{ik} are vectors of the coefficients on the R&D expenditures scaled by the sale revenues of pre-patenting year for patenting firms or of the year when non-patenting firms invest in R&D first time. Note that we intend to capture a quadratic relationship between the commitment to research and development and patenting outcome, on the basis that R&D investment positively affects patenting outcome, but firms experience decreasing returns to R&D investment. c_{ik} and d_i are vectors of the coefficients on the pre-patenting firm characteristics and per capita GDP growth of provinces where firms locate. In the case of non-patenting firms, these firm characteristics are collected for the years when the firms invested in R&D first time over 2013-2016. The firm characteristics include firm age, firm size proxied by log total assets, state ownership concentration, liquidity as a ratio of current assets to current liability and leverage as a ratio of total liability to total assets. A firm's innovation process changes over its life course, but the impact of firm age on innovation can be positive or negative (Coad, et al., 2016). As firms get older, they gain experience and become more routinized and less adventurous. On the other hand, the experience allows mature firms to innovate more effectively, refining older technologies on the basis of the existing capacities and competences. As usual, firm size is included to control for the economies of scale that decrease the fixed patenting cost proportionally as firm size increases. Liquidity and leverage are included to indicate firm's short-term and long-term financial positions. State ownership concentration is measured by the percentage of shares that are owned by the state. It is expected that the more heavily a firm is owned by the state, the more likely a firm will get a state subsidy to innovate. Note that Eberhardt et al. (2017) find that patent applications by Chinese firms are directly driven by the government subsidies. Therefore, we expect the coefficient of state ownership concentration to be positive. Finally, the provincial economic indicator, the growth rate of per capita GDP, controls for the environments, such as education and training programmes, that might facilitate the absorption of knowledge spillovers and the development of new ideas.

In the context of potential-outcome framework, equation (1), a linear regression model, is the outcome model, while equation (2) is a treatment assignment and is usually estimated as a multinomial logistic model. We will estimate equations (1) and (2) using the inverse-probability-weighted regression adjustment[3] (IPWRA) estimator, a technique suitable for the case when we assume that the treatment assignment and potential outcomes are independent and conditional on the given specification of the outcome and treatment models. Due to the property of double-robust, the IPWRA estimator only requires one of equations (1) and (2) to be correctly specified in order to correctly estimate the average treatment effects. The average treatment effects of the specific patenting strategies are computed as the differences between the weighted means of the treatment-specific predicted outcomes and that of the predicted outcomes of the control group.

The successful estimation of equations (1) and (2) using any treatment effects estimator, e.g., the IPWRA or propensity-score matching estimator, relies on the assumption of overlap. In the context of our study, firstly, each firm must have a positive probability of patenting so that the predicted inverse-probability weights do not get too large. Over-sized weights will make the estimator unstable. Secondly, there must be a chance of seeing observations in both the control and treatment groups at each combination of covariate values. As the treatment level in our study is as high as eight, it is very likely that one or two variables may violate the overlap assumption in our treatment model. In such case, we could simply remove the affected variables from the treatment model.

[3] This estimator uses the inverse of the probabilities estimated from the treatment model as weights to address the missing-data problem arising from the fact that each subject is observed in only one of the potential outcomes. The missing-data-corrected regression coefficients are subsequently used to compute the potential outcomes.

3.2 Data sources, variables, and samples

Our data are sourced from two databases, namely China Stock Market Accounting Research database (CSMAR) and the Chinese National Intellectual Property Administration (CNIPA). We include Chinese firms in all sectors, except financials and real estates, that are listed on the stock exchanges in Shanghai and Shenzhen over 2013-2018. We download their financial information, including their R&D investment, over 2013-2016 and their daily stock returns and annual market values over 2015-2018 from the CSMAR databases. On the basis of the list of firms that have complete data on the financial ratios, R&D expenditures and market values, we further collect these companies' invention patent information, including submission dates of the invention patents, ownership of the invention patents and legal status of the invention patents over the period of 2009 – 2017 from the CSMAR database. We collect the international patent classification (IPC) codes of these invention patents additionally from the website of CNIPA.

From the raw data of CSMAR, we generate firm characteristics, Tobin's q and market uncertainty. For parenting firms, their firm characteristics are some conventional annual financial ratios in the years before they submitted patent applications first time over 2014-2017. For non-patenting firms, firm characteristics are financial ratios of the years when the firms invested in R&D first time over 2013-2016. Tobin's q of a patenting firm is calculated as the ratio of the firm's market values in the years following its patenting year until 2018 to its total assets from patenting year to 2017. This ratio is therefore forward-looking and reflects the time lag between the innovative activities and their outcomes. For a non-patenting firm, Tobin's q is the ratio of the firm's market values of the years following its first R&D investment until 2018 to its total assets of the years from its first R&D investment to 2017. Market uncertainty is measured by the average standard deviation of a firm's daily stock returns during 2015-2018, and it controls for the uncertainty, which firms face, about future prices, wages rates, exchange rates, technologies, consumer tastes and government policies.

From the patenting information, we generate indicators of various innovative activities, invention patent count, average degree of exploration and average extent of collaboration for each firm over 2014-2017. Patenting information in the initiation period of 2009-2013 helps distinguish continually patenting firms from first-timers in the estimation period of 2014-2017. We include, in the patent count, the invention patent applications that are under review and patents that are valid or expired[4]. The degree of exploration is measured by the number of IPC classes[5], in which a firm has never patented in the previous five years (2009-2013), scaled by the firm's invention patent count over 2014-2017, while the extent of collaboration is captured by the percentage of invention patents that are jointly owned by a focal firm and at least one external partner organisation. Hence, the rate of exploration[6] calculated by this way is a variable specific to the continually patenting firms, while the rate of collaboration is pertaining to all patenting firms. The degree of exploration for the continually patenting firms ranges from 0% to more than 100%. Firms with the rate of exploration at 0% and 100% (and greater) are categorised as purely exploitative and purely explorative firms respectively. Firms with any rate of exploration greater than 0% and below 100% attempt both exploitative and explorative technological activities, therefore they are categorised as mixed patenting firms. After removing firms that have missing data, our sample size is restricted to 1735 firms. 654 of the

[4] The legal status of invention patents includes invention patent applications that have been rejected by the review panel or withdrawn by the patent applicants before a judgement was made by the panel. We disregard these invention patent submissions, but keep patents that are expired in the sample. These patents are useful as they are the evidence of areas of technology firms have explored in the five years prior to the period of 2014-2017.

[5] We follow Guide to the International Patent Classification (Version 2019, WIPO) and use the second level of hierarchy of the Classification, Class (represented by a section symbol followed by a two-digit number), to identify the content of patents. By reading the IPC codes awarded to each patent a firm filed over 2009-2013, we collect all classes that the firm has once patented. For each of patents that the firm filed in 2014-2017, we check its IPC codes against the firm's pool of classes of 2009-2013 and note down the number of new class(es) each patent acquires.

[6] For the first-time patenting firms, their rate of exploration is the number of IPC classes divided by the patent count over 2014-2017.

firms did not submit any invention patent application over 2014-2017, while 1082 firms have attempted at least one invention patent application which is either under review or granted.

4. Empirical results

4.1 Preliminary data analysis

[Table 1 is about here.]

The break-down of the Chinese patenting firms during 2014-2017 are tabulated in Table 1. Majority of the listed firms in China attempt to innovate (1082 patenting firms versus 654 non-patenting firms) and most of the patenting firms innovate continually throughout the initiation period of 2009-2013 and the estimation period of 2014-2017 (892 firms in both periods versus 190 firms in the estimation period only). We consider the 892 firms as continual patenting firms and the 190 firms as first-time patenting firms. Among the continually innovating firms, the majority attempt mixed exploitative and explorative innovative activities (80.6%), followed by purely exploitative activities (14.2%) and purely explorative activities (5.2%). It is noted that more first-time patenting firms (65.8%) pursue solitary innovative activities, while slightly more continually patenting firms (53.6%) seek collaboration with external partners. Among the continually patenting firms, moreover, those pursuing the purely exploitative or purely explorative innovation rely greatly on their own efforts, while those attempting the mixed exploitative and explorative innovation are more likely (59.4%) to collaborate with external partners.

Although the majority (62.4%) of the Chinese listed firms in our sample attempt patenting activities, 448 out of 1082 patenting firms acquire or submit less than 10 patents each during 2014-2017. As shown by Table 2, the average patent counts are under 10 in the cases of first-time patenting firms, purely exploitative patenting firms and purely explorative patenting firms. But three firms that own more than 10,000 patents each push the average patent count to 99.05

in the sample of all patenting firms. Overall, the average extent of collaboration is as low as 19.67% in all patenting firms. It is noted that the average extent of collaboration (23.32%) for the first-time patenting firms is slightly greater than that (18.89%) of the continually patenting firms. As expected, the average extent of collaboration in the sample of purely explorative firms (20.11%) is higher than that in the sample of purely exploitative firms (15.11%). For the continually patenting firms that engage in mixed explorative and exploitative innovation, both their average degree of exploration and extent of collaboration are moderate, at 20.94% and 19.47% respectively. We will see whether the variations in exploration and/or collaboration have caused the variation in financial performance of firms in the subsequent sections.

[Table 2 is about here.]

Firm characteristics and market values of the firms under study are reported in Table 3. The t statistics of the tests for the two-sample means indicate that the patenting firms differ from the non-patenting ones in age, size, ownership structure, leverage as well as R&D spending. The patenting firms on average invest more heavily in R&D as expected. They are also younger, larger in size and less highly geared. More importantly, the patenting firms are less heavily owned by the state. We will investigate whether these factors affect corporate patenting decisions in the following section. On the other hand, the summary statistics of Tobin's q show that financial performance of the patenting firms does not differ from that of the non-patenting firms. The further t statistics of the tests for the two-sample means (not reported) confirm that firms exploiting their familiar areas of technology enjoy the highest average forward-looking market value, while firms that innovate first time expect the lowest average market value. In the subsequent sections, we will verify the potential Tobin's q of all these patenting firms while controlling for the decisions to innovate.

[Table 3 is about here.]

4.2 Patenting activities categorised by time, exploration or collaboration

In this section, we categorise the Chinese patenting firms by the dimensions of time, degree of exploration or extent of collaboration. The resulting three groups of treatment assignments are, respectively, first-time and continual patenting firms, continual patenting firms attempting purely exploitative, purely explorative or mixed patenting activities, and solitarily and collaboratively patenting firms. On the basis of the treatment groups, we construct five settings to estimate the system of the outcome model (Eq. (1)) and the treatment model (Eq. (2)) using the inverse-probability weighted regression adjustment technique. Setting 1 consists of the treatment groups of first-time and continual patenting firms versus the control group of non-patenting firms. Setting 2 involves the firms that seek continual patenting in specific forms against the first-time patenting firms. Setting 3 includes only all continual patenting firms, with the purely exploitative firms being the control group. Settings 4 and 5 contrast between firms pursuing solitary patenting and firms engaging in collaborative patenting using the samples of all patenting firms and all continual patenting firms respectively.

We report the estimates of the treatment models of all five settings together in Table 4 to show the differences in the determination of the corporate patenting decisions. The estimates of the outcome models of settings 2 to 5 are respectively summarised in Tables 5 and 6 to facilitate the examination of the impacts of collaboration or exploration in the presence of the direct and interacting effects of market uncertainty. In the case of setting 1, we can only estimate a simplified outcome model due to the inclusion of non-patenting firms, in the sample, that do not have any data of collaboration or exploration. The unconditional causal effects of these various forms of patenting activities in all settings are summarised in Table 7.

4.2.1 Determinants of corporate patenting decisions

The determinants of the invention patenting decisions can be examined on the basis of the estimates of the treatment models (Eq.2), reported in Table 4. The treatment models are estimated as multinomial logistic models in settings 1 to 3, while the models are estimated as binary logistic models in settings 4 to 5. As expected, R&D spending of pre-patenting year positively affects the probabilities to innovate in most patenting forms and the firms experience diminishing returns to R&D investment in all these cases. For instance, R&D investment encourages the firms to start innovation, to progress towards the exploitative or mixed exploitative and explorative innovations and to innovate in collaboration with external partners. However, R&D investment does not cause firms to purely explore beyond their familiar areas of technologies. That is, simply increasing R&D investment will not make firms progress from first-time innovation to purely explorative innovation or from purely exploitative innovation to purely explorative innovation. R&D spending will not shift a firm's decision to pursue a mixed innovation strategy from the purely exploitative innovation either. Firm age is generally found to be irrelevant to any patenting decision, be it the first-time patenting decision for non-patenting firms or any continual patenting decision for first-time patenting firms. These results together support the proposition of Coad et al. (2016) that patenting firms gain experience and become more routinized and less adventurous, as they get older. Consistent with the finding by Eberhardt et al. (2017), firm size is statistically significant in explaining most decisions to innovate. For instance, large firms are more likely to initiate an innovation programme and to innovate in collaboration with external partners. Furthermore, firm size positively affects the probability to adopt a strategy of mixed exploitative and explorative innovation by the first-time patenting firms. Neither a firm's short-term liquidity position nor its long-term financial position is relevant to any decision to innovate, unless it is the decision to collaborate with external partners. Firms with a better liquidity position or a lower gearing ratio will seek less collaboration with external partners. These results could be explained by the proposition that debt is not suitable for investment in research and development, because creditors cannot share the returns from the patenting decision. The economic environment represented by the provincial per capita GDP growth is positively correlated with the decisions to innovate continually or in collaboration with external partners. It is surprising that state ownership concentration does not affect any decision to innovate in most settings. In the only setting where state ownership concentration is found statistically significant, the state actually discourages the decision to innovate continually. Considering the finding by Eberhardt et al. (2017) that patent applications by Chinese firms are directly driven by the government subsidies, we could infer that the distribution of the government subsidies had not been related to state ownership.

[Table 4 is about here.]

4.2.2 **Impacts of collaboration or exploration**

The outcome models within the potential-outcome framework enable us to examine the role of collaboration and the direct and interacting effects of market uncertainty, when the patenting firms are categorised by the dimensions of time or exploration. Table 5 reports the estimates of the outcome models in these cases where we contrast behaviours between the first-time patenting firms and continual patenting firms (setting 2) and within the continual patenting firms (setting 3). Firstly, the extent of collaboration does not influence Tobin's q, either linearly or non-linearly, in any setting. That is, collaboration does not have any value-enhancing or value-reducing potential for firms attempting first-time patenting or any form of continual patenting. These results fail to support our Hypothesis 2A that there are positive relationships between collaboration and financial performance of first-time patenting firms and continual patenting firms with a purely explorative focus, but they back Hypothesis 2B that there is no relationship between collaboration and financial performance of the continual patenting firms with a purely exploitative focus. Secondly, in both samples of all patenting firms and all continual patenting firms, patent count has a positive effect only on market values of the firms that pursue a mixed innovative strategy, i.e., pursuing patenting in both familiar and unfamiliar areas of technology. But the positive patenting effects are partially cancelled by the interacting effects of patent count and uncertainty, given their statistically significant but negative cross derivatives. These results suggest that disembodied patents increase the market values of firms that attempt a mixed explorative and exploitative innovation strategy, but higher uncertainty will decrease the value of extra patents of such nature. However, when facing uncertain market conditions, all patenting firms see an increase in their market values. This is evident by the statistically significant and positive coefficients of market uncertainty in both samples. Following Bloom and Van Reenen (2002), we interpret the positive coefficients as evidence that patents possess a real option value only in the case of firms that pursue a mixed exploitative and explorative innovation strategy. Only these firms place a value on the attribute of patents that allows firms to choose the timing of their investment in patented technologies when this involves sunk cost.

[Table 5 is about here.]

Similarly, the outcome models allow us to examine the role of exploration in the presence of direct and interacting effects of uncertainty, when the patenting firms are categorised by the dimension of collaboration. That is, we estimate the system using patenting firms that are grouped into solitarily and collaboratively innovative firms using the samples of all patenting firms (setting 4) and all continual patenting firms (setting 5) respectively. The results reported in Table 6 show that the degree of exploration has a statistically significant but negative linear term and a statistically significant and positive quadratic term in all but one groups, suggesting an U-shaped relationship between the degree of exploration and the market value as we expected in Hypothesis 1A rather than an inverted U-shaped relationship found by Belderbos et al. (2010).

[Table 6 is about here.]

The U-shaped relationship between the degree of exploration and the market value found in this study indicates that there is a threshold in the degree of exploration, beyond which firms could improve their financial performance by increasing the rate of exploration. With the estimated coefficients of the linear and quadratic terms in Table 6, we estimate that the lowest point of the U-curve is at the exploration rate of 67.1% for firms attempting solitary innovation and at 84% for firms attempting collaborative innovation in the sample of all patenting firms. Although both rates are on the high side, it is as predicted in Hypothesis 1B that the threshold for the collaboratively innovating firms is higher than that for the solitarily innovating firms. Compared with these lowest points, 21% of the firms attempting solitary innovation and 6% the firms attempting collaborative innovation have a higher rate of exploration. Therefore, these firms have passed the thresholds that permit improvement in their financial performance by increasing their rates of exploration. However, it should be noted that first-time innovating firms and continually innovating firms are both included in the sample, even though their rates of exploration are not fully compatible[7]. On the other hand, in the sample of all continual patenting firms where the rates of exploration are compatible, the lowest point of the U-curve is at 54.7% of the rate of exploration for the firms attempting solitary innovation, while there is no relation between the rate of exploration and Tobin's q for the firms attempting collaborative innovation. Compared with this threshold, 16.7% of the firms attempting solitary innovation in the sample of all continual patenting firms have achieved a higher rate of exploration, permitting better financial performance by increasing their rate of exploration. As the thresholds are rather high, only small percentages of firms in both samples could benefit

[7] While the rate of exploration for the continual patenting firms is calculated as the new IPC classes awarded to patents filed in 2014-2017 relative to those filed in 2009-2013 scaled by the patent count of 2014-2017, the rate for the first-time patenting firms is calculated as the IPC classes awarded to patents filed in 2014-2017 scaled by the patent count of 2014-2017.

from increasing rate of exploration. Majority of the Chinese listed firms would experience lower financial performance until they reach the threshold of exploration.

In these settings of collaborative innovation against solitary innovation, patent count has a positive effect on the market values of all innovative firms. When facing uncertain market conditions, all patenting real options enhance the firms' market values. However, the positive patenting effect and the patenting real options are partially cancelled by the interacting effect of patent count and uncertainty respectively, given the statistically significant and negative cross derivatives in both settings. These results suggest that disembodied patents may have an option value, but higher uncertainty will decrease the value of extra patents for all firms that attempt innovation solitarily or collaboratively.

4.2.3 Average treatment effects and potential outcomes

Table 7 summarises the average treatment effects and potential outcomes estimated in the five settings of the previous sections. In the setting (setting 1) against the control group of no patenting activity, the average treatment effects of first-time patenting and continual patenting strategies are found statistically significant and positive. That is, firms could increase their market values by initiating or continually pursuing innovation. For instance, if all firms were to pursue innovation first time, the average potential Tobin's q would have been 1.124 units higher than that (0.943) if all firms did not seek innovation. It is also noted that the average potential Tobin's q could have increased to a greater extent (by 1.608 units) if all firms were to continually innovate.

In the setting (setting 2) against first-time patenting activity, we find statistically significant and positive average treatment effects of the purely exploitative innovation and the mixed innovation. These estimates mostly confirm the observation in setting 1 that the average treatment effect of the continual innovation is higher than that of first-time innovation.

Specifically, the average potential Tobin's q would have been greater if all patenting firms were to continue innovation by pursuing either purely exploitative or a mixed innovative strategy. However, it is noted that the average treatment effect of the purely explorative innovation is statistically insignificant, suggesting no improvement in the average potential Tobin's q of the firms engaging in continual innovation through pure exploration over that of the first-time patenting firms. Furthermore, the estimates obtained from the setting (setting 3) against the purely exploitative innovation show that the average treatment effect of the mixed innovation is statistically insignificant and the average potential Tobin's q of the firms attempting the mixed innovation would not have differed from that of the purely exploitative firms. Hence there is no evidence to support the proposition of O'Reilly and Tushman (2004) and Raisch et al. (2009) that firms must undertake balanced explorative and exploitative innovative activities in order to improve their performance. Furthermore, given the statistically significant but negative average treatment effect of the purely explorative innovation, the average potential Tobin's q of purely explorative firms would have been lower than that of the purely exploitative firms. These results together with the high threshold of exploration under which patenting firms could improve their financial performance confirm a relatively weak value-enhancing role of the explorative innovation.

In the binary treatment settings of the collaborative innovation versus the control group of solitary innovation, the average treatment effect of innovation is either statistically insignificant (setting 4) or negative (setting 5), suggesting that, if all patenting firms or all continual patenting firms were to pursue collaborative innovation, the average potential Tobin's q would not have been higher than that if all firms were to attempt solitary innovation. These results are consistent with the impacts of collaboration reported in Table 5 and the finding of a negative impact of collaboration by Belderbos et al. (2010).

[Table 7 is about here.]

Taken together, firms cannot improve financial performance simply by increasing the rate of exploration, i.e., simply exploring beyond their familiar areas of technology. Although firms benefit from continual patenting through a mixed explorative and exploitative strategy, the threshold beyond which solitarily continual patenting firms could improve their financial performance is as high as 54.7%. Furthermore, the rate of exploration is not related to the financial performance of firms pursuing continual patenting activities in collaboration. There is insufficient evidence to support the proposition that firms in a developing economy like China benefit from a balanced mix of exploration and exploitation activities.

4.3 Patenting activities categorised by time, exploration and collaboration

Belderbos et al. (2010) find a positive indirect relationship between collaboration in explorative activities and financial performance of firms through the total share of exploration in technological activities. Our unique dataset permits us to detect whether collaboration in explorative activities directly affects financial performance of firms instead. To do so, we re-categorise the patenting firms by the degree of exploration **and** extent of collaboration and estimate the average treatment effect of the collaboratively explorative innovation within the potential-outcome framework. Specifically, by assigning the treatment groups by the dimensions of exploration **and** collaboration for the first-time patenting firms and the continually patenting firms, including purely exploitative, purely explorative and mixed patenting ones, we obtain eight patenting types, namely, solitary first-time, collaborative first-time, solitarily exploitative, collaboratively exploitative, solitarily explorative, collaboratively explorative, solitarily mixed and collaboratively mixed innovative firms. From the eight types of patenting firms, we establish three multivalued treatment settings for a robust determination of the average treatment effect of the collaboratively explorative innovation on the market value. The first setting facilitates the contrast of the behaviour of the collaboratively explorative patenting firms with that of the control group of non-patenting firms in the presence of the firms pursuing other seven types of innovation strategies. The second setting enables the examination of the behaviour of the collaboratively explorative patenting firms relative to the control group of first-time patenting firms in the presence of other continual patenting firms. The third setting helps the contrast with other continual patenting firms, while the solitarily exploitative patenting firms are set as the control group.

[Table 8 is about here.]

The estimates of the average treatment effects and potential outcomes obtained from these three settings are reported in Table 8. It is evident by the statistically significant and positive average treatment effect (Panel A) that collaboratively explorative innovation would unconditionally increase firms' ability to increase market values. That is, the average potential market value of firms attempting collaboratively explorative innovation would have been greater than the case if all firms did not attempt any patenting. The remaining statistics report in Panel A of Table 8 show that the collaborative efforts are related to the improvement of the financial performance of all patenting firms over the control group of the non-patenting firms and the average treatment effect of the collaboratively first-time patenting is even greater than that of its solitarily counterpart. It is confirmed that collaborative efforts are particularly beneficial to first-time patenting activities, although we did not find any evidence to support the positive relationship between the extent of collaboration and financial performance when grouping all first-time patenting firms together in the previous section.

However, the collaborative efforts become statistically insignificant when contrasting the behaviours between the continually patenting firms and first-time patenting firms or within the continually patenting firms. For instance, the average treatment effect of the collaboratively explorative innovation would be statistically insignificant, when contrasted with the control groups of the first-time innovation (panel B) or the solitarily exploitative innovation (panel C).

In either case, the average potential market value of firms pursuing collaboratively explorative innovation would not have differed from that of the control group. These results confirm the finding of insignificant impact of the degree of collaboration on firm's market value reported in Table 5.

Finally, it should be noted that the average treatment effect of the collaboratively mixed exploitative and explorative innovation would not have differed from that of its solitary counterpart in any of the three settings. While they are not statistically different from that of the control group of first-time patenting activity, the average treatment effects of the collaboratively or solitarily mixed innovative strategy become statistically significant and negative against the control group of the solitarily exploitative innovation. On the contrary, the average potential market value of solitarily exploitative innovation is consistently the highest across all types of innovation and over the three treatment settings. Taken together, these results suggest that it might not be necessary to balance simultaneously with respect to collaboration and exploration at least in the short run.

5 Conclusion

We examine the impacts of explorative and collaborative innovations on financial performance through multivalued treatment effect analyses of a sample of 1082 Chinese listed firms that filed invention patent applications with the Chinese National Intellectual Property Administration (CNIPA) against a sample of 654 firms that did not patent during 2009-2017.

As expected, the average potential market value of firms attempting first-time patenting or continual patenting would have been higher than that of firms that did not innovate at all. The value-enhancing potential is more likely to arise from the real option value of disembodied patents under market uncertainty, but higher uncertainty reduces the impact of extra new patents on market values. As opposed to the commonly found inverted U-shaped relationship for high-tech firms in the developed economies, we observe a U-shaped relationship between the degree of exploration and financial performance, particularly for solitarily innovative firms in China. In contrast to the maximum share of exploration as low as 39% found by Belderbos et al. (2010), we obtain the minimum level of exploration to be as high as 54% in order for the solitarily continual patenting firms in an emerging economy like China to benefit from the improvement of financial performance by increasing the degree of exploration.

As we expand the scope of examination by re-categorising the patenting firms by time, exploration and collaboration, we find the positive impacts of collaboration that are missing in the study of Belderbos et al. (2010). We observe statistically significant and positive collaborative efforts that lead to greater average potential market values for firms seeking any form of innovation than that of non-patenting firms. Furthermore, the collaboratively first-time patenting activity possesses a value-creation potential greater than its solitarily counterpart does, although the reverse is true for the continual patenting activities. Nonetheless, it is the strategy of solitarily exploitative innovation that would have produced the highest potential market value. Given our results that the mixed innovation strategy does not improve firms' financial performance as much as the purely exploitative strategy does and the value-creation ability of the mixed innovation strategy does not differ between collaborative and solitary efforts, it might not be necessary for firms to strike for a balance simultaneously with respect to collaboration and exploration in their innovation at least in the short run.

Data Availability statement

The data that support the findings of this study are available in China Stock Market and Accounting Research databases at http://us.gtadata.com/Home/Index and in the public domain of Chinese National Intellectual Property Administration at http://english.sipo.gov.cn/index.htm. The data sources are included in the reference list of this paper, being reference numbers 8 and 28. We have also cited the information in the following public domains: China Statistical Yearbook (various issues, National Bureau of Statistics of China) at http://www.stats.gov.cn/english/Statisticaldata/AnnualData/ and Global Innovation Index 2019 (edited by Dutta et al., World Intellectual Property Organisation) at https://www.wipo.int/global_innovation_index/en/2019/. Their reference numbers are 7 and 15 respectively.

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Table 1 Invention patenting types of Chinese listed firms over 2014-2017

Number of firms with patents		Collaborative (patent owners>1)	Solitary (patent owner=1)	Total
First-time patenting (Without patenting experience in the previous five years)		65	125	190
Continual patenting	Exploitative (No. new classes/No. patents=0)	37	90	127
	Explorative (No. new classes/No. patents≥100%)	10	36	46
	Mixed (100%> No. new classes/No. patents>0)	427	292	719
Total		539	543	1082

Notes: Number of new classes = sum of new classes in which invention patent applications fall in 2014-2017 relative to 2009-2013.

Table 2 Descriptive statistics of patent count and degrees of collaboration and exploration

	Patenting firms					
	All (n=1082)	First-time (n=190)	Continual			
			All (n=892)	Exploitative (n=127)	Explorative (n=46)	Mixed (n=719)
Patent count						
Mean	99.05	9.77	118.07	9.15	1.65	144.75
Stan Dev	667.43	17.44	733.71	12.48	0.79	815.07
Minimum	1	1	1	1	1	1
Maximum	13455	124	13455	81	4	13455
Extent of collaboration						
Mean	19.67	23.32	18.89	15.11	20.11	19.47
Stan Dev	32.15	38.37	30.63	29.57	39.31	30.19
Minimum	0	0	0	0	0	0
Maximum	100	100	100	100	100	100
Degree of exploration						
Mean		68.78	22.04			20.94
Stan Dev		30.99	25.59			18.33
Minimum		5.71	0			0.04
Maximum		100	100			85.71

Note: Degree of exploration of the first-time patenting firms is calculated using total classes in which invention patents fall of technology divided by number of invention patents over 2014-2017, while it is calculated for the continual patenting firms as the ratio of total new classes in which invention patents fall over 2014-2017 in relation to 2009-2013 to total invention patent count in 2014-2017.

Table 3 Descriptive statistics of firm characteristics and Tobin's q

	R&D	Age	Size	Liquidity	Leverage	SOE	GDP growth	Tobin's q
Non-patenting firms (n = 653)								
Mean	2.73	2.79	1.26	2.29	0.46	5.82	8.79	2.43
Stan Dev	6.04	0.42	1.29	4.61	0.21	15.62	1.53	3.58
Minimum	0.00	0.0*	-2.92	0.18	0.01	0.00	-2.50	0.00
Maximum	125.91	3.66	6.40	104.67	1.06	85.32	12.50	69.31
Patenting firms (n = 1082)								
Mean	3 .85	2.70	1.44	2.42	0.43	3.51	8.80	2.29
Stan Dev	4.01	0.35	1.26	2.77	0.20	11.57	1.39	2.48
Minimum	0.01	1.39	-1.40	0.13	0.03	0.00	-2.50	0.14
Maximum	51.55	3.91	7.23	32.02	1.01	83.68	12.50	40.73
One-tail t-test for means of non-patenting and patenting firms assuming unequal variances								
T-stat	-4.22***	4.59***	-2.77***	-0.66	2.91***	3.27**	-0.16	0.90
Means of firm characteristics and Tobin's q of specific patenting types								
First-time (n=190)	3.07	2.74	1.47	2.22	0.45	4.21	8.17	2.02
Exploitative (n=127)	4.62	2.693	1.08	2.91	0.40	2.03	8.52	3.31
Explorative (n=46)	3.81	2.78	1.20	2.77	0.40	3.78	8.26	3.02
Mixed (n=719)	3.93	2.68	1.51	2.37	0.44	3.57	9.06	2.13

Notes: Firm characteristics are financial ratios at the year (year$_{t0}$) over 2014-2017 when non-patenting firms had R&D investment first time and at the year (year$_{t-1}$) before patenting firms filed patents first time in 2014-2017.

For patenting years, R&D = (R&D expenditure$_{t-1}$/operating revenue$_{t-1}$)*100

Age = log(number of years until the year when the first patent application is submitted or the year when a non-patented firm has R&D data +1).

Size = log(total asset$_{t-1}$)

Liquidity = (current asset/current liability)$_{t-1}$

Leverage=(total liability/total asset)$_{t-1}$

SOE = % shareholding by the state at year t-1

GDP growth = per capita gdp growth of province where a firm locates at year t-1 for patenting firms and year 0 for non-patenting firms

Tobin's q = market value at year t+1 / total asset at year t

Table 4 Estimates of the determinants of probabilities to innovate in specific forms

Setting	(1)		(2)			(3)		(4)	(5)
Control group	Non-patenting		First-time patenting			Exploitative patenting		Solitary patenting	Solitary patenting
Treatment group(s)	First-time patenting	Continual patenting	Exploitative patenting	Explorative patenting	Mixed patenting	Explorative patenting	Mixed patenting	Collaborative patenting	Collaborative patenting
Constant	1.602* (0.934)	0.062 (0.647)	-1.927 (1.315)	-3.100 (1.843)	-3.118*** (1.030)	-1.154 (2.004)	-1.121 (1.140)	-1.157 (0.710)	-0.699 (0.806)
R&D expenditure/ sale revenue	0.160*** (0.049)	0.307*** (0.045)	0.135** (0.065)	0.124 (0.101)	0.193*** (0.059)	-0.019 (0.099)	0.053 (0.050)	0.134*** (0.036)	0.142*** (0.041)
(R&D expenditure/ sale revenue)^2	-0.004*** (0.001)	-0.007*** (0.002)	-0.002* (0.001)	-0.003 (0.002)	-0.004** (0.002)	-0.0004 (0.002)	-0.002 (0.002)	-0.004*** (0.001)	-0.005*** (0.001)
Firm age	-0.329 (0.236)	-0.508*** (0.174)	-0.148 (0.332)	0.470 (0.550)	-0.307 (0.253)	0.597 (0.562)	-0.112 (0.274)	-0.209 (0.185)	-0.297 (0.206)
Firm size	0.245*** (0.076)	0.361*** (0.053)	-0.156 (0.115)	-0.068 (0.177)	0.177** (0.075)	0.101 (0.187)	0.316*** (0.100)	0.636*** (0.072)	0.695*** (0.085)
Liquidity	-0.024 (0.039)	-0.020 (0.016)	0.025 (0.055)	-0.011 (0.058)	-0.006 (0.047)	-0.016 (0.053)	-0.032 (0.042)	-0.084** (0.035)	-0.082** (0.036)
Leverage	-0.635 (0.562)	-0.934*** (0.327)	0.071 (0.809)	-0.593 (1.102)	-0.250 (0.594)	-0.771 (1.181)	-0.304 (0.703)	-0.829* (0.478)	-1.078** (0.519)
State ownership concentration	-0.010 (0.007)	-0.016*** (0.004)	-0.013 (0.013)	0.001 (0.013)	-0.005 (0.007)	0.015 (0.017)	0.009 (0.013)	-0.005 (0.006)	-0.002 (0.006)
Provincial per capita GDP growth	-0.262*** (0.064)	0.100** (0.042)	0.195** (0.100)	0.041 (0.117)	0.532*** (0.075)	-0.144 (0.134)	0.317*** (0.092)	0.114** (0.046)	0.103* (0.054)
Pseudo R^2	0.0705		0.0609			0.0498		0.0854	0.0948
LR χ^2	155.78*** (d.f. = 16)		92.28*** (d.f.=24)			46.96*** (d.f. = 16)		107.45*** (d.f.=8)	91.33*** (d.f. =8)
No. observations	1735		1082			892		1082	892

Note: The dependent variables are treatment indicators in all models. The estimates are obtained from the treatment models (Eq. 2) that are estimated simultaneously with their corresponding outcome models (Eq.1) using the inverse-probability weighted regression adjustment technique. The estimates of their corresponding outcome models are reported in Tables 5 and 6.

Table 5. Estimates of impact of collaboration and direct and interacting effects of uncertainty

Setting	(2)				(3)		
	Among all patenting firms				Among all continual patenting firms		
	Control group	Treatment groups			Control group	Treatment groups	
	First-time patenting	Exploitative patenting	Explorative patenting	Mix patenting	Exploitative patenting	Explorative patenting	Mixed patenting
Rate of collaboration	1.482 (1.629)	0.816 (1.207)	3.326 (4.898)	-0.524 (0.536)	0.850 (1.240)	3.347 (5.060)	-0.400 (0.465)
(Rate of collaboration)^2	-1.465 (1.730)	-1.981 (1.684)	-4.543 (5.123)	0.519 (0.506)	-2.146 (1.757)	-4.723 (5.331)	0.408 (0.456)
Log(Number of patenting)	1.030 (0.877)	0.506 (0.822)	1.697 (2.695)	0.671* (0.358)	0.524 (0.820)	1.059 (2.921)	0.710** (0.346)
Uncertainty$_{t+1}$	1.379** (0.682)	1.709*** (0.393)	1.944** (0.845)	1.301** (0.623)	1.755*** (0.404)	1.839** (0.906)	1.334** (0.589)
Interaction between uncertainty and log(number of patenting)	-0.449 (0.311)	-0.257 (0.253)	-1.198 (0.812)	-0.249* (0.134)	-0.257 (0.250)	-1.053 (0.844)	-0.257** (0.128)
Market value$_t$ /Total asset$_{t-1}$	0. 281*** (0.134)	0.936*** (0.168)	0.774*** (0.124)	0.602*** (0.077)	0.922*** (0.162)	0.788*** (0.124)	0.607*** (0.080)
Constant	-2.305 (2.069)	-4.531*** (1.233)	-2.965 (3.003)	-3.015* (1.624)	-4.667 (1.252)	-2.416 (3.370)	-3.194** (1.557)
No. observations	1082				892		

Note: The dependent variables are Tobin's q (= Market value$_{t+1}$/Total asset$_t$) in all settings. The estimates are obtained from outcome models (Eq. 1) that are estimated simultaneously with their corresponding treatment models (Eq.2) using the inverse-probability weighted regression adjustment technique. The estimates of their corresponding treatment models are reported in Table 4. The outcome model for setting 1 (three treatment groups against the control group of non-patenting firms) is simplified to contain a constant and lagged Tobin's q, due to the inclusion of the non-patenting firms in the sample. The estimates of the outcome models of setting 1 are omitted to save space.

Table 6. Estimates of impact of exploration and direct and real options of patenting within the potential outcome framework

Setting	(4)		(5)	
	All patenting firms		All continual patenting firms	
	Control group	Treatment group	Control group	Treatment group
	Solitary patenting	Collaborative patenting	Solitary patenting	Collaborative patenting
Rate of exploration	-1.042** (0.548)	-2.282*** (0.825)	-2.690*** (0.999)	-0.760 (0.526)
(rate of exploration)^2	0.776* (0.483)	1.358** (0.676)	2.458*** (0.876)	0.411 (0.519)
Log(Number of patenting)	0.526*** (0.165)	0.903*** (0.264)	1.070*** (0.318)	0.653*** (0.185)
Uncertainty$_{t+1}$	0.875*** (0.224)	1.614*** (0.280)	1.752*** (0.385)	1.038*** (0.252)
Interaction between uncertainty and log(number of patenting)	-0.201*** (0.063)	-0.387*** (0.097)	-0.438*** (0.098)	-0.241*** (0.068)
Market value$_t$ /Total asset$_{t-1}$	0.778*** (0.030)	0.481*** (0.111)	0.700*** (0.072)	0.788*** (0.030)
Constant	-2.092*** (0.573)	-2.757*** (0.684)	-3.739*** (0.994)	-2.654*** (0.671)
No. observations	1082		892	

Note: The dependent variables are Tobin's q (= Market value$_{t+1}$/Total asset$_t$) in all settings. The estimates are obtained from outcome models (Eq. 1) that are estimated simultaneously with their corresponding treatment models (Eq.2) using the inverse-probability weighted regression adjustment technique. The estimates of the corresponding treatment models are reported in Table 4. In the sample of all patenting firms, rate of exploration of first-time patenting firms is calculated using (classes of technology/patent count) of 2014-2017, as opposed to continual patenting firms' (new classes of technology/patent count) of 2014-2017 relative to 2009-2013.

Table 7 Estimates of average treatment effects and potential outcomes of treatment groups categorised by time, exploration **or** collaboration

Setting	(1)		(2)			(3)		(4)	(5)
Control group	Non-patenting firms		First-time patenting firms			Exploitative patenting firms		Solitary patenting firms	Solitary patenting firms
Treatment group(s)	First-time patenting	Continual patenting	Exploitative patenting	Explorative patenting	Mixed patenting	Explorative patenting	Mixed patenting	Collaborative patenting	Collaborative patenting
Average treatment effect	1.124*** (0.348)	1.608*** (0.343)	0.451** (0.186)	-2.090 (1.546)	0.467*** (0.188)	-3.330* (1.973)	0.040 (0.135)	0.002 (0.084)	-0.141* (0.085)
Mean potential Tobin's q of control group	0.943*** (0.304)		1.843*** (0.163)			2.208*** (0.122)		2.284*** (0.075)	2.380*** (0.067)
Mean potential Tobin's q of treatment group(s)	2.067*** (0.148)	2.551*** (0.111)	2.295*** (0.116)	-0.247 (1.542)	2.310*** (0.1145	-1.123 (1.971)	2.247*** (0.097)	2.286*** (0.084)	2.239*** (0.067)
Sample size	1735		1082			892		1082	892

Note: The above estimates of settings 2 to 5 are obtained through their corresponding estimated outcome models (Eq. 1) reported in Tables 5 and 6. The estimates of setting 1 are obtained through the estimated simplified outcome model. Outcome models of setting 1 are simplified due to the nature of the sample, while its treatment model has omitted squared R&D. Settings 2 to 5 includes the full sets of variables.

Table 8 Estimates of average treatment effects and potential outcomes of treatment groups categorised by time, exploration **and** collaboration

Panel A: Control group = Non-patenting firms								
Treatment group	Solitary first-time	Collaborative first-time	Solitary exploitative	Collaborative exploitative	Solitary explorative	Collaborative explorative	Solitary mixed	Collaborative mixed
Average treatment effect	1.181*** (0.371)	1.226*** (0.382)	2.267*** (0.525)	1.837*** (0.449)	2.222*** (0.425)	1.876*** (0.525)	1.489*** (0.361)	1.483*** (0.343)
Mean potential Tobin's q of control group	0.880** (0.322)							
Mean potential Tobin's q of treatment group	2.061*** (0.171)	2.107*** (0.171)	3.147*** (0.385)	2.717*** (0.286)	3.103*** (0.274)	2.756*** (0.405)	2.369*** (0.123)	2.363*** (0.066)
Sample size	1735 (whole sample)							
Panel B: Control group = First-time patenting firms								
Treatment group	Solitary exploitative	Collaborative exploitative	Solitary explorative	Collaborative explorative	Solitary mixed	Collaborative mixed		
Average treatment effect	0.685** (0.337)	0.433 (0.281)	0.928*** (0.323)	0.631 (0.405)	0.127 (0.185)	0.127 (0.165)		
Mean potential Tobin's q of control group	2.126*** (0.169)							
Mean potential Tobin's q of treatment group	2.811*** (0.304)	2.558*** (0.237)	3.054*** (0.288)	2.757*** (0.371)	2.253*** (0.103)	2.253*** (0.067)		
Sample size	1082 (all patenting firms)							
Panel C: control group = Solitary exploitative firms								
Treatment group	Collaborative exploitative	Solitary explorative	Collaborative explorative	Solitary mixed	Collaborative mixed			
Average treatment effect	-0.299 (0.357)	0.289 (0.428)	0.088 (0.483)	-0.554* (0.302)	-0.566* (0.290)			
Mean potential Tobin's q of control group	2.757*** (0.298)							
Mean potential Tobin's q of treatment group	2.459*** (0.213)	3.046*** (0.326)	2.846*** (0.387)	2.203*** (0.095)	2.192*** (0.062)			
Sample size	892 (all continually patenting firms)							

Note: The above estimates are obtained through their corresponding estimated outcome models (Eq. 1). Due to the assignment of treatment groups by time, exploration **and** collaboration, the outcome models are simplified to include only a constant and Tobin's q lagged by one year in all cases. Squared R&D,

liquidity and SOE are omitted from the treatment models of panels A and B, while squared R&D, SOE and leverage are omitted from the treatment model of Panel C, due to their violation of the overlap assumption.