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Department of Accounting

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研發合作之決定因素與績效：以台灣高科技產業為例

The Determinants and Performance of R&D Cooperation: Evidence from Taiwan's High-Technology Industries

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To my mother, my wife Mirrian, and two sons Yu-Tang and Yu-Chen

獻給我的母親、我的太太瑞芬、與兩個小孩語棠和語晨

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Overseas Chinese Institute of Technology as well as Tunghai University (my next academic home), for your confidence in me and your support and encouragement for my work.

Finally, I would like to dedicate this dissertation to my mother, my wife, and my two sons: Yu-Tang and Yu-Chen. I am deeply indebted to their unfailing support, both in the emotional and the financial aspects. My mother’s blessing and, especially, my wife’s great sacrifices have made this dissertation possible.

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近七年的博士班生活即將告一段落，回首過往，歷經了許多難得且精彩的人生，而最大的體會是，論文與博士學位絕非只靠一個人可以完成的，需要許多師長、朋友、甚至貴人的從旁協助，才能順利度過每一個重要的關卡。

我想，進入政大博士班以來最明智的決定就是選擇了吳安妮教授作為我的指導教授，吳老師從我入學後就費心地教導我如何作研究，連家裡的事也常常讓她擔心。老師每天總是工作到晚上12點才得以休息，近20年來如一日。老師的學術成就和研究精神是我最敬佩的，她總是說：「我要做研究直到離開人世間的前一天」，環視整個學術界，應該很難再找到如此對學術研究堅持的學者吧！老師不僅著重學術研究外，更特別重視品格與道德，強調做一個學者，誠信與正直更是重要，正如「勇者無懼、智者無惑、仁者無敵」。對於我而言，吳老師做了最好的身教與言教的典範，是我終生學習的標竿。

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在博士班求學過程中，有幸獲得國科會「千里馬計畫」之補助赴美國亞利桑納大學進行為期一年的研究，會計系教授Leslie Eldendurg從頭到尾全力地協助我處理學校與生活的事情，她在教學與研究上敬業的態度，也讓我深深欽佩。感恩節大餐後與她、師丈John、及他們家人玩橋牌、玩拼圖的熱絡景象，讓我永難忘懷。系上博士生Lance亦常邀請我參加家庭聚會，他與太太Krystyl準備的美食，五位活潑的小孩Kaihe、Krykyt、Mela、Piikea、Samuel，加上搞笑又感人的夏威夷傳奇電影，讓我度過最快樂的週末時光。Kendra是一位亞利桑納大學英語文學系退休的老師，她用心地幫我修改論文，下午茶時間與她及師丈Ken分享不同文化的差異、卻能激盪出相同的價值觀，聆聽共同喜愛的大樂團時代爵士樂以及馬友友的大提琴，真是人生一大享受。

撰寫論文過程中若有貴人的話，那非信銘莫屬，他早我一週到亞利桑納大學報到，就讀MIS博士班，我一到美國就是先借住他的宿舍，後來我們變成好鄰

居。由於他過去念經濟，又精通程式，因此論文數學模式推導與網路資料蒐集方面的問題，都是他一一幫我解決，沒有他，我想論文大概很難順利完成的。另外，Rabah Amir 教授是一位研究傑出的經濟系老師，雖然之前我們從未謀面，但他仍熱心的為我解答模型設定上的問題，讓我更有信心解決理論上所遭遇的困難，在此一併感謝。而 Jim 是我在美國時的會友，他總是固定每週來看我，不斷鼓勵我，給我信心與勇氣，希望 2009 年我們有機會在台灣相聚。最後，在美期間，語言所博士班的鎮城也正在撰寫論文，因此我們成為無所不聊的好朋友，我會珍惜這難得的友誼。

博士班的生活中，由於修課、準備資格考、長時間在研究室中和學長姐、同學、學弟妹們的相處，因此培養出特殊的革命情感，包括淩淇、秋田、佳琪、美珠、心瑤、玉麟、全斌、惠玲與倩如，謝謝妳們無時無刻的關心與鼓勵，隨樺、伶珠、俊儒、翠菱、與素芳更是互相扶持與勉勵的好伙伴，特別是俊儒，從一年級到現在（甚至未來），一直受到他的照顧與幫忙，實在難以用筆墨形容，「大師兄」的稱號實至名歸。碩士班同學玉元早從碩士論文程式與實證分析，他與姊姊就提供我極大的協助，沒想到在博士論文的撰寫階段，仍借重不少他在實務界豐富的經驗，使得本論文可以在理論與實務方面有更密切的結合，是我另一位貴人。感謝我在僑光技術學院任教期間，商學院院長暨會計系主任賴怡君教授與同事們對我的照顧與支持，也感謝東海大學會計系許恩得主任與各位老師們願意接納我，讓我加入東大會計的大家庭。最後，我也要特別感謝助理育綺、景良、順華、及怡霙在博士班過程中的熱心協助。

其實，這七年一路走來最辛苦的人，就是我的太太—瑞芬，六年多前就讀博士班的同時，我們結婚了，自此，她就承擔起家裡所有的事情。隨著老大語棠與老二語晨的出生，負擔越來越重，為此還捨棄進修研究所的計畫。尤其在我出國的一年期間，工作與小孩兩頭忙，心力交瘁。記得剛到美國不久，語棠半夜因細菌感染發燒而掛急診住院，電話結束前妳流下了無助的眼淚，但我卻一點忙都幫不上，心裡真的很難受。長時間的睡眠不足，也讓妳身體健康大受影響，大家都說妳的犧牲太大了，面對這七年來的煎熬，好像也只能用「妳上輩子欠我的」，才能合理解釋這完全不對等的付出。希望畢業後，我可以為家庭分擔更多的家事，也能協助妳達成夢想。

最後，我要把這本博士論文獻給我的母親，她年輕時獨自扶養我長大，現在則總是默默地祝福我做的每一件事，做我最佳的後盾，希望自己有更多的時間陪伴她，讓過去所有的辛苦與犧牲都值得。博士班學業的結束，只是劃下人生一個逗點，新的學術生涯才要真正開始，未來的日子，我會盡力投入研究、教學、與家庭上，期望這一生能為社會作出更大的貢獻。

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Abstract

Innovation is complex, costly, and risky and incurs externalities. R&D cooperation is thus a proper mechanism to encourage firms to innovate. The purposes of this dissertation are to extend the prior theoretical framework and empirical studies to establish a research framework for the R&D cooperation—innovation—financial performance chain. The research questions are as follows:

1. Do absorptive capacity, knowledge spillovers, and uncertainty affect the intensity of R&D cooperation?
2. Does R&D cooperation result in higher R&D investments, R&D outputs, and financial performance?
3. How do different R&D cooperation types influence the determinants of R&D cooperation?
4. How do different R&D cooperation types influence the performance of R&D cooperation?
5. Is the effect of R&D cooperation on financial performance mediated by R&D investments and R&D outputs?

In this dissertation I apply the two-industry, n-firm-per-industry Cournot competition models to theoretically examine the relationship between R&D cooperation, R&D investments (input perspective of innovation), R&D outputs (output perspective of innovation—non-financial performance), and financial performance. I then use Taiwan's high-technology industry as a research sample and empirically test my research hypotheses. The results provide academia and practitioners with a more comprehensive view of R&D cooperation and innovation activity among Taiwan's high-technology industries.

The empirical results support the argument that absorptive capacity has a positive impact on the frequency of R&D cooperation in high-technology industry. In addition, an increase in knowledge spillovers also tends to increase intensity to collaborate in R&D. Under high absorptive capacity and knowledge spillover, generalized R&D cooperation is preferred to other cooperative models.

The empirical results also show that R&D cooperation does encourage Taiwan's high-technology firms to invest more resources in R&D, and leads to higher R&D outputs and financial performance under the characteristic of high knowledge spillovers. Relative to other cooperation types, generalized cooperation leads to higher R&D outputs and financial performance and is a superior cooperative model. Due to the nature of market competition, horizontal cooperative firms are not willing to invest too much in R&D relative to vertical cooperation and generalized cooperation. Finally, simply investing in R&D alone is not enough to achieve breakthrough performance and sustain a competitive advantage. The ability to innovate and generate R&D outputs determines the profitability of the cooperative company.

Key words: R&D cooperation, Innovation, R&D investments, R&D outputs, financial performance, high-technology industry, mediating effect.

摘要

創新是複雜、昂貴、且高風險的活動，並且存在外部性，研發合作為促使企業從事創新的重要機制。本研究目的在於延伸過去理論性架構與實證研究，建立研發合作—創新—財務績效價值鏈。以下為研究問題：

1. 吸收能力、知識外溢、與不確定性是否會影響研發合作的頻率？
2. 研發合作是否可以提高研發投資、研發產出、與財務績效？
3. 不同的研發合作型態如何影響研發合作的決定因素？
4. 不同的研發合作型態如何影響研發合作的績效？
5. 研發合作與財務績效的關係是否會受到研發投資與研發產出的中介影響？

本研究採用 two-industry, n-firm-per-industry Cournot 競爭模型探討研發合作、研發投資（創新之投入面）、研發產出（創新之產出面—非財務績效）、與財務績效的關係，並以台灣高科技產業為研究對象進行實證分析。對於台灣高科技產業的研發合作與創新活動，研究結果提供學術界與企業界更完整且廣泛的觀點。

實證結果支持公司擁有較高吸收能力的員工是從事研發合作的決定因素之一。另外，知識外溢的提高，亦將促使高科技公司進行研發合作。而在高度吸收能力與知識外溢下，公司採行一般合作之頻率較其他合作模式高。

另外，實證結果也發現研發合作的確鼓勵台灣高科技產業的公司進行更多研發的投資，並且持續創造較高的研發產出與財務績效。相對於其他合作型態，一般合作可以創造較高的研發產出與財務績效，因此為較佳的合作模式。而由於市

場競爭的本質，使得水平合作公司之研發投資較垂直合作與一般合作少。最後，僅有研發投資並不足以提升公司的績效與維持競爭優勢,研發合作公司的創新能力與研發產出才是獲利力的決定因素。

關鍵字：研發合作、創新、研發投資、研發產出、財務績效、高科技產業、中介效果

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Chapter 1: Introduction

1.1 Research background

Innovation[1] has been shown to have significant effects on economic development in both academia and practice. In 1934 the well-known economist Schumpeter emphasized that innovation is a critical force that drives economic growth (Schumpeter 1934). Innovation is also one of the central points in Peter Drucker's publications, "The Practice of Management" and "Innovation and Entrepreneurship" (Drucker 1954, 1985), in which he wrote, "The economy is forever going to change and is biological rather than mechanistic in nature. The innovator is the true subject of economics." Intellectual property nowadays in fact receives a lot more attention, because innovation has become the most important resource, replacing land, equipment, and raw materials, in the knowledge economy (Lev 2004; Cukier 2005). As much as three-quarters of the value of U.S. publicly-traded companies comes from intangible assets. Alan Greenspan, former Chairman of the U.S. Federal Reserve, also pronounced: "The economic product of the United States has become predominantly conceptual" (Cukier 2005).

Innovation in technology industries shows several interesting trends. First, information technology (IT) has become so complicated that firms are more willing to accept the innovation of others. Second, consumers are demanding "interoperability"[2] and common standards rather than proprietary systems, which means that different firms' technologies must work together smoothly. Third, information technology and telecommunications also rely on "network effects," suggesting that as more people use a system, interoperability among different technologies becomes essential (Cukier 2005). Therefore, innovative activity, especially in high-technology industries, is increasingly *cooperative*.

Externalities also exist in innovation process. Externalities occur when a firm invests in research and development (R&D) that spills over to other firms, including competitors. Thus, any one firm benefits from other firms' research. In this way,

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[1] Innovation is a creation (a new device or process) resulting from study and experimentation (Webster dictionary, http://www.websters-online-dictionary.org/). Innovation is also the implementation of a new or significantly improved idea, good, service, process, or practice that is intended to be useful.

[2] Interoperability is defined as the ability of software and hardware on multiple machines from multiple vendors to communicate (Webster dictionary, http://www.websters-online-dictionary.org/).

innovative companies will limit their new investments in R&D if they see a decreased likelihood of being able to make exclusive use of the results of their efforts (e.g. Spence 1984). On the other hand, if imitator firms can use the public stock of technological knowledge, then they reduce the level of effort invested in innovation (e.g. Levin and Reiss 1988; Henderson and Cockburn 1996). Therefore, externalities decrease both innovators' and imitators' incentives to invest in R&D (e.g. Kamien, Muller, and Zang 1992; Martin 2002).

A proper mechanism[3] is needed to encourage firms, or the incentives to innovate will be distorted. According to prior literature (e.g. Kamien et al. 1992), R&D cooperation[4] can restore firms' incentive to engage in R&D, as it not only accelerates the speed of innovation with less risk, but also produces synergetic effects through the combination of new information, teams of specialists, and resources (e.g. Jacquemin 1988; Kamien 1992). Therefore, the cooperation between academies and industries (e.g. the cooperation between Taiwan's Industrial Technology Research Institute (ITRI) and its high-technology industries) and the cooperation in inter-industry and intra-industry (e.g. the technology transfer between AUO, IBM Japan, and Matsushita) represent popular phenomena.

1.2 Research motivation

Starting with the work of D'Aspremont and Jacquemin (1988) and Kamien et al. (1992), a large number of theoretical research papers have emerged over the past decade attempting to formalize a firm's private incentives to engage in horizontal R&D cooperation[5] with horizontal knowledge spillovers (Ishii 2004). Researchers frequently use oligopoly models that allow for strategic interactions between firms. Although there are differences in assumptions across the various models, the results are quite robust: while non-cooperative R&D levels decrease with an increase in

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[3] Three instruments are usually considered to restore firms' incentives to engage in R&D: (1) tax policies and direct subsidies, (2) patents and licensing, and (3) ex-ante R&D cooperation. While the first two instruments require government intervention to determine taxes and subsidies or to strengthen property rights, R&D cooperation is assumed to work through private incentives, because of the possibility to internalize R&D spillovers between cooperating firms (Katz and Ordover 1990).

[4] R&D cooperation is defined as joint operation or action with R&D (Webster dictionary, http://www.websters-online-dictionary.org/). I also use the word "R&D cooperation", "R&D collaboration", "research partnership", and "research joint venture", etc, interchangeablely. For a more detailed description of R&D cooperation, please see Chapter 2.

[5] Horizontal R&D cooperation means R&D cooperation between competing companies, while vertical R&D cooperation indicates R&D cooperation between buyers and suppliers. Generalized cooperation reflects the complexity of R&D cooperation, which firms may be adopting more than one structure simultaneously (Atallah 2002).

knowledge spillovers, it has been shown that cooperative R&D investments, outputs, and social welfare tend to increase with the increase in spillovers (e.g. Veugelers 1998).

Most theoretical studies in R&D cooperation deal with horizontal cooperative R&D, with vertical cooperative R&D receiving little attention until recently (e.g. Atallah 2002; Ishii 2004). Cooperative relationships between final-goods manufacturers and input suppliers are crucial for successful innovation (Ishii 2004). Vertical R&D cooperation is desirable and is often voluntary under buyer-seller relationships, whereas horizontal R&D cooperation is involuntary and undesirable, because innovating firms have to face their competitors (Atallah 2002). Furthermore, the network relationships between firms become more complex, and the opportunities of engaging in R&D cooperation simultaneously among competitors, customers, and suppliers are getting more popular. Therefore, vertical R&D cooperation and generalized R&D cooperation should merit more attention from researchers.

Several studies also indicate that R&D cooperation provides future benefits (e.g. Kamien et al. 1992; Hagedoorn and Schakenraad 1994; Belderbos, Carree, and Lokshin 2004; Ishii 2004). Kamien et al. (1992) indicate that a research joint venture (RJV) that cooperates in its R&D decisions yields the highest consumer and producer surplus. Ishii (2004) points out that a RJV yields the largest social welfare. However, the direct relationship between R&D cooperation and financial performance does raise doubts because R&D cooperation must also invest in R&D and generate R&D outputs in order to lead eventually to profit generation. Therefore, I argue that R&D cooperation does not imply automatically higher levels of financial performance, and the impact of R&D cooperation on financial performance is mediated by R&D investments and R&D outputs (forward-looking measures). The relationship between R&D cooperation, R&D investments, R&D outputs, and financial performance needs further examination.

1.3 Research purposes and research questions

The purposes of this study are to extend prior theoretical framework and to introduce two industries, n-firm-per-industry models. In addition, I examine the determinants for engaging in R&D cooperation and the performance of R&D cooperation. I also provide a hypothetical framework for the R&D cooperation —

innovation — financial performance chain (See Figure 5).

Mathews and Cho (2000) show that the importance of R&D cooperation activity is instrumental in explaining the successful development of Taiwan’s high-technology industries. Taiwan’s high-technology industries are highly competitive and play a major role in the world, due to the successful business model of highly vertical disintegration (or vertical specialization).[6] Nevertheless, Taiwan has received little attention because of the problem of difficult data collection. In this study, I use Taiwan’s high-technology industries as a research sample and empirically test the research hypotheses. The results provide companies, industries, and academia with a more comprehensive view of R&D cooperation and innovation activity in Taiwan’s high-technology industries.

The research questions are as follows:

1. Do absorptive capacity, knowledge spillovers, and uncertainty affect the intensity of R&D cooperation?
2. Does R&D cooperation result in higher R&D investments, R&D outputs, and financial performance?[7]
3. How do different R&D cooperation types influence the determinants of R&D cooperation?
4. How do different R&D cooperation types influence the performance of R&D cooperation?
5. Is the effect of R&D cooperation on financial performance mediated by R&D investments and R&D outputs?

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[6] Vertical disintegration indicates industrial decentralization. Vertical disintegration spreads the risks and costs of R&D investments across multiple firms. In addition, every segment of production operates independently, and so the degree of specialization is high and the management difficulty is relatively lower. Vertical disintegration also enhances a firm’s ability to identify and respond quickly to potential market niches.

[7] In contrast with R&D cooperation, R&D competition (or noncooperative R&D) means that each firm noncooperatively chooses its level of R&D. Regarding the measurement of R&D cooperation and R&D competition, please refer to variable measurement.

1.4 Significance of the research

This study contributes significantly to both academia and practice:

1. Contributions to academia:

(1) R&D cooperation studies face the problem of difficult data collection (e.g. Veugelers 1998). Thus, a survey questionnaire becomes a primary tool of R&D cooperation research and allows easy collection of data (e.g. Kaiser 2002a; Caloghirou, Hondroyiannis and Vonortas 2003; Chang 2003; Belderbos et al. 2004). However, certain limitations should be considered, as respondents may not understand or truly express the reality of R&D activity in firms. Respondents are likely influenced by the gaps between individuals' and researchers' perceptions of questionnaires. In this study I use archival data to prevent the deficiencies in the questionnaire survey. This is the first comprehensive empirical research discussing the relationships among R&D cooperation, R&D investments, R&D outputs, and financial performance in Taiwan.

(2) In multiple linear regressions all effects are modeled to occur at a single level. In order to analyze the variance in outcome variables at multiple hierarchical levels, I employ the Hierarchical Linear Model (HLM) to examine the determinants of R&D cooperation. In addition, to avoid sample selection bias, I apply the Heckman two-step model and treatment effects model to estimate the probability of whether or not a firm engages in R&D cooperation. I then use OLS with adjusted items to estimate the impact of R&D cooperation intensity on R&D investments, R&D outputs, and financial performance. These methods will enhance the reliability of the empirical results and open new avenues in R&D cooperation research.

2. Contributions to practice:

(1) Prior literature indicates that companies concentrating on R&D cooperation have significantly higher profits (e.g. Hagedoorn and Schakenraad 1994; Ernst 2001). However, I suggest that R&D cooperation does not imply automatically higher levels of financial performance, and leading indicators in fact drive the financial performance of R&D cooperation. Therefore, this study first addresses an integrated R&D cooperation—R&D investments—R&D

outputs—financial performance framework and then applies the Path analysis to empirically test the causal relationship among R&D cooperation, R&D investments, R&D outputs, and financial performance. The research results may have an important application for practitioners.

(2) Prior research discusses whether R&D cooperation impacts company's R&D investments, R&D outputs, and financial performance, and what the motivation of R&D cooperation is. This study first points out that not every R&D cooperation type can improve R&D investments, R&D outputs, and financial performance. In addition, the intensity of R&D cooperation is also impacted by different R&D cooperation types.

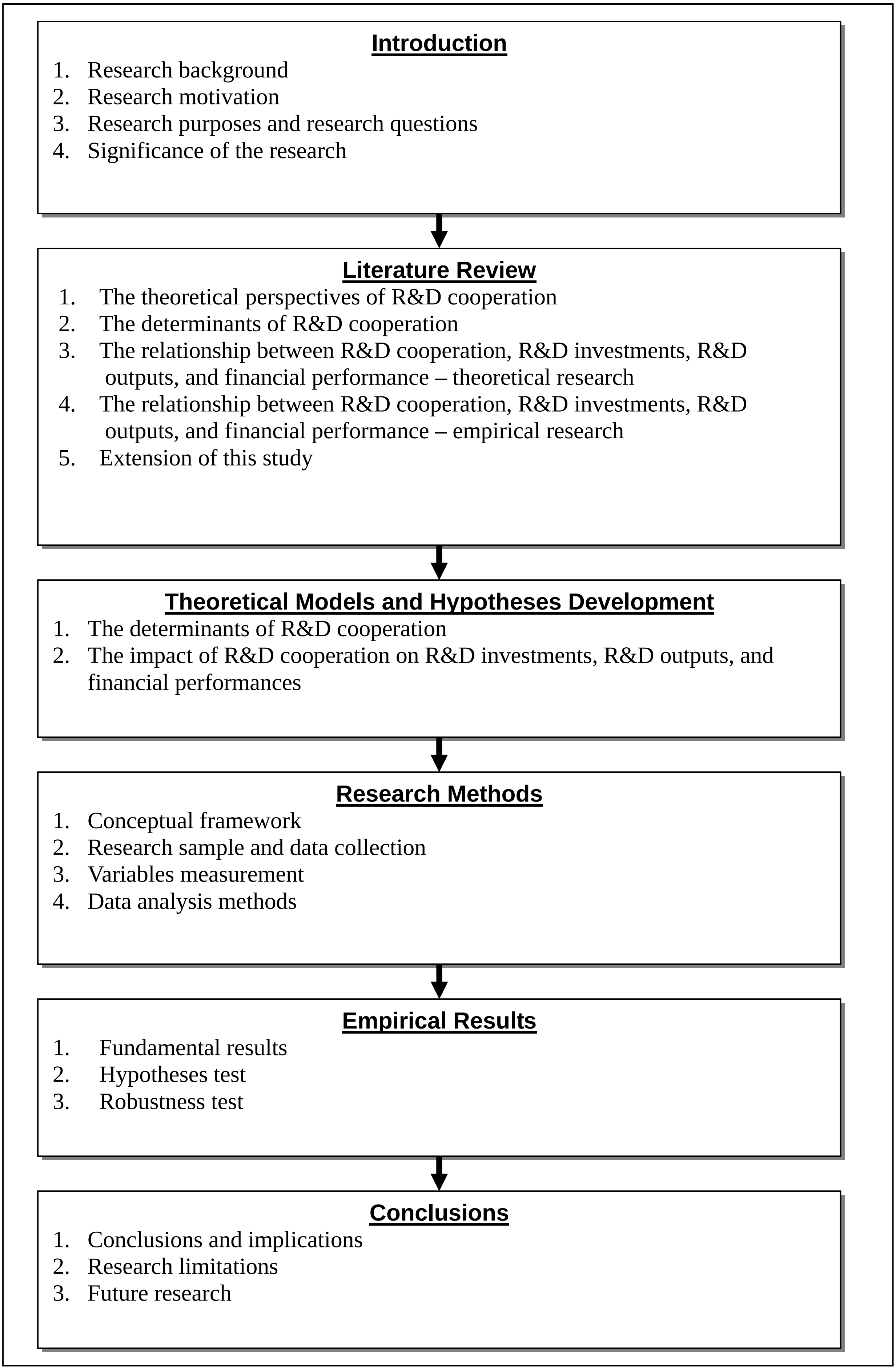
(3) Taiwan is deemed a core innovator internationally. Based on the World Economic Forum's (WEF) "Global Information Technology Report 2005-2006", Taiwan is ranked seventh in the world. It is an innovation powerhouse, with levels of patents registration per capita exceeded only by the United States and Japan (Dutta, Lopez-Claros, and I. Mia 2006). Therefore, Taiwan has a high national competitive ability and has acquired international affirmation in innovation and technology aspects, especially in its high-technology industries. The use of Taiwan's high-technology industries in the research sample will enable the results of the relationship between R&D cooperation, R&D investments, R&D outputs, and financial performance to provide important meanings for international high-technology industries.

1.5 Research framework

This study is divided into six parts. See Figure 1.

1. Introduction: The first section explains the research background, research motivation, research purpose, research questions, and contributions.
2. Literature review: This section reviews theoretical and empirical findings related to R&D cooperation. First of all, I discuss the definitions, the classifications, the benefits, and the theoretical perspectives of R&D cooperation. Second, I review the related papers of the determinants of participating in R&D cooperation. Third, I present the theoretical research and empirical research related to R&D cooperation, R&D investments, R&D outputs, and financial performance. I will further discuss the extension of this paper.

3. Theoretical model and hypotheses development: I discuss the hypotheses related to the factors that influence the intensity of R&D cooperation. I then apply Cournot-Nash equilibrium theory to derive the hypotheses regarding the impact of different types of R&D cooperation on R&D investments, R&D outputs, and financial performance.
4. Research method: This section describes the conceptual framework, research sample, variables measurement, and data analysis methods.
5. Empirical results: I discuss the findings of the factors of engaging in R&D cooperation. I also examine the results of the relationship between R&D cooperation, R&D investments, R&D outputs, and financial performance.
6. Conclusions: I conclude by reviewing the research findings, and by discussing the implications of this research for academia and practice, the research limitations, and future research.



Introduction

1. Research background
2. Research motivation
3. Research purposes and research questions
4. Significance of the research

Literature Review

1. The theoretical perspectives of R&D cooperation
2. The determinants of R&D cooperation
3. The relationship between R&D cooperation, R&D investments, R&D outputs, and financial performance – theoretical research
4. The relationship between R&D cooperation, R&D investments, R&D outputs, and financial performance – empirical research
5. Extension of this study

Theoretical Models and Hypotheses Development

1. The determinants of R&D cooperation
2. The impact of R&D cooperation on R&D investments, R&D outputs, and financial performances

Research Methods

1. Conceptual framework
2. Research sample and data collection
3. Variables measurement
4. Data analysis methods

Empirical Results

1. Fundamental results
2. Hypotheses test
3. Robustness test

Conclusions

1. Conclusions and implications
2. Research limitations
3. Future research

Figure 1: Research framework of this study

Chapter 2: Literature review

This section reviews the literature related to R&D cooperation, R&D investments, R&D outputs, and financial performance, including: 1. The theoretical perspectives of R&D cooperation; 2. The determinants of R&D cooperation; 3. The relationship among R&D cooperation, R&D investments, R&D outputs, and financial performance-theoretical research; 4. The relationship between R&D cooperation, R&D investments, R&D outputs, and financial performance-empirical research; and 5. Extensions of this study.

2.1 The theoretical perspectives of R&D cooperation

2.1.1 The definitions of R&D cooperation

Given the wide range of R&D cooperation activities, there are different kinds of definitions for R&D cooperation in academia. The synonyms of R&D cooperation used in research include R&D collaboration, research partnership, R&D consortia, R&D joint venture, R&D alliance, R&D strategic alliance, R&D cooperative or collaborative agreement, etc. For examples, research partnership is an innovation-based relationship that involves a significant effort in R&D (Hagedoorn, Link, and Vonortas 2000). R&D agreement is an agreement that regulates R&D sharing and/or transferring between two or more parent companies (Harabi 1998). Siegel (2003) defines strategic research partnership as a cooperative relationship involving organizations that conduct or sponsor R&D, in which there is a two-directional flow of knowledge between the partners. According to Teece (1992), R&D strategic alliance is an agreement characterized by the commitment of two or more firms to reach R&D goals entailing the pooling of their resources and activities. According to prior researchers' viewpoints, I define R&D cooperation as a cooperative relationship involving two or more organizations that pool their resources and activities to reach an R&D goal. I summarize different definitions of R&D cooperation by prior researchers as follows:

Table 1: The definitions of R&D cooperation

The synonyms of R&D cooperation	Definition	Author (year)
R&D Collaboration	The process of working together with competitors for R&D.	Gibson and Rogers (1994)
Research partnership	Cooperative arrangements engaging companies, universities, and government agencies and laboratories in various combinations to pool resources in pursuit of a shared R&D objective.	Council on Competitiveness (1996)
	An innovation-based relationship that involves a significant effort in R&D.	Hagedoorn et al. (2000)
R&D partnership	The specific set of different modes of inter-firm collaboration where two or more firms that remain independent economic agents and organizations share some of their R&D activities.	Hagedoorn (2002)
R&D consortia	R&D consortia are self-governing, usually nonprofit organizations run for the benefit of their members. The owners are the customers, and their purpose is to develop new technology and put it into practice.	Corey (1997)
R&D joint venture	R&D joint ventures are operations whereby a legally independent and autonomously managed business enterprise is set up by two or more parent companies to run a clearly defined set of R&D activities in the common interest of the founding firms.	Harabi (1998)
R&D agreements	R&D agreements cover agreements that regulate R&D sharing and/or transfer between two or more parent companies.	Harabi (1998)

Cooperative agreements	Common interests between industrial partners that are not connected through ownership.	Hagedoorn et al. (2000)
Strategic research partnership	Strategic research partnerships are primarily entered into by high-technology alliance members to exercise an 'option' to acquire first mover advantage resulting from the emergence of a potential dominant design technology or process innovation.	Hemphill and Vonortas (2003)
	A cooperative relationship involving organizations that conduct or sponsor R&D, in which there is a two-directional flow of knowledge between the partners. The implication is that there is a mutually beneficial transfer of knowledge that, in theory, enables all of the partners to achieve a strategic objective.	Siegel (2003)
R&D strategic alliance	Agreements characterized by the commitment of two or more firms to reach R&D goals entailing the pooling of their resources and activities.	Teece (1992)
	Strategic alliances embrace a diversity of collaborative forms. The activities covered include supplier-buyer partnerships, outsourcing agreements, technical collaboration, joint research projects, shared new product development, shared manufacturing arrangements, common distribution agreements, cross-selling arrangements, and franchising.	Grant and Baden-Fuller (2004)

2.1.2 The classification of R&D cooperation

R&D cooperation can come from either the public sector (e.g. universities and government agencies) or the private sector (e.g. companies). R&D cooperation can also be formal, as expressed in an official pact between the two units detailing the scope and nature of the cooperation; or informal, in which one individual exchanges information with another individual over a period of time without any written or official authorization to do so (Gibson and Rogers. 1994; Hagedoorn et al. 2000). R&D cooperation is an example of formal cooperation. However, very little is known about informal R&D cooperation. The classification of R&D cooperation can also be described as nonexclusive, exclusive, or closed. Nonexclusive cooperation tends to focus on technology for both collective and selective[8] products used by a broad membership. Exclusive cooperation also pursues selective technology, but it is organized to advance the interests of some specific group. Closed cooperation seeks to develop proprietary technology, often to enhance members' market shares in inter-firm and or international competition. Unlike the products of nonexclusive and exclusive cooperation, the more widely proprietary technology is shared, the less its value to any individual cooperative partner (Corey 1997).

Finally, some R&D cooperation is structured horizontally to include firms at only one level of the industry (e.g. competitors). Others are organized vertically to bring together firms at different levels such as suppliers or customers. For example, IC design industry emphasizes system on chip (SOC). SOC is an idea of integrating all components of a computer or other electronic system into a single integrated circuit (chip). However, a single company cannot own all the techniques in the system, so it has to obtain techniques or complete a product together through cooperation with its competitors. Opposite to IC design industry, system assembling companies pay more attention to vertical cooperation. For example, notebook OEM companies, such as Quanta and Compal, emphasize cooperation between suppliers and customers. They

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[8] Collective products, such as technology for improving the quality of the environment or the development of an industry supply infrastructure, are available to all, consortia members and nonmembers alike. Selective products are R&D achievements made available to individual member firms for such purposes as advancing operations technology, training personnel, and developing new products; their benefits are not easily accessible to nonmembers. Proprietary technology is intended to be appropriable by member only, and is usually undertaken to gain some margin of competitive advantage at the level of the firm (Corey 1997).

have to cooperate with upstream computer component suppliers to insure the specification and yield rate of the components, and rely on the upstream computer component suppliers' help to complete system design. Upstream firms also cooperate with downstream firms on R&D in order to establish a closed production relationship with downstream customers.[9]

In this paper, I focus on the influence of horizontal and vertical R&D cooperation, and only include formal cooperation in the private sector. Most of my research samples engage in closed cooperation, but still have some cases of open cooperation. Table 2 summarizes the different classifications of R&D cooperation.

Table 2: The classifications of R&D cooperation

Classifications	Description
1. Public vs. private sector cooperation	R&D cooperation can come from either the public sector (e.g. universities and government agencies) or the private sector (e.g. companies).
2. Formal vs. informal cooperation	R&D cooperation can also be formal, as expressed in an official pact between the two units detailing the scope and nature of the cooperation; or informal, in which one individual exchanges information with another individual over a period of time without any written or official authorization to do so.
3. Open vs. closed cooperation	Nonexclusive cooperation tends to focus on technology for both collective and selective products used by a broad membership. Exclusive cooperation also pursues selective technology, but it is organized to advance the interests of some specific group. Closed cooperation seeks to develop proprietary technology, often to enhance members' market shares in inter-firm and international competition.

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[9] Please refer to Appendix D for more information about R&D cooperation.

4. Horizontal vs. vertical cooperation	R&D cooperation can be structured horizontally to include firms at only one level of the industry (e.g. competitors). Others are organized vertically to bring together firms at different levels such as suppliers or customers. In addition, generalized cooperation (cooperating with supplier, customer, and competitors simultaneously) is also a widespread form of R&D cooperation.

2.1.3 The benefits of R&D cooperation

The economic reason for the formation of R&D cooperation is the anticipation of a greater benefit through R&D partners than any benefit arising if the partners were to undertake the same activities independently, that is, cost-benefit analyses (Corey 1997). Several types of potential benefits of R&D cooperation can be identified as follows. First, the cost of R&D continues to escalate, taking it beyond the point at which any one company could afford the requisite R&D investment. Therefore, cost sharing opportunities are prime motivators in the formation of consortia for the development of collective and selective R&D products in noncompetitive domains (Corey 1997). Learning from failures is also offered as a benefit of R&D consortia. If ten companies invest in a risky technology and it fails, then each company learns what not to do at one-tenth the cost (Gibson and Rogers 1994). Second, sharing complementary technical knowledge is often the purpose of consortia that are formed to develop proprietary technology to advance competitive advantage (Corey 1997). Third, risk reduction opportunities provide an incentive for collaboration on large-scale projects with a relatively high degree of uncertainty. In addition, risk reduction can provide the opportunity to monitor technological advances in competitors’ R&D activities (Corey 1997). Fourth, synergy allows an R&D consortium with many researchers and resources to enjoy certain benefits that each of its member firms acting alone could not achieve (Gibson and Rogers 1994). By using coalitions, a firm can benefit from a broader scope of activities without spending precious resources to enter new market segments (Porter 1986). Choi (1993) also indicates that the benefits of research joint venture are as follows: pooling of risk and financial resources under market imperfections in capital market, complementary assets owned by different firms, prevention of duplicative research effort, and coordination of research technology choices, etc. Table 3 summarizes the benefits of R&D cooperation.

Table 3: The benefits of R&D cooperation

	Benefits	Author (year)
1. Cost sharing	Cost sharing opportunities are prime motivators in the formation of consortia for the development of collective and selective R&D products in noncompetitive domains.	Corey (1997)
	Benefits to MCC (Microelectronics and Computer Technology Corporation) included improved financing and access to low-cost manufacturing.	Gibson and Rogers (1994)
	Learning from failures is also offered as a benefit of R&D consortia. If ten companies invest in a risky technology and it fails, then each company learns what not to do at one-tenth the cost.	Gibson and Rogers (1994)
2. Avoiding duplication R&D	When companies share information completely the R&D process can be divided up into small bits so that the cost of duplicating fruitful and fruitless approaches is avoided.	Kamien, Muller, and Zang (1992).
	Avoiding duplication of effort.	Scotchmer (2005)
3. Sharing complementary technology	Technology know-how for joint technology development.	Gibson and Rogers (1994)
	Sharing complementary technical knowledge is often the purpose of consortia that are formed to develop proprietary technology to advance competitive advantage.	Corey (1997)
	Sharing technical information that might be hidden if firms compete.	Scotchmer (2005)

4. Risk reduction	Risk reduction opportunities provide an incentive for collaboration on large-scale projects with a relatively high degree of uncertainty.	Corey (1997)
	Risk reduction can provide the opportunity to monitor technological advances in competitors' R&D activities.	Corey (1997)
	A firm may decide to enter into a technology alliance that has significant technological or market uncertainties attached to it.	Hemphill and Vonortas (2003)
5. Synergy	Coordination of research technology choices.	Choi (1993)
	Synergy allows an R&D consortium with many researchers and resources to enjoy certain benefits that each of its member firms acting alone could not achieve.	Gibson and Rogers (1994)
	Delegating effort to the more efficient firms.	Scotchmer (2005)

2.1.4 Theoretical perspectives on R&D cooperation

There is a vast literature that attempts to explain, from a theoretical perspective, why firms engage in R&D cooperation and what are the results of such cooperation to the partners, industry, and society, respectively. Hagedoorn et al. (2000) distinguish three theoretical perspectives on R&D cooperation: transaction costs, strategic management, and industrial organization theory. First, transaction cost theory is used to explain why an R&D cooperation is formed. One must determine why participating organizations have a cost advantage over the market or a hierarchical organization form of operation for R&D activity (Hagedoorn et al. 2000). Technological transactions in the marketplace can have high transaction costs. Internal R&D limits these costs, but blocks the access to specialized resources in other firms. Through R&D cooperation, firms can get access to these specialized resources, while at the same time allowing for the transfer of technology and knowledge at lower transaction costs (Oerlemans and Meeus 2001).

Second, strategic management scholars use five approaches to discuss strategic technical alliances as below:

1. Competitive force: Cooperation is seen as a means of shaping competition by improving a firm’s comparative competitive position. By using coalitions, a firm can react swiftly to market needs and bring technology to the marketplace faster (Porter 1986).
2. Strategic network: The network is a new form of organization and strategy. Multiple cooperative relationships of a firm can be the source of its competitive strength. Strategic networks can achieve efficiency, synergy, and power (Hagedoorn et al. 2000).
3. Resource-Based View: The resources of sustained competitive advantage are firm resources that are valuable, rare, and not easily substitutable. Access to external complementary resources may be necessary in order to fully exploit the existing resources and develop sustained competitive advantages (Teece 1986). Alliances, including R&D cooperation, can facilitate access.
4. Dynamic capabilities: Dynamic capabilities are defined as the firm’s ability to integrate, build, and reconfigure internal and external competence to address rapidly changing environments (Teece, Pisano, and Shuen 1997). Inter-firm cooperation can be viewed as a vehicle for organizational learning (Hamel and Prahalad 1989; Mody 1993) and for entering new technological areas (Dodgson 1991).
5. Strategic options to new technologies: This approach to explaining cooperation complements the dynamic capabilities approach by considering how managers can determine prospectively the set of resources and capabilities necessary for superior future performance in uncertain market environments (Sanchez 1993). Cooperation may assist companies to gain valuable experience and increase their exposure to related markets and their ability to sense and respond to new opportunities (Kogut 1991).

Third, industrial organization scholars have long been interested in the resource allocation and economic welfare effects of inter-firm cooperation in R&D. The models can essentially be categorized into two categories: non-tournament models and tournament models:

1. Non-tournament models: The vast majority of the theoretical work on cooperative R&D has followed the non-tournament approach (e.g. D’Aspremont and Jacquemin 1988; Kamien et al. 1992; Atallah 2002; Ishii 2004). The literature is replete with strategic, static, multistage models comparing the performance of cooperative and non-cooperative industrial setups in the presence of imperfectly appropriable, cost-reducing R&D. A consistent finding is that R&D competition seems better in the absence of knowledge spillovers, while R&D cooperation performs consistently better under the higher rate of knowledge spillovers. The mathematical modeling of this study follows non-tournament approach.
2. Tournament models: Tournaments models emphasize the timing of innovation where the winner of an innovative race (often takes the forms of a patent race) earns the right to an exogenously or endogenously determined monopolistic return. The winner shares the available information with the loser means that partnership will not form unless it is subsidized. In addition, firms choose to cooperate fully when they undertake complementary R&D, while they share no information outside the partnership if they undertake substitutive R&D.

I summarize the theoretical perspectives on R&D cooperation as Table 4:

Table 4: Theoretical perspectives on R&D cooperation

Theory	Categories
1. Transaction cost: Why participating organizations have a cost advantage over the market or a hierarchical organization form of operation for R&D activity.	Through R&D cooperation, firms can get access to the specialized resources of other firms, while at the same time allowing for the transfer of technology and knowledge at lower transaction costs than transactions through the market place (Oerlemans and Meeus 2001).

2. Strategic management scholars: Five approaches are used to discuss strategic technical alliances.	1. Competitive force: Cooperation is seen as a means of shaping competition by improving a firm's comparative competitive position. By using coalitions, a firm can react swiftly to market needs and bring technology to the marketplace faster (Porter 1986).
	2. Strategic network: Multiple cooperative relationships of a firm can be the source of its competitive strength. Strategic networks can achieve efficiency, synergy, and power (Hagedoorn et al 2000).
	3. Resource-Based View: The resources of sustained competitive advantage are firm resources that are valuable, rare, and not easily substitutable. Access to external complementary resources may be necessary in order to fully exploit the existing resources and develop sustained competitive advantages (Teece 1986). Alliances, including R&D cooperation, can facilitate access.
	4. Dynamic capabilities: The primary focus is on the mechanisms by which firms accumulate and deploy new skills and capabilities, and on the contextual factors that influence the rate and direction of this process. Inter-firm cooperation can be viewed as a vehicle for organizational learning (Hamel and Prahalad 1989; Mody 1993) and for entering new technological areas (Dodgson 1991).
	5. Strategic options to new technologies: This approach to explaining cooperation complements the dynamic capabilities approach by considering how managers can determine prospectively the set of resources and capabilities necessary for superior future performance in uncertain market environments (Sanchez 1993). Cooperation may assist companies to gain valuable experience and increase their exposure to related markets and their ability to sense and respond to new opportunities (Kogut 1991).

3. Industrial organization: Recent theoretical literature has depended heavily on game-theoretic tools and formal mathematical modeling.	1. Non-tournament models: The vast majority of the theoretical work on cooperative R&D has followed the non-tournament approach. Strategic, static, multistage models comparing the performance of cooperative and non-cooperative industrial setups in the presence of imperfectly appropriable, cost-reducing R&D are abundant in the literature. A consistent finding is that R&D competition seems better in the absence of knowledge spillovers, while R&D cooperation performs consistently better under the higher rate of knowledge spillovers. The mathematical modeling of this study follows non-tournament approach.
	2. Tournament models: Tournaments models emphasize the timing of innovation where the winner of an innovative race earns the right to an exogenously or endogenously determined monopolistic return. The winner shares the available information with the loser means that partnership will not form unless it is subsidized. In addition, firms choose to cooperate fully when they undertake complementary R&D, while they share no information outside the partnership if they undertake substitutive R&D.

2.2 The determinants of R&D cooperation

Ample empirical research and examples exist covering the incentives of engaging in R&D cooperation. Using Microelectronics and Computer Technology Corporation as a case, Gibson and Rogers (1994) summarize the motivations to form R&D consortia, including the following: efficiencies of shared cost and risk, exploration of new concepts, pooling scarce talent, sharing research or manufacturing facilities, desire for research synergy, diversification of a technology portfolio, developing frameworks into which other technology modules or tools can fit, setting standards, marketing products, pre-competitive sharing of research results, industrial organization and accelerated technology development, big science and large projects, infrastructure development, and facilitating technology transfer or partnering, whether domestic or foreign. Using a database of European research joint ventures (RJVs), Hernan, Marin, and Siotis (2003) find that R&D intensity, industry concentration, firm size, technological spillovers, and post-RJV participation all positively influence the probability of forming RJVs. Belderbos, Carree, Diederen, Lokshin, and Veugelers (2004) explore the determinants of innovating firms' decisions to engage in R&D cooperation. They observe that the determinants of R&D cooperation differ significantly across cooperation types. The positive impacts of firm size, R&D intensity, and incoming spillovers are weaker for competitor cooperation. Based on German manufacturing enterprises, Fritsch and Lukas (2001) analyze the propensity to maintain different forms of R&D cooperation with customers, suppliers, competitors and public research institutions. According to their results, enterprises that maintain R&D cooperation relationships tend to be relatively large and have a high share of R&D.

R&D cooperation can be considered to restore private incentives, because of internalizing the knowledge spillovers between cooperating firms (e.g. D'Aspremont and Jacquemin 1988; Kamien et al. 1992; Ishii 2004). Peters and Beck (1997-98) analyze the role of knowledge spillovers between automakers and suppliers in vertical corporate networks, both theoretically and empirically. In the empirical results they find evidence for the importance and effects of the transfer of technological information between manufacturers and their suppliers in the R&D process to develop and produce a custom-tailored good. Cassiman and Veugelers (2002) empirically explore the effects of knowledge flows on R&D cooperation. They discover that there is a significant relation between external information flows and the decision to cooperate in R&D. Firms that generally rate available external information sources as more important inputs to their innovation process are more likely to be actively engaged in cooperative R&D agreements. At the same time, firms that are more effective in appropriating the results from their innovation process are also more likely to cooperate in R&D. Kaiser (2002a) uses innovation survey data from the German service sector to explore research expenditures and research cooperation. The main results show that RJVs are more widespread among vertically-related firms than among horizontally-related firms. An increase in horizontal spillovers tends to increase incentives to collaborate in R&D. In addition, R&D efforts are larger under RJV than under R&D competition with a sufficiently large spillover. Sakakibara and Dodgson (2003) evaluate the role that strategic research partnerships (SRPs) play in

Asia and conclude that SRPs are formed to facilitate technological diffusion in Taiwan. Milliou (2004) analyzes the impact of R&D information flow on the incentives of innovation and social welfare under vertical integration. His results show that R&D information flow has a positive impact on innovation, outputs, and profits for R&D-integrated firms, but a negative impact for the R&D non-integrated firm.

Absorptive capacity and uncertainty[10] are also deemed as crucial factors that influence the decision of R&D cooperation. Bayona, Garcia-Marco, and Huerta (2001) test firms' motivations for cooperative R&D using Spanish firms that carried out R&D activities. The results obtained therein suggest that firms' motivations for cooperative R&D include technology's complexity and the fact that innovation is costly and uncertain. To undertake cooperative R&D, it is necessary to have certain internal capacities in this area. Becker and Dietz (2004) investigate the role of R&D cooperation in the innovation process. The results suggest that joint R&D is used to complement internal resources in the innovation process, enhancing the innovation input and output. The intensity of in-house R&D (absorptive capacity) also significantly stimulates the probability and the number of joint R&D activities with other firms and institutions. Caloghirou et al. (2003) investigate partnership performance and find that partnership success depends on the closeness of the cooperative research to the in-house R&D efforts of the firm, as well as on the firm's effort to learn from the partnership and its partners. Sakakibara (2002) investigates economic and strategic incentives of R&D cooperation. She finds that a firm's R&D capabilities, network formation through past consortia, encounters with other firms in the product market, age, and past participation in large scale consortia also positively affect its tendency toward consortia formation. Corey (1997) indicates that the risk-reduction opportunities provide an incentive for collaboration on large-scale projects with a relatively high degree of uncertainty. Another form of risk reduction that a collaborative venture provides is the opportunity to monitor technological advances in competitors' R&D programs. Caloghirou et al. (2003) also find that firms use partnerships as vehicles of risk and uncertain reduction by collaborating with competitors as well as with suppliers and buyers.

Mathews and Cho (2000) indicate the importance of collaborative research

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[10] Risk represents the degree of uncertainty (Chatterjee 2003). Thus, I use the word 'risk" and the word 'uncertainty' interchangeably.

relationships for the development of the industry in Taiwan. However, very little research has focused on R&D cooperation activity because of data availability. In this study I provide a comprehensive analysis of R&D cooperation within Taiwan's high-technology industries. Furthermore, a common feature in the prior R&D cooperation literature is the absence of uncertainty. Therefore, in addition to the factors used in Sakakibara's research, I discuss the relationship between uncertainty and R&D cooperation.

See Table 5 for a literature summary of the determinants of R&D cooperation.

Table 5: Literature summary of the determinants of R&D cooperation

Author/Year	Research topic	Research method	Research conclusion and research implication
Atallah (2002)	Author studies vertical R&D spillovers between upstream and downstream firms.	1. Analytical research. 2. The model includes two vertically related industries, with horizontal spillovers within each industry and vertical spillovers between the two industries.	**Research conclusion:** Author finds that vertical spillovers affect R&D investments directly and indirectly through their influence on the impact of horizontal spillovers and R&D cooperation. In addition, no matter what type the cooperation is, vertical spillovers always increase R&D efforts and welfare. **Research implication:** Based on the two vertical industry model, Atallah (2002) includes four R&D scenarios: R&D competition, vertical R&D cooperation, horizontal R&D cooperation, and generalized R&D cooperation. In this study I adopt his R&D cooperation scenarios in my theoretical model.
Cassiman and Veugelers (2002)	Authors empirically explore the effects of knowledge flows	1. Empirical research. 2. The data are drawn from the Community	**Research conclusion:** They discover that there is a significant relation between external information flows and the decision to cooperate in

Author/Year	Research topic	Research method	Research conclusion and research implication
	(knowledge spillovers) on R&D cooperation.	Innovation Survey (CIS) conducted in Belgian manufacturing firms in 1993.	R&D. Firms that generally rate available external information sources as more important inputs to their innovation process are more likely to be actively engaged in cooperative R&D agreements. At the same time, firms that are more effective in appropriating the results from their innovation process are also more likely to cooperate in R&D. **Research implication:** Authors use survey data to explore the effects of knowledge flows on R&D cooperation and suggest that incoming spillovers and appropriability have important effects on R&D cooperation. In this study I will use archival data to test the determinants of R&D cooperation.
Kaiser (2002a)	Author uses innovation survey data from the German service sector to explore research expenditures and research	1. Empirical research. 2. The empirical analysis is based on the survey data of the Mannheim	**Research conclusion:** The main results show that RJVs are more widespread among vertically-related than horizontally-related firms. An increase in horizontal spillovers tends to increase incentives to collaborate in R&D. In addition, R&D efforts are larger under

Author/Year	**Research topic**	**Research method**	**Research conclusion and research implication**
	cooperation.	Innovation Panel in the Service Sector (MIP-S).	RJV than under R&D competition with a sufficiently large spillover. **Research implication:** The types of R&D cooperation of my study are the same with those of Kaiser’s research. This makes my research results are more comparable with Kaiser (2002a)’s.
Sakakibara (2002)	Author investigates economic and strategic incentives of R&D cooperation and focus on factors that affect a firm’s rate of participation in R&D consortia.	1. Empirical research. 2. Research sample includes 312 Japanese firms in 74 industries between 1969 and 1992.	**Research conclusion:** She finds that a firm with weak competition and higher spillover has a higher rate of R&D cooperation. A firm’s R&D capabilities, network formation through past consortia, encounters with other firms in the product market, age, and past participation in large scale consortia also positively affect its tendency at consortia formation. **Research implication:** A common feature in the prior R&D cooperation literature is the absence of uncertainty. Therefore, in addition to the

Author/Year	Research topic	Research method	Research conclusion and research implication
			factors used in Sakakibara's research, I discuss the relationship between uncertainty and R&D cooperation.
Sakakibara and Dodgson (2003)	Authors evaluate the role that strategic research partnerships (SRPs) play in Asia.	1. Descriptive research. 2. Asian countries include Korea, Japan, and Taiwan.	**Research conclusion:** Authors indicate that the networks created among small Taiwanese firms through their research links with research organizations and conclude that SRPs are formed to facilitate technological diffusion in Taiwan. **Research implication:** Mathews and Cho (2000) indicate the importance of collaborative research relationships for the development of the industry in Taiwan. However, very little research has focus on R&D cooperation activity because of data availability. In this study I provide a comprehensive analysis of R&D cooperation on Taiwan's high-technology industries.

2.3 The relationship between R&D cooperation, R&D investments, R&D outputs, and financial performance-theoretical research

Knowledge spillovers are known as “knowledge externalities”, meaning the involuntary leakage or voluntary exchange of useful technological information (Bondt 1996). Information spillovers between competing firms are often involuntary, whereas spillovers between buyers and sellers are one instance of a voluntary exchange of information. The leaking of firms’ knowledge to competitors has a negative impact on the firms’ own profitability, thus reducing incentives for investing in R&D (e.g. Spence 1984; Veugelers 1998). Through cooperation in R&D, this externality problem can be internalized, which will have a positive impact on R&D levels and profitability when spillovers are high (e.g. Goel 1995; Veugelers 1998).

D’Aspremont and Jacquemin (1988) pioneered theoretical research in R&D cooperation by introducing a two-stage duopoly model to formalize firms’ incentives to engage in R&D cooperation. Over the past decade more research has emerged related to R&D investments in a cooperative situation compared to non-cooperation (e.g. Kamien et al. 1992; Steurs 1995; Petit and Tolwinski 1999; Cassiman and Veugelers 2002). Kamien et al. (1992) analyze the effects of R&D cartelization and the effects of research joint ventures on firms, finding that when research joint ventures (RJV) cooperate in R&D decisions, the result is the highest consumer surplus and producer surplus. Vonortas (1994) suggests that R&D cooperation allows members to coordinate their actions in pre-competitive research, which can restore firm incentives for both pre-competitive research and development in the presence of high knowledge spillovers. Petit and Tolwinski (1999) also find that the creation of research joint ventures actually improves social welfare and is beneficial to the firms involved. Likewise, welfare levels with industry-wide cooperation are always higher than in the R&D competition case (Veugelers 1998). Steurs (1995) analyzes the impact of intra-industry and inter-industry knowledge spillovers on the level of strategic R&D investments, output, profits and total welfare. The results show that inter-industry cooperation is more socially beneficial than cooperation in single industry firms (intra-industry cooperation).

Recent research studies have focused more on vertical R&D cooperation. The difference between horizontal R&D cooperation and vertical R&D cooperation is that while horizontal R&D cooperation may mitigate competition between firms and is often closely monitored by regulators, vertical cooperation is less likely to hinder competition (Atallah 2002). Geroski (1995) finds that the rich information flows that connect innovation producers and users (upstream/downstream spillovers) seem to be much more important than pure information externalities that arise between horizontally related firms. Harhoff (1996) investigates why suppliers engage in vertical R&D cooperation and create knowledge spillovers strategically. The analytical results suggest that high levels of knowledge spillovers induce downstream firms to improve product quality and reduce R&D cost. The effects cause an increase in downstream outputs and thus stimulate the demand for suppliers' intermediate goods. Under four R&D scenarios: R&D competition, horizontal intra-downstream and intra-upstream industry R&D cooperation, and vertical inter-industry R&D cooperation, Inkmann (2000) shows that vertical R&D cooperation is usually the only stable equilibrium — that is, no firm has an incentive to choose any other R&D scenario. Ishii (2004) indicates that vertical RJV yields the largest social welfare when vertically-related firms can coordinate their R&D decisions and fully share useful knowledge.

The standard framework of R&D cooperation in prior analytical literature considers two vertically-related industries (upstream and downstream industries) with two identical firms in each industry. In this paper I extend D'Aspremont and Jacquemin's (1988) models and use a more general market structure, including upstream and downstream industries with n firms in each industry. I also apply their effective R&D investment assumption. In Kamien et al. (1992)'s model, most propositions and corollaries obtained for quantity-settings (Cournot competition) continue to hold in the price-competition setting (Bertrand competition). Therefore, in this paper I apply only quantity competition models. Regarding the types of R&D cooperation, Inkmann (2000) applies the following R&D scenarios: R&D competition, horizontal R&D cooperation, and vertical R&D cooperation. In this study I extend his setting and include generalize R&D cooperation in my theoretical model and empirical test. In addition, following the approach proposed by Steurs (1995), I use numerical simulations to compare the ranking of R&D investments, R&D outputs, and financial performance in different scenarios.

See Table 6 for related literature summary of the relationship between R&D cooperation, R&D investments, R&D outputs, and financial performance.

Table 6: Literature summary of the relationship between R&D cooperation, R&D investments, R&D outputs, and financial performance-theoretical research

Author/Year	Research topic	Research method	Research conclusion and research implication
D'Aspremont and Jacquemin (1988)	D'Aspremont and Jacquemin pioneer theoretical research in R&D cooperation by introducing a generalized two-stage duopoly model to formalize firms' incentives to engage in R&D cooperation.	1. Analytical research. 2. In the first stage, R&D cooperation can take place at the "precompetitive stage". In the second stage, firms play a Cournot game.	**Research conclusion:** R&D cooperative behavior can play a positive role in industries having a few firms and characterized by R&D activities generating spillover effects. **Research implication:** Starting with the research of D'Aspremont and Jacquemin (1988), a large number of theoretical research papers have emerged over the past decade. In this paper I extend their models to examine the relationship between R&D cooperation and firm performance. In addition, I also apply their effective R&D investment assumption.
Kamien et al. (1992)	Authors analyze the effects of R&D cartelization and research joint ventures on firms that engage in either	1. Analytical research. 2. Authors apply two stages game including	**Research conclusion:** A research joint venture that cooperates in its R&D decisions yields the highest consumer plus producer surplus under

Author/Year	Research topic	Research method	Research conclusion and research implication
	Cournot and Bertrand competition in their product market.	four models: R&D competition, R&D cartelization, research joint venture competition, and research joint venture cartelization.	Cournot competition and under most of Bertrand competition. **Research implication:** In Kamien et al. (1992)'s model, most propositions and corollaries obtained for quantity-settings (Cournot competition) continue to hold in the price-competition setting (Bertrand competition). Therefore, in this paper I apply only quantity competition models.
Steurs (1995)	In the first part of the paper author analyzes the impact of intra- and inter-industry R&D spillovers on the level of R&D investments, output, profits and total welfare when firms compete in both the R&D and output stage. In the second part, he compares the	1. Analytical research. 2. Author extends D'Aspremont and Jacquemin (1988)'s framework to a two-industry, two-firm-per-industry model allowing for R&D spillovers to occur within industries as well as between	**Research conclusion:** R&D agreements that cut across industries may be more socially beneficial than cooperatives whose membership comes from a single industry. **Research implication:** The ranking of R&D investments, R&D outputs, R&D outputs, and financial performance in different scenarios is difficult to interpret. Therefore, following the approach proposed by Steurs (1995), I use numerical simulations by varying spillover parameters.

Author/Year	**Research topic**	**Research method**	**Research conclusion and research implication**
	equilibrium outcomes that result from R&D cooperation.	industries.	
Inkmann (2000)	Author introduces a second, vertically related industry into the usual one industry oligopoly framework of cooperative R&D investment between firms operating on the same product market.	1. Analytical research. 2. R&D efforts are affected by intra- and inter-industry R&D spillovers. Horizontal and vertical R&D cooperation scenarios are compared to R&D competition.	**Research conclusion:** Author shows that vertical R&D cooperation is usually the only stable equilibrium - that is, no firm has an incentive to choose any other R&D scenario. **Research implication:** Author applies four R&D scenarios: R&D competition, horizontal intra-downstream and intra-upstream industry R&D cooperation, and vertical inter-industry R&D cooperation. In this study I extend Inkmann (2000)'s setting and include generalized R&D cooperation in theoretical model and empirical test.
Ishii (2004)	Author analyzes the impact of R&D cooperation in two vertically related duopolies	1. Analytical research. 2. His setting focuses on a case where a final-good	**Research conclusion:** His results indicate that vertical RJV yields the largest social welfare when vertically-related firms can coordinate their R&D decisions and fully share useful knowledge.

Author/Year	Research topic	Research method	Research conclusion and research implication
	with horizontal and vertical spillovers.	manufacturer and an input supplier cooperate in their R&D activities in the presence of horizontal and vertical spillovers.	**Research implication:** The standard framework of R&D cooperation in prior analytical literature considers two vertically-related industries (upstream and downstream industries) with two identical firms in each industry. However, these models are quite restrictive. In this paper I extend prior models and use a more general market structure, including upstream and downstream industries with n firms in each industry.

2.4 The relationship between R&D cooperation, R&D investments, R&D outputs, and financial performance-empirical research

A number of empirical studies have found a positive impact of engaging in R&D cooperation on R&D investments and firm performance. Hagedoorn and Schakenraad (1994) study the effects of strategic technology alliances on company performance. The results indicate that companies attracting technology through their alliances, and companies concentrating on R&D cooperation, have significantly higher rates of profit. Stuart (2000) investigates the relationship between intercorporate technology alliances and firm performance. The findings from models of sales growth and innovation rate confirm that organizations with large and innovative alliance partners perform better than comparable firms that lack such partners. Sarkar, Echambadi, and Harrison (2001) also investigate the effect of alliance entrepreneurship on market-based firm performance. Results indicate that alliance proactiveness leads to superior market-based performance, and that this effect is stronger for small firms and in unstable market environments. From the supplier's standpoint, Chung and Kim (2003) analyze the effects of supplier involvement in a manufacturer's new product development on the supplier's financial performance, innovation, and product quality. The results indicate that a higher level of supplier's involvement positively impacts innovation and financial performance.

Shrader (2001) employs transaction cost theory to explore factors moderating the relationship between collaboration and performance in foreign markets. The results indicate that R&D intensity and advertising intensity are significant moderators of this relationship. Chang (2003) investigates the innovative activities and inter-organizational cooperation of integrated circuits and biotechnology sectors across Taiwan and the UK. The results reveal that a firm's innovative performance is not only shaped by internal R&D effort, but also by external links with other firms. Moreover, Chang (2003) argues that the latter becomes a more powerful factor in influencing a firm's innovativeness. Belderbos et al. (2004) examine the impact of R&D cooperation in 1996 on subsequent productivity growth from 1996-1998. The results confirm a major heterogeneity in the goals of R&D cooperation. The cooperation between competitor and supplier focuses on incremental innovations, improving the productivity performance of firms, while university cooperation and competitor cooperation are instrumental in creating innovations, generating sales of products, and improving the growth performance of firms.

Based on prior literature, most research uses questionnaires as a tool to examine the relationship between R&D cooperation and firm performance. Hagedoorn and Schakenraad (1994) pioneer in R&D cooperation empirical research by using a systematic collective database. I follow their method to collect R&D cooperation data in Taiwan’s high technology industries. I also follow Stuart’s (2000) variable measurement and use the number of R&D cooperation to measure R&D cooperation intensity. Furthermore, in this study I divide R&D cooperation into horizontal cooperation, vertical cooperation, generalized cooperation, and R&D competition, and examine how different R&D cooperation types impact companies’ R&D investments, R&D outputs, and financial performance. Finally, according to Shrader’s results, R&D intensity moderates the relationship between collaboration and performance. However, more studies (e.g. Steurs 1995; Inkmamn 2000; Ishii 2004) indicate that R&D cooperation leads to higher R&D investments. Thus, further examination is needed to verify the relationship between R&D cooperation, R&D investments, R&D outputs, and financial performance.

See Table 7 for related literature summary of the relationship between R&D cooperation, R&D investments, R&D outputs, and financial performance.

Table 7: Literature summary of the relationship between R&D cooperation, R&D investments, R&D outputs, and financial performance-empirical research

Author/Year	Research topic	Research method	Research conclusion and research implication
Hagedoorn and Schakenraad (1994)	Authors study the effects of strategic technology alliances on company performance.	1. Empirical research. 2. The statistical procedure used in study is linear structural modeling (LISREL). 3. The sample of companies covers European, American, and Japanese firms operating in three industrial sectors: information technologies and electronics, mechanical engineering, and	**Research conclusion:** The results indicate that companies attracting technology through their alliances and companies concentrating on R&D cooperation have significantly higher rates of profit. **Research implication:** Most research uses questionnaires as a tool to examine the relationship between R&D cooperation and firm performance. Hagedoorn and Schakenraad (1994) pioneer in R&D cooperation empirical research by using systematic collective database. In this study I follow their method to collect R&D cooperation data in Taiwan’s high technology industries. Furthermore, I adopt path analysis to analyze causal relations.

Author/Year	Research topic	Research method	Research conclusion and research implication
		process industries.	
Stuart (2000)	Author investigates the relationship between intercorporate technology alliances and firm performance.	1. Empirical research. 2. Author draws the sample from the semiconductor industry and focuses only on horizontal alliance.	**Research conclusion:** The findings from models of sales growth and innovation rate confirm that organizations with large and innovative alliance partners perform better than comparable firms that lack such partners. **Research implication:** Stuart (2000) includes only horizontal cooperation in his research. In this study I divide R&D cooperation into horizontal cooperation, vertical cooperation, generalized cooperation, and R&D competition. In addition, I follow his variable measurement and use the number of R&D cooperation to measure R&D cooperation intensity.
Sarkar et al. (2001)	Authors investigate the effect of alliance entrepreneurship on market-based firm performance.	1. Empirical research. 2. Data are collected by mail survey. A total of 184 companies responded.	**Research conclusion:** Results indicate that alliance proactiveness leads to superior market-based performance, and that this effect is stronger for small firms and in unstable market environments.

Author/Year	Research topic	Research method	Research conclusion and research implication
			Research implication: Most of the prior studies use survey data in R&D cooperation research which remain some limitations. Therefore, we need more archival data to support the argument and results.
Shrader (2001)	Author employs transaction cost theory to explore factors moderating the relationship between collaboration and performance in foreign markets.	1. Empirical research. 2. Data are collected for new ventures headquartered in the United States that were founded between 1983 and 1988 and issued initial public offerings (IPOs) while they were still new ventures.	**Research conclusion:** The results indicate that R&D intensity and advertising intensity are significant moderators of the relationship between collaboration and profitability in foreign markets; however, they were not significantly related to the use or nonuse of collaboration. **Research implication:** According to Shrader's results, R&D intensity moderates the relationship between collaboration and performance. However, based on more prior research (Steurs 1995; Inkmamn 2000; Ishii 2004), R&D cooperation leads to higher R&D investments. Thus, further examination is needed to verify the relationship between R&D cooperation, R&D investments, R&D outputs, and financial performance.

Author/Year	Research topic	Research method	Research conclusion and research implication
Chang (2003)	Author investigates the innovative activities and inter-organizational cooperation of integrated circuits and biotechnology sectors across Taiwan and the UK.	1. Empirical research. 2. The research surveyes 400 IC and biotechnology firms across the UK and Taiwan. One hundred and sixty-two questionnaires were received.	**Research conclusion:** The results reveal that a firm's innovative performance is not only shaped by internal R&D effort, but also by external links with other firms. Moreover, the paper argues that the latter becomes a more powerful factor in influencing a firm's innovativeness. **Research implication:** Chang (2003) is one of the few researchers analyzing R&D cooperation in Taiwan via a postal questionnaire survey. However, a questionnaire survey still remains limited. Thus, in this study I use archival data to comprehensively investigate R&D cooperation and innovation activity in Taiwan's high technology industries.
Chung and Kim (2003)	Authors analyze the effects of supplier involvement in a manufacturer's new product development on the supplier's financial	1. Empirical research. 2. 128 suppliers in the Korean automobile and electronics industries.	**Research conclusion:** The results indicate that a higher level of supplier's involvement positively impacts innovation and financial performance. **Research implication:**

Author/Year	Research topic	Research method	Research conclusion and research implication
	performance, innovation, and product quality.		"Supplier involvement in new product development" is a very popular phenomenon in high-technology industry. Chung and Kim's (2003) results further confirm the importance of considering vertical cooperation in the model.
Belderbos et al. (2004)	Authors examine the impact of R&D cooperation in 1996 on subsequent productivity growth from 1996-1998.	1. Empirical research. 2. Research questionnaires include Dutch innovating firms in two waves of the Community Innovation Survey (CIS) (1996, 1998).	**Research conclusion:** Cooperation between competitor and supplier focuses on incremental innovations, improving the productivity and performance of firms, while university and competitor cooperation are instrumental in creating innovations, generating sales of products, and improving the growth performance of firms. **Research implication:** The results indicate a major heterogeneity in the goals of R&D cooperation. In this study, I use R&D investments, R&D outputs, and financial performance to measure the performance of R&D cooperation. I also divide R&D cooperation into four types: horizontal R&D cooperation, vertical R&D cooperation, generalized R&D cooperation, and R&D competition, to examine the impact of different R&D cooperation types on the performance of R&D cooperation.

2.5 Extension of this study

Based on the literature review, this study adopts and extends the theoretical framework and the research method of prior research as follows:

2.5.1 Adoption from prior research

(1) Theoretical and research framework

To keep the theoretical model tractable, the simplified assumptions of the models introduced by D'Aspremont and Jacquemin (1988) and Kamien et al. (1992) are maintained. The main assumption is that the firms play a two-stage game. In the R&D stage, the firms simultaneously decide on their level of R&D investments. In the output stage, the firms in each industry decide on the quantity they will produce and sell on the market. By backward induction, I derive the subgame perfect Nash equilibrium.

Based on the two vertical industry models, Atallah (2002) includes four R&D scenarios: R&D competition, vertical R&D cooperation, horizontal R&D cooperation, and generalized R&D cooperation. In this study I adopt his R&D cooperation scenarios in my theoretical model.

- I also follow the approach proposed by Steurs (1995) to simulate and compare the equilibrium R&D investments, R&D outputs, and profits for different cooperative scenarios.

(2) Research method

- Hagedoorn and Schakenraad (1994) pioneer in R&D cooperation empirical research by using a systematic collective database. In this study I follow their method to collect R&D cooperation data in Taiwan's high technology industries.
- To capture the frequency and intensity of R&D cooperation, I follow Stuart's (2000) approach and use the number of R&D cooperation to measure R&D cooperation intensity.
- Prior studies only measure uncertainty as the dispersion from the mean and do not detect the ordering of the data points. However, it is unable to detect variation from a trend line. Therefore, I apply Dess and Beard's (1984)

approach to solve this problem..

2.5.2 Complement of prior research

(1) Theoretical and research framework

- Incremental to prior literature (e.g. D’Aspremont and Jacquemin 1988; Kamien et al. 1992; Inkmann 2000; Atallah 2002; Ishii 2004), this paper introduces two-industry, n-firm-per-industry models to facilitate generalization of analytical results.

(2) Research method

- Few empirical papers comprehensively examine the direct and indirect relationships among R&D cooperation, R&D investments, R&D outputs, and financial performance, and most of them use survey data to test the theoretical hypothesis (e.g. Peters and Becker 1997-98; Bayona et al. 2001; Cassiman and Veugelers 2002; Becker and Dietz 2004; Belderbos et al. 2004). In this study I develop an integrated R&D cooperation—innovation—financial performance framework and apply path analysis to analyze the direct and indirect relationships among R&D cooperation, R&D investments, R&D outputs, and financial performance.
- This paper first includes four types of R&D cooperation, including horizontal R&D cooperation, vertical R&D cooperation, generalized R&D cooperation, and R&D competition, to empirically test how they influence companies’ R&D investments, R&D outputs, and financial performance in Taiwan high-technology industry. I also examine how the intensity of different types of R&D cooperation is influenced by three factors: knowledge spillovers, uncertainty, and absorptive capacity.
- To avoid sample selection bias, I apply the Heckman two-stage model and treatment effects model to test the impact of R&D cooperation on R&D investments, R&D outputs, and financial performance. In addition, to incorporate multiple level variables into an empirical test, I use the HLM (Hierarchical linear model) to examine the determinants of R&D cooperation.
- Taiwan is a core innovator internationally, according to the World Economic Forum (WEF). However, few studies examine the relationship between

R&D cooperation and firm performance in Taiwan with small databases (e.g. Chang 2003; Sher and Yang 2005). This study is the first to use Taiwan's high-technology industries as a research sample and to thoroughly explore the relationships among R&D cooperation, R&D investments, R&D outputs, and financial performance in Taiwan.

- In this study I argue that higher frequency of inter-industry or intra-industry strategy alliance implies higher knowledge spillovers among firms. Therefore, I first use the number of strategy alliance for each industry to proxy knowledge spillovers. In addition, a common feature in the prior R&D cooperation literature is the absence of uncertainty. Therefore, I will discuss the relationship between uncertainty and R&D cooperation in this paper.

See Table 8 for the summary of the extension of this study.

Table 8: Summary of the extension of this study

Item	Adoption from prior research	Complement of prior research
Theoretical and research framework	1. To keep the theoretical model tractable, the simplified assumptions of the models introduced by D'Aspremont and Jacquemin (1988) and Kamien et al. (1992) are maintained. 2. In this study I adopt Atallah's (2002) four R&D cooperation scenarios, including R&D competition, vertical R&D cooperation, horizontal R&D cooperation, and generalized R&D cooperation, in my theoretical model. 3. I follow the approach proposed by Steurs (1995) to simulate and compare the equilibrium R&D investments, R&D outputs, and profits for different cooperative scenarios.	This paper introduces two-industry (upstream and downstream industries), n-firm-per-industry models to facilitate generalization of analytical results.
Research method	1. In this study I follow Hagedoorn and Schakenraad's (1994) method to collect R&D cooperation data in Taiwan's high technology industries.	1. In this study I develop an integrated R&D cooperation—innovation—financial performance framework and apply path analysis to analyze the direct

Item	Adoption from prior research	Complement of prior research
	2. I follow Stuart's (2000) approach and use the number of R&D cooperation to measure R&D cooperation intensity. 3. I apply Dess and Beard's (1984) approach to measure uncertainty which considers variation from a time trend.	and indirect relationships between R&D cooperation, R&D investments, R&D outputs, and financial performance. 2. This paper first includes four types of R&D cooperation, including horizontal R&D cooperation, vertical R&D cooperation, generalized R&D cooperation, and R&D competition, to empirically test how they influence companies' R&D investments, R&D outputs, and financial performance in Taiwan high-technology industry. I also examine how the intensity of different types of R&D cooperation is influenced by three factors: knowledge spillovers, uncertainty, and absorptive capacity. 3. To avoid sample selection bias, I apply the Heckman two-stage model and treatment effects model to test the impact of R&D cooperation on R&D investments, R&D outputs, and financial performance. In addition, to incorporate multiple level variables into empirical test, I use the HLM (Hierarchical linear model) to examine the determinants of R&D cooperation.

Item	Adoption from prior research	Complement of prior research
		4. This study is the first to use Taiwan’s high-technology industries as a research sample and thoroughly explores the relationships between R&D cooperation and firm performance in Taiwan. 5. In this study I first use the number of strategy alliances for each industry to proxy knowledge spillovers. In addition, I discuss the relationship between uncertainty and R&D cooperation.

Chapter 3: Theoretical model and hypotheses development

3.1 The determinants of R&D cooperation

In this section, I develop hypotheses regarding the determinants of R&D cooperation at the firm level (absorptive capacity) and industry level (knowledge spillover and uncertainty) in the following subsection.

Firm level determinants of R&D cooperation

Absorptive capacity

R&D activity has two faces: R&D investments not only increase firms' innovative abilities, but also enhance their ability to learn from others (Cohen and Levinthal 1989). To understand and implement ideas and concepts of other innovators, firms must have competencies that enable them to understand, decodify, and utilize these ideas (e.g. Levin, Klevorick, Nelson, Winter, Gilbert, and Griliches 1987). Therefore, external knowledge is more effective for the innovation process when firms engage in their own R&D (e.g. Kamien and Zang 2000).

From the Resource-Based View, absorptive capacity is used to measure a firm's ability to value, assimilate, and apply new knowledge. Sakakibara (2003) suggests that when R&D cooperation consists of firms with complementary knowledge, then R&D participants increase the chance of knowledge sharing, which in turn intensifies firms' R&D efforts to learn from other members. This type of R&D cooperation is welfare enhancing relative to R&D competition. Within strategic management, the Resource-Based View (RBV) suggests that firm capabilities which are valuable, rare, and inimitable will determine long-term competitive advantage (Barney 1991). From this perspective, organizational knowledge is the most strategically important resource of the firm (e.g. Grant 1996; Hill and Deeds 1996; DeCarolis and Deeds 1999).

D'Aspremont and Jacquemin (1988) and Kamien et al. (1992) failed to take into account the idea that spillovers also depend on the R&D activity of the knowledge absorbing firms. They assume that firms can learn from external R&D without effort in the learning process. The external R&D appears to come to the firms as 'manna from heaven' (Grunfeld 2003). However, it is now widely accepted that external knowledge is not 'manna from heaven', and firms need an absorptive capacity to assimilate and exploit knowledge (Kamien and Zang 2000). Porter and Full (1986), Dodgson (1992), and Hugedoorn (1993) indicate that by combining firms' absorptive capacity, they can reduce R&D uncertainty and increase the possibility of obtaining positive results in R&D cooperation scenarios. Thus I expect to find that firms with higher absorptive capacity are more likely to engage in R&D cooperation.

H1: The greater the absorptive capacity, the greater the intensity will be for engaging in R&D cooperation.

Industry level determinants of R&D cooperation

Knowledge Spillovers

Mansfield (1985) finds that information concerning firms' decisions to develop major new products or new processes falls into the hands of rivals within 12 to 18 months. Therefore, when large spillovers exist, it is impossible for the innovator to appropriate all of the benefits from an innovation. As a consequence, there is too little incentive to innovate when firms operate independently (Miyagiwa and Ohno 2002).

Cooperative R&D agreements are usually regarded as a proper and important mechanism that can internalize spillover externalities (e.g. Katz and Ordover 1990; Choi 1993). Moreover, through R&D cooperation, firms can transfer knowledge at lower transaction costs (Oerlemans and Meeus 2001). Peters and Beck (1997-98) analyze the role of knowledge spillovers in vertical corporate networks. They suggest that the effects of technological information transfers between manufacturers and their suppliers in the R&D process are significant. Kaiser (2002a) uses innovation survey data to examine research expenditures and research cooperation. The results show that an increase in horizontal spillovers tends to increase incentives to collaborate in R&D. Most authors provide consistent conclusions, such as once spillovers are sufficiently high, R&D cooperation becomes increasingly attractive as spillovers increase and play a positive role in industries (e.g. Katz 1986; D'Aspremont and Jacquemin 1988; Peters and Beck 1997-98; Petit and Tolwinski 1999; Cassiman and veugelers 2002; Sakakibara and Dodgson's 2003; Atallah 2005). Therefore, I develop the following hypothesis.

H2: The greater the knowledge spillovers, the greater the intensity will be for engaging in R&D cooperation.

Uncertainty

An organization's perceived environmental uncertainty is viewed as its ability to anticipate changes in competitors' strategies, consumers' new product requirements, technology, emergence of new regulations, and constraints on product performance and design (Gupta, Raj, and wilemon 1986). To maintain equivalent levels of performance, managers of high uncertainty projects should process more information than those of projects with low uncertainty (e.g. Tushman and Nadler 1980). Where clarity of project requirement is low, or constraints are confusing and variable, research managers are more likely to believe that the probability of success is comparatively low (e.g. Omta and De Leeuw 1997).

A common feature in prior R&D cooperation literature is the absence of uncertainty. However, in the real world innovation is always regarded as a risky activity (e.g. Miyagiwa and Ohno 2002). FASB states that "there is often a high degree of uncertainty about whether R&D expenditures will provide any future benefits" (FASB 1974). Kay (1993) points out that innovation is costly and uncertain, with its results being difficult to appropriate. Contingency theory predicts that high degrees of integration are important to new product development effectiveness in high uncertainty environments (e.g. Souder, Sherman, and Davies-Cooper 1998). All this justifies the need for firms to cooperate in R&D.

Oerlemans and Meeus (2001) investigate R&D cooperation between buyers and suppliers, finding that uncertainty has a moderating influence on the features of R&D relationships (frequency and dependency) between buyers and suppliers. Firms use partnerships to reduce risk and uncertainty when collaborating with competitors (horizontal R&D cooperation) as well as with suppliers and buyers (vertical R&D cooperation) (Caloghirou et al. 2003). Therefore, under high uncertainty, firms are more likely to engage in R&D cooperation, because of such benefits as pooling risk and uncertainty (Choi 1993). A proposition regarding the relationship between uncertainty and R&D cooperation can be stated as follows.

H3: The greater the uncertainty, the greater the intensity will be for engaging in R&D cooperation.

Most of the relationships among high-technology firms are based on dyadic alliance. Although there are some multilateral types of alliances, the quantity is rather low. However, if the network relationship between high-technology companies is only dyadic, then it can not exert the full advantage of network organization. According to the views of sociology and strategic management, diverse cooperation relationships should be formed and can be the source of its competitive strength (Hagedoorn et al. 2000; Chen 2003). For examples, most of the knowledge spillovers are internalized under generalized R&D cooperation relative to other cooperation types when spillovers are high.[11] Furthermore, generalized R&D cooperation companies have more chances to share the risk with their suppliers, customers, and competitors simultaneously under a high degree of environmental uncertainty.

Finally, high absorptive capacity provides companies more ability and chances to adopt more than one cooperation structure (horizontal R&D cooperation and vertical R&D cooperation) simultaneously. MediaTek Inc. provides an useful example: MediaTek Inc. is very good at graphics processing, but still needs other strategic abilities, such as power management. Therefore, MediaTek Inc. seeks R&D cooperation with Global Mixed-mode technology Inc., which is the leader in power management, and then further integrates with the products of BenQ. This is the typical case of generalized R&D cooperation. Companies with lower absorptive capacity have fewer chances to get involved in this kind of cooperative relationship. I suggest that when knowledge spillovers, uncertainty, and absorptive capacity are greater, companies will tend to engage in generalized R&D cooperation relative to other cooperation types.

H4a: The greater the absorptive capacity, the greater the intensity will be for engaging in generalized R&D cooperation relative to other cooperation types.

H4b: The greater the knowledge spillovers, the greater the intensity will be for engaging in generalized R&D cooperation relative to other cooperation types.

H4c: The greater the uncertainty, the greater the intensity will be for engaging in generalized R&D cooperation relative to other cooperation types.

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[11] Please refer to Section 3.2 and Figure 5.

3.2 The impact of R&D cooperation on R&D investments, R&D outputs, and financial performance

This section extends prior non-tournament models (e.g. D'Aspremont and Jacquemin 1988; Kamien et al. 1992; Inkmann 2000; Atallah 2002; Ishii 2004) and uses a more general market structure, including upstream and downstream industries with n firms located in each industry (See Figure 2). This model is capable of analyzing the influence of different types of R&D cooperation on R&D investments, R&D outputs, and financial performance.

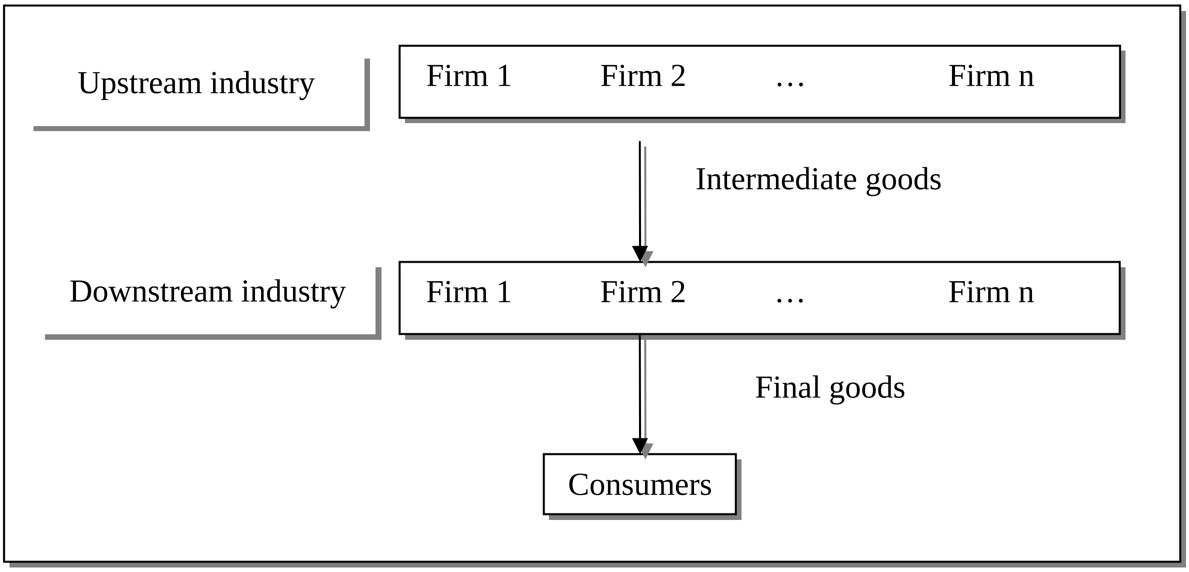

Figure 2: Market structure of the theoretical model of this study

Consistent with prior literature, I assume that upstream firms sell a homogeneous input to downstream firms at price p^u. Downstream firms then use the same technology and intermediate inputs to produce the same amount of homogenous final goods, and finally sell them to consumers at price p^d. These assumptions lead to the following three-stage model:[12]

1. The first stage: All firms choose their R&D outputs simultaneously to maximize their own profits.
2. The second stage: Upstream firms engage in Cournot competition and decide the quantity and price of intermediate inputs based on the derived inverse demand of

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[12] In practice, the interaction between industries is not necessary to follow the certain sequence. However, for the convenience of modeling, I assume that the industries follow the sequence of upstream-downstream. I appreciate Ph. D. committee members' suggestion.

upstream firms.

3. The third stage: Downstream firms engage in Cournot competition and decide the quantity and price of final goods given the price of the intermediate good and R&D in all industries. (See Figure 3).

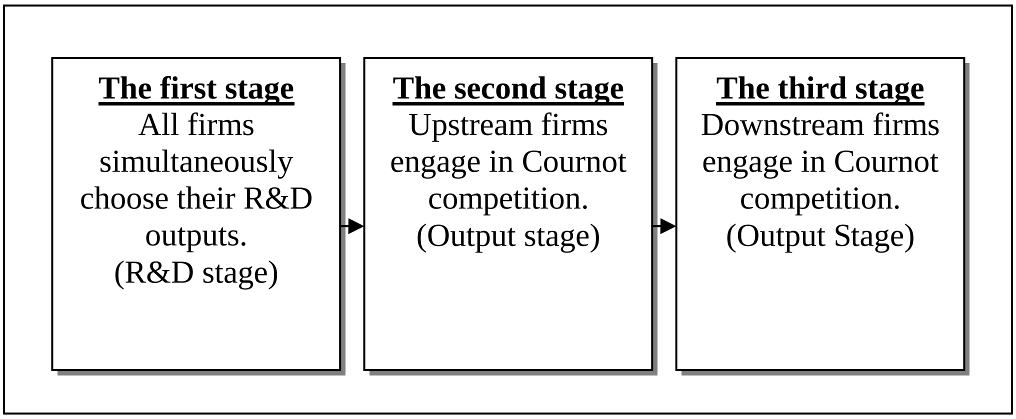

Figure 3: The three-stage Cournot competition

Downstream firm i $(i = 1,2,...n)$ produces y_i^d units of final goods. Upstream firm i $(i = 1,2,...n)$ produces y_i^u units of the outputs. Downstream and upstream firms incur marginal production costs of c and d. Downstream firms face the linear inverse demand function:

$$p^d = a - bY^d ,$$

where $a > 0$ and $Y^d = \sum_{i=1}^{n} y_i^d$.

Firms can engage in cost-reducing R&D activities. Denoting the R&D output of the downstream firms by x_i^d and upstream firms by x_i^u $(i = 1,2,...n)$, the effective R&D level (D'Aspremont and Jacquemin 1988) is defined as:

$$X_i^d = x_i^d + h\sum_{j \neq i}^{n} x_j^d + v\sum_{i=1}^{n} x_i^u \qquad (i, j = 1,2,...n) \tag{1}$$

$$X_i^u = x_i^u + h\sum_{j \neq i}^{n} x_j^u + v\sum_{i=1}^{n} x_i^d \qquad (i, j = 1,2,...n), \tag{2}$$

---

[14] R&D has two effects. One is that one firm can benefit from other firms' research, which is spillover (positive effect). Another one is that other firms' research will reduce the probability of success in R&D, which is competition (negative effect). In this study, I suppose that spillover rate ($h \in [0,1], v \in [0,1]$) is the net effect of these two effects. I appreciate Ph. D. committee members' viewpoint.

where $h \in [0,1]$ is the horizontal spillover rate of competitors' R&D, and $v \in [0,1]$ is the vertical spillover rate between upstream and downstream firms.[14] According to D'Aspremont and Jacquemin (1988), firm i's effective R&D (X_i) includes producing R&D by itself (x_i) and receiving R&D from competitors ($h\sum_{j \neq i}^{n} x_i$) and vertically related industry ($v\sum_{i=1}^{n} x_i$). Taking downstream firm i as an example, firm i's effective R&D level (X_i^d) consists of the firm i's own R&D level, the percentage h of the firm i's competitors' R&D outputs ($h\sum_{j \neq i}^{n} x_j^d$), and the fraction v of the total R&D outputs produced by upstream industry ($v\sum_{i=1}^{n} x_i^u$). If there are no knowledge spillovers ($h = v = 0$), then the effective R&D level is firm i's own R&D outputs. (See Table 9 for notation references).

Table 9: Summary of model notation

Notation	Description
a	Inverse demand intercept
b	Inverse demand slope
p^u	Price charged by upstream firms
p^d	Final product price
π	Profits of firm i
y_i^u	Outputs of upstream firm i
y_i^d	Outputs of downstream firm i
Y	Total outputs
c	Basic costs of production of a downstream firm
d	Basic costs of production of a upstream firm
γ	Parameter of the R&D cost function
h	Horizontal knowledge spillovers
v	Vertical knowledge spillovers between upstream firms and downstream firms
x^u	R&D outputs of upstream firm i
x^d	R&D outputs of downstream firm i
X	Effective R&D level
NC	R&D competition (No cooperation)
VC	Vertical cooperation
HC	Horizontal cooperation
GC	Generalized cooperation

Output stages

The third stage

Solving the model by means of backward induction, I begin with the third stage in which downstream firms engage in Cournot competition given the price of the intermediate goods and the R&D, and assume that diminishing returns in R&D outputs are measured by the parameter γ.[15] The profit function can be written as:

$$\pi_i^d = (a - bY^d - p^u - c + X_i^d)y_i^d - \left(\frac{\gamma}{2}\right)x_i^{d\,2}. \tag{3}$$[16]

The first-order conditions for the maximization of π_i^d with respect to y_i^d yields:

$$y_i^d = \frac{1}{(n+1)b}\left(a - p^u - c + \left(n - (n-1)h\right)x_i^d + (2h-1)\sum\nolimits_{j\neq i}^{n} x_j^d + v\sum\nolimits_{i=1}^{n} x_i^u\right) \tag{4}$$

and

$$p^d = \frac{1}{(n+1)}\left(a + n(p^u + c) - \left(1 + (n-1)h\right)\sum\nolimits_{i=1}^{n} x_i^d - nv\sum\nolimits_{i=1}^{n} x_i^u\right). \tag{5}$$

Solving the total downstream industry output $Y^d = \sum_{i=1}^{n} y_i^d$, I obtain:

$$Y^d = \frac{1}{(n+1)b}\left(n(a - p^u - c) + \left(1 + (n-1)h\right)\sum\nolimits_{i=1}^{n} x_i^d + nv\sum\nolimits_{i=1}^{n} x_i^u\right). \tag{6}$$

The produced quantity of downstream firm i (eq. 4) increases with its own R&D outputs and with the amount of R&D outputs engaged by upstream firms. The quantity decreases with increasing upstream intermediate goods prices and with increasing R&D outputs of competitors, unless horizontal spillovers are sufficiently high ($h > 0.5$). However, total downstream industry output (eq. 6) increases with R&D output, no matter who engages in R&D activities.

From equation (6) I derive the inverse demand function for the upstream

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[15] $\left(\frac{\gamma}{2}\right)x_i^{d\,2}$ and $\left(\frac{\gamma}{2}\right)x_i^{u\,2}$ represent the costs of R&D investments of the downstream and upstream firm. The R&D cost function is the standard quadratic cost function introduced by D'Aspremont and Jacquemin (1988) to capture the phenomenon of decreasing returns to R&D expenditure.

[16] X_i^d means cost reduction (i.e. profit increase) when firms engage in cost-reducing R&D activity with R&D spillover effect.

industry:

$$p^u = a - c + v\sum_{i=1}^{n} x_i^u + \frac{1}{n}\left(1+(n-1)h\right)\sum_{i=1}^{n} x_i^d - \frac{(n+1)}{n}Y^d \,. \tag{7}$$

The second stage

In the second stage, after replacing p^u in the upstream profit function with (7), upstream firms decide non-cooperatively on their output. Upstream firm i solves the following problem:

$$\pi_i^u = (p^u - d + X_i^u)y_i^u - \left(\frac{\gamma}{2}\right){x_i^u}^2 \,. \tag{8}$$

A stable Cournot equilibrium exists which is characterized by the produced quantities $(i, j = 1,2,...n)$:

$$y_i^u = \frac{1}{(n+1)^2 b}\left(\begin{array}{l} n(a-c-d) + n\left(n-(n-1)h+v\right)x_i^u + n(-1+2h+v)\sum_{j\neq i}^{n} x_j^u \\ +\left(1+(n-1)h+nv\right)\sum_{i=1}^{n} x_i^d \end{array}\right) \tag{9}$$

Solving the total upstream industry outputs $Y^u = \sum_{i=1}^{n} y_i^u$, I obtain:

$$Y^u = \frac{1}{(n+1)^2 b}\left(\begin{array}{l} n^2(a-c-d) + n\left(1+(n-1)h+nv\right)\sum_{i=1}^{n} x_i^u \\ + n\left(1+(n-1)h+nv\right)\sum_{i=1}^{n} x_i^d \end{array}\right). \tag{10}$$

The produced quantity of upstream firm i (eq. 9) increases with its own R&D outputs and with the amount of R&D outputs engaged by upstream and downstream firms. The quantity decreases with increasing upstream intermediate goods' prices and with increasing R&D outputs of competitors unless knowledge spillovers are sufficiently high ($2h + v_1 > 1$). However, total upstream industry output (eq. 10) increases with R&D outputs, no matter who engages in R&D activities.

Given that each unit bought from the upstream industry is transformed into the same unit used by the downstream industry, and total output is the same for upstream and downstream industries, I substitute Y^d in (7) with Y^u determining price p_u of the intermediate goods in terms of R&D.

$$p^u = \frac{1}{n(n+1)}\begin{pmatrix} n(a-c+nd) - n(1+(n-1)h-v)\sum_{i=1}^{n} x_i^u \\ +(1+(n-1)h-n^2v)\sum_{i=1}^{n} x_i^d \end{pmatrix}. \tag{11}$$

R&D stage

The first stage

The first stage profit function in the two industries can be expressed as follows:

$$\pi_i^u = \frac{n}{(n+1)} b\left(Z + Ax_i^u + B\sum_{j\neq i}^{n} x_j^u + \frac{1}{n}(A+(n-1)B)\sum_{i=1}^{n} x_i^d \right)^2 - b\Gamma x_i^{u\,2} \tag{12}$$

$$\pi_i^d = \frac{n^2}{(n+1)^2} b\begin{pmatrix} Z + \frac{1}{n^2}((n(n+1)-1)A-(n-1)B)x_i^d \\ +\frac{1}{n^2}(5(n-1)B-A)\sum_{j\neq i}^{n} x_j^d + \frac{1}{n}(A+(n-1)B)\sum_{i=1}^{n} x_i^u \end{pmatrix}^2 - b\Gamma x_i^{m\,2}\cdot \tag{13}$$

Here, $Z = (a-c-d)/(n+1)b$, $A = (n-(n-1)h+v)/(n+1)b$, $B = (-1+2h+v)/(n+1)b$, and $\Gamma = \gamma/2b$ are introduced for computational convenience. In the first stage, firms maximize their profits with respect to R&D, regardless of R&D competition or R&D cooperation.

To compare the variety in R&D cooperation, four R&D scenarios are distinguished in this stage (See Figure 4).

(1) R&D competition (or No cooperation) (NC): R&D competition between firms.

(2) Vertical cooperation (VC): R&D cooperation between upstream and downstream industries.

(3) Horizontal cooperation (HC): R&D cooperation with competitors.

(4) Generalized cooperation (GC): R&D cooperation with competitors and vertical industries simultaneously.

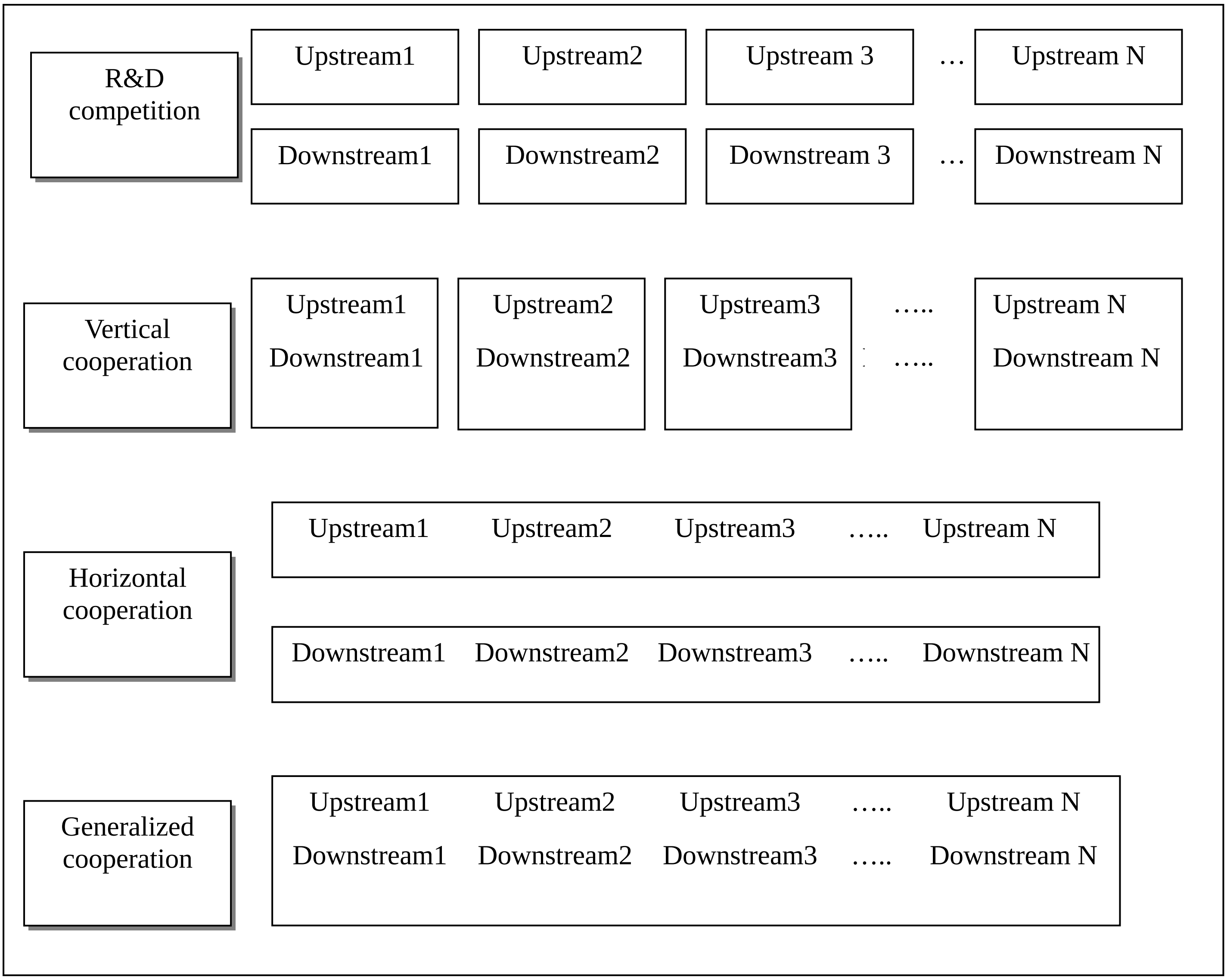

Figure 4: Different types of R&D cooperation

R&D competition (NC)

In the no cooperation scenario, each firm chooses its R&D to maximize its own profits with respect to its R&D, given that other firms do the same. The problem of upstream firm i is noted as:

$$Max_{x_{iu}} \pi_i^u = \frac{n}{(n+1)} b\left(Z + Ax_i^u + B\sum_{j\neq i}^{n} x_j^u + \frac{1}{n}(A+(n-1)B)\sum_{i=1}^{n} x_i^d \right)^2 - b\Gamma {x_i^u}^2 . \quad (14)$$

R&D efforts conducted in the downstream industries always serve as a strategic complement for an upstream firm’s own R&D investment, while the R&D investment of the firm’s competitor is a strategic substitute unless overall knowledge spillovers are sufficiently high ($B > 0 \Leftrightarrow 2h + v > 1$).

The problem of downstream firm i is:

$$MAX_{xid}\, \pi_i^d = \frac{n^2}{(n+1)^2} b \begin{pmatrix} Z + \frac{1}{n^2}\big((n(n+1)-1)A - (n-1)B\big)x_i^d \\ + \frac{1}{n^2}\big(5(n-1)B - A\big)\sum_{j\neq i}^{n} x_j^d + \frac{1}{n}\big(A + (n-1)B\big)\sum_{i=1}^{n} x_i^u \end{pmatrix}^2 - b\Gamma x^{m2} \tag{15}$$

.

R&D efforts conducted in the upstream industries always serve as a strategic complement for a downstream firm’s own R&D investment, while the R&D investment of the firm’s competitor is a strategic substitute unless overall knowledge spillovers are sufficiently high ($5(n-1)B - A > 0 \Leftrightarrow 11(n-1)h + (4n-5)v > 6n + 5$)).

The maximization and simultaneous solving of the first-order condition of equations (14) and (15) yield research outputs under NC by each upstream and downstream firm:

$$x_{NC}^u = \frac{(n+1)nAZ}{(n+1)^2\Gamma - \big((2n(n+1)-1)A - (n-1)B\big)\big(A + (n-1)B\big)} \tag{16}$$

$$x_{NC}^d = \frac{\big((n(n+1)-1)A - (n-1)B\big)Z}{(n+1)^2\Gamma - \big((2n(n+1)-1)A - (n-1)B\big)\big(A + (n-1)B\big)} \tag{17}$$

Vertical cooperation (VC)

Under the vertical R&D cooperation scenario, given that downstream firms are identical, as well as upstream firms, I assume that downstream firm i cooperates with upstream firm i. All firms maximize the joint profits:

$$Max_{x_i^u, x_i^d}\, \pi_i^u + \pi_i^d\ . \tag{18}$$

The maximization of equation (18) yields research outputs under VC:

$$x_{VC}^u = x_{VC}^d \frac{n\big((n+2)A + (n-1)B\big)Z}{(n+1)^2\Gamma - 2n\big((n+2)A + (n-1)B\big)\big(A + (n-1)B\big)}. \tag{19}$$

Horizontal cooperation (HC)

Under HC, there is intra-industry cooperation, but no inter-industry cooperation. Upstream firms maximize their joint profits $\pi_i^u + ... + \pi_n^u$ with respect to their R&D level:

$$Max_{x_i^u,...x_n^u} \pi_i^u + ... + \pi_n^u , \tag{20}$$

Downstream firms maximize their joint profits $\pi_i^d + ... + \pi_n^d$:

$$Max_{x_i^d,...x_n^d} \pi_i^d + ... + \pi_n^d . \tag{21}$$

Simultaneous solving the first-order condition of equations (20) and (21) yields research outputs under HC:

$$x_{HC}^u = \frac{n(n+1)(A+(n-1)B)Z}{(n+1)^2\Gamma - n(2n+1)(A+(n-1)B)^2} \tag{22}$$

$$x_{HC}^d = \frac{n^2(A+(n-1)B)Z}{(n+1)^2\Gamma - n(2n+1)(A+(n-1)B)^2} . \tag{23}$$

Generalized cooperation (GC)

Under GC each firm chooses its R&D to maximize the total profits of all firms:

$$Max_{x^u,x^d} \pi^u + \pi^d . \tag{24}$$

The maximization of equation (24) yields research efforts under GC:

$$x_{GC}^u = x_{GC}^d \frac{n(2n+1)(A+(n-1)B)Z}{(n+1)^2\Gamma - 2n(2n+1)(A+(n-1)B)^2} \quad . \tag{25}$$

Finally, the equilibrium profits can be obtained as follows:

$$\pi_i^u = \frac{(n+1)}{n} b\left(y^N\right)^2 - b\Gamma\left(x^u\right)^2 \tag{26}$$

$$\pi_i^d = b\left(y^N\right)^2 - b\Gamma\left(x^d\right)^2 , \tag{27}$$

where $y^N = \frac{n}{(n+1)}\left(Z + (A+(n-1)B)\left(x^u + x^d\right)\right)$.

Comparison of R&D cooperation scenarios

In this section the different types of cooperation are compared with R&D competition, in terms of R&D investments, R&D outputs,[17] and firm profits.[18] Following the approach proposed by Steurs (1995), I simulate the equilibrium R&D investments, R&D outputs, and profits by varying the two spillover parameters v and h for given values of parameters a, b, c, d, γ, and set the number of firms as two for convenience of comparison. The simulations reveal that the R&D investments and profits in most cases display exactly the same ranking as the R&D outputs given above. The simulation results also show that vertical cooperation always dominates R&D competition regarding R&D investments, R&D outputs, and profits. For generalized cooperation, the R&D investments, R&D outputs, and profits are higher than those of horizontal cooperation, vertical cooperation, and R&D competition when vertical and horizontal spillovers are high. All in all, R&D cooperation leads to higher R&D investments, R&D outputs, and financial performance under high spillovers (see Table 10).

In order to make sure that simulation results are robust, I also test the impact of the numbers of cooperative firms (2, 5, 10, and 20) on R&D investments, R&D outputs, and profits. The simulation results are presented in Appendix A and Table A1-A12, and show that same ordering usually applies to different numbers of cooperative firms. Therefore, the results are further confirmed.

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[17] I focus on R&D outputs, not effective R&D. Although the latter is more meaningful from a social point of view, R&D outputs are more amenable to empirical testing.

[18] R&D investments $b\Gamma x^2$ exist under a functional relationship with R&D outputs x. Therefore, the comparison results of R&D outputs can be analogized to those of R&D investments.

Table 10: Ranking of firms' R&D investments, R&D outputs, and firm profits (a=100, b=1, c=1, d=1, γ =70, n=2)

		No spillovers (0,0)	Perfect horizontal spillovers and no vertical spillovers (1,0)	No horizontal spillover and perfect vertical spillovers (0,1)	Perfect spillovers (1,1)
R&D competition	R&D investments	2	4	3	4
	R&D outputs	2	4	3	4
	Profits	2	4	3	4
Vertical cooperation	R&D investments	1	2	2	2
	R&D outputs	1	2	2	2
	Profits	1	2	2	2
Horizontal cooperation	R&D investments	4	2	4	2
	R&D outputs	4	2	4	2
	Profits	4	2	4	2
Generalized cooperation	R&D investments	3	1	1	1
	R&D outputs	3	1	1	1
	Profits	3	1	1	1

Analyzing R&D cooperation with asymmetric spillovers, Atallah (2005) finds that R&D cooperation increases total R&D investments when the average of firms' spillover rates is sufficiently high. According to Griliches's (1990) surveys of the empirical literature, knowledge spillovers are both prevalent and important. Mansfield, Schwartz, and Wagner (1981) show that about 60% of the patented innovations in their sample were imitated within 4 years. Veugelers (1998) points out that telecommunications, semi-conductors, instruments, chemicals, and electronics industries all have high spillovers.

Irrespective of whether the research is theoretical or empirical, more literature has emerged to identify a positive impact on firm performance of engaging in R&D cooperation (e.g. Kamien et al. 1992; Hagedoorn and Schakenraad 1994; Steurs 1995; Petit and Tolwinski 1999; Sarkar et al. 2001; Cassiman and Veugelers 2002; Chung and Kim 2003). Steurs (1995) analyzes the impact of intra-industry and inter-industry knowledge spillovers on the level of strategic R&D investments, output, profits and total welfare. The results show that inter-industry cooperation is more socially beneficial than cooperation in single industry firms (intra-industry cooperation). Hagedoorn and Schakenraad (1994) study the effects of strategic technology alliances on company performance. The results indicate that companies attracting technology through their alliances, and companies concentrating on R&D cooperation, have significantly higher rates of profit. Sarkar et al. (2001) also investigate the effect of alliance entrepreneurship on market-based firm performance. Results indicate that alliance proactiveness leads to superior market-based performance. From the supplier's standpoint, Chung and Kim (2003) analyze the effects of supplier involvement in a manufacturer's new product development on the supplier's financial performance, innovation, and product quality. The results indicate that a higher level of supplier's involvement positively impacts innovation and financial performance.

Engaging in R&D collaboration also has positive impact on R&D investments and R&D outputs. Peters and Becker (1997-98) provide empirical evidence that R&D spillovers strategically transferred from the manufacturers to their suppliers in vertical cooperative networks increase the probability of members' successfully realizing an innovation and stimulating R&D investments over the case with nonmembers. Kaiser (2002) uses innovation survey data of the German service sector and finds that cooperating firms invest more in research than do non-cooperating firms. Stuart (2000) investigates the relationship between intercorporate technology alliances and innovation rates. The findings from models of innovation rate confirm that organizations with large and innovative alliance partners perform better than comparable firms that lack such partners. Chang (2003) surveys the innovative activities and inter-organizational cooperation of integrated circuits and biotechnology sectors across Taiwan and UK. The result reveals that firms with a more active role in establishing inter-organizational linkages increase their chances to innovate.

During my interview with Corporation A, the largest high-technology company in the world, one manager indicated that R&D is very complex and risky nowadays. Even a large-scale company can not monopolize product innovation completely. The company needs to cooperate with its suppliers, customers, and even competitors in R&D. In addition, the company needs to make compatible products because of customers' demand. Therefore, R&D cooperation is a popular phenomenon for high-technology industry relative to other industries. R&D cooperation leads his company to higher profits and creates an economy of large scale. Based on the theoretical model, simulation results, prior literature, and interview, I develop the following hypotheses.

H5a: Higher R&D cooperation intensity leads to higher R&D investments.

H5b: Higher R&D cooperation intensity leads to higher R&D outputs.

H5c: Higher R&D cooperation intensity leads to higher financial performance.

Summarizing several calculations, the following ranking of the equilibrium R&D outputs can be established[19]:

Proposition 1

$(1) x_{GC} > x_{HC}$

$(2) x_{VC} > x_{NC}$

$(3) x_{VC} > x_{HC} \, if \, (h < 1)$

$(4) x_{HC} > x_{NC} \, if \, (23h + 10v > 13)$

$(5) x_{GC} > x_{VC} \, if \, (7h + 5v > 2)$

$(6) x_{GC} > x_{NC} \, if \, (11h + 10h > 1)$

---

[19] Without losing generality, I set the number of firms as two.

Proof. See Appendix B.

Figure 5 illustrates the ranking of different R&D cooperation types based on above conditions. This figure is divided into 5 regions, each region being characterized by a ranking of different cooperation. The parameter space is spanned by the horizontal spillover parameter h in the horizontal dimension and the vertical spillover parameter v in the vertical dimension. Region 1 is characterized by low spillovers. In this region VC>NC>GC>HC. As spillovers increase, we move into Region 2, where the ranking of GC and NC is reversed: VC>GC>NC>HC. As spillovers increase further, we move into Region 3, where GC comes to dominate all other cooperation types. When spillovers increase further, we move into Region 4: HC>NC. Finally, when h=1 (Region 5), the horizontal competitive externality increases further: HC=NC. Note that for the largest part of the spillovers space, GC dominates all other cooperation types, followed by VC. R&D investments and profits also lead to the same conclusions.

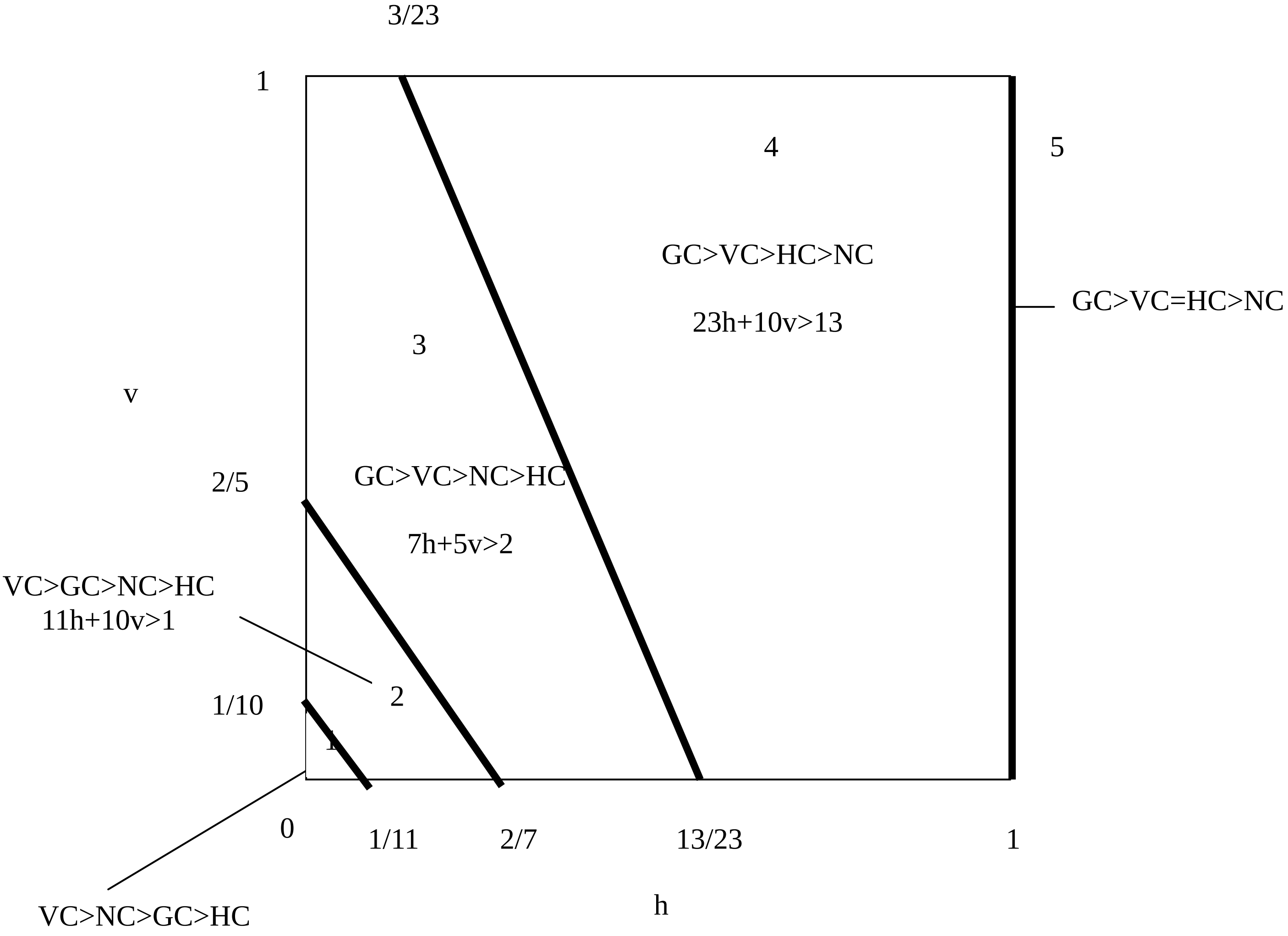

Figure 5: The effect of cooperation types on R&D outputs

The strategic network theory argues that network organizations are able to capture the benefits of specialization, focus, and scale (Hagedoorn et al. 2000). Networks can be formed to exploit the different competencies of cooperative firms (Miles and Snow 1984). In addition, early adopters of network strategies can enjoy a first-mover advantage (Miles and Snow 1984). Regarding the research related to the Taiwanese industry system and industry organization, the results consistently point out that the network organization is a widespread form of industry system in Taiwan (Chen 2003). For example, MediaTek Inc. cooperates with Global Mixed-mode technology Inc. (MediaTek Inc.'s competitor) on power management. Then they integrate their IC with the products of BenQ (customer). In this kind of cooperation relationship, partners benefit from each other, which in turn leads to higher R&D investment, R&D outputs, and financial performance. Therefore, I propose following hypotheses:

H6a: Generalized R&D cooperation leads to higher R&D investments relative to other cooperation types if knowledge spillovers are "large" (7h+5v>2)**.**

H6b: Generalized R&D cooperation leads to higher R&D outputs relative to other cooperation types if knowledge spillovers are "large" (7h+5v>2)**.**

H6c: Generalized R&D cooperation leads to higher financial performance relative to other cooperation types if knowledge spillovers are "large" (7h+5v>2)**.**

During the industrial era, companies succeeded based on how well they captured the benefits from scales of economy. The traditional financial performance measures worked quite well in that period. However, with a shift from the industrial economy towards an economy now predominantly characterized by intangible assets such as knowledge and innovation, the ability of a firm to mobilize and exploit its intangible assets has become far more decisive than investing and managing tangible assets (e.g. Kaplan and Norton 1992; 1996). Research results also show that the relevance of financial statement information has diminished over time, and that nowadays firm performance cannot be found in financial measures alone (e.g. Collins, Maydew, and Weiss 1997; Francis and Schipper 1999). Thus, measures are needed that drive future performance and complement financial measures of past performance.

Several articles indicate that non-financial measures are significantly associated with future financial performance (e.g. Ittner and Larker 1998; Behn and Riley 1999; Banker, Potter, and Srinivasan 2000) and are highly value-relevant (e.g. Amir and Lev 1996; Ittner and Larker 1998; Said, HassabElnaby, and Wier 2003). Ittner and Larcker (1998) use customer-level satisfaction survey data for a telecommunications company and document a significant relation between customer satisfaction and next year's revenue. Similarly, using time-series data from the hotel industry, Banker et al. (2000) examine whether current non-financial measures are better predictors of long-term financial performance than current financial measures. They find that measures of customer complaints and returning customers are leading indicators of revenues and profits.

Innovation is a crucial resource and the major driver of firms' growth in the long run. R&D investments and innovation cover the input side and output side of the innovation process and have a positive impact on financial performance. Aboody and Lev (2001) study 83 publicly-traded chemical companies, evaluating the return of R&D investments from 1980 to 1999. Results show that a dollar invested in chemical R&D increases current and future operating income by two dollars. Chen, Cheng, Hwang (2005) investigate the relationship between intellectual capital and firms' market value and financial performance. Evidence shows that R&D expenditure has a positive effect on firm value and profitability. Eberhart, Maxwell, and Siddique (2004) examine the long-term abnormal stock returns and operating performance following R&D increases. They find consistent evidence that sample firms experience significantly positive long-term abnormal stock returns and abnormal operating performance following R&D increases. Ernst (2001) tests the relationship between patent applications and subsequent changes of company performance, showing that national patent applications lead to increases in sales. Using survey data for the Netherlands, Klomp and Leeuwen (2001) analyze the input and output stages of the innovation process and the links between the innovation process and overall economic performance. The results show that the impact of innovation on a firm's growth rate of total turnover increases considerably. Accordingly, I suggest the following hypothesis:

H7a: R&D investments are positively related with financial performance.

H7b: R&D outputs are positively related with financial performance.

As noted earlier, R&D investments and R&D outputs have a more direct effect on financial performance than R&D cooperation. Accordingly, not only can R&D cooperation directly affect financial performance, but the relationship also could be mediated by R&D investments and R&D outputs. As a result, I propose following hypotheses:

H8a: The impact of R&D cooperation intensity on financial performance is mediated by R&D investments.

H8b: The impact of R&D cooperation intensity on financial performance is mediated by R&D outputs.

Chapter 4: Research method

4.1 Conceptual framework

Based on prior research, this study develops two research topics: (1) the determinants of R&D cooperation; and (2) the impact of R&D cooperation on R&D investments, R&D outputs, and financial performance.

Research topic 1: The determinants of R&D cooperation

In this research topic, I examine the impact of knowledge spillovers, absorptive capacities, and uncertainty on the intensity of engaging in R&D cooperation.

Research topic 2: The impact of R&D cooperation on R&D investments, R&D outputs, and financial performance

According to D'Aspremont and Jacquemin (1988) and Kamien et al. (1992), the theoretical background of the above research topics is built on the Cournot-Nash equilibrium analysis. The main assumptions are that firms engage in Cournot competition at output stages. At R&D stages, all firms decide simultaneously on R&D investments. In the empirical analysis I divide Taiwan's high-technology industries into four groups—R&D competition, horizontal cooperation, vertical cooperation, and generalized cooperation—and examine the impact of R&D cooperation on R&D investments, R&D outputs (non-financial performance), and financial performance.

The hypothetical research framework, R&D cooperation—innovation —financial performance chain, is shown in Figure 5.

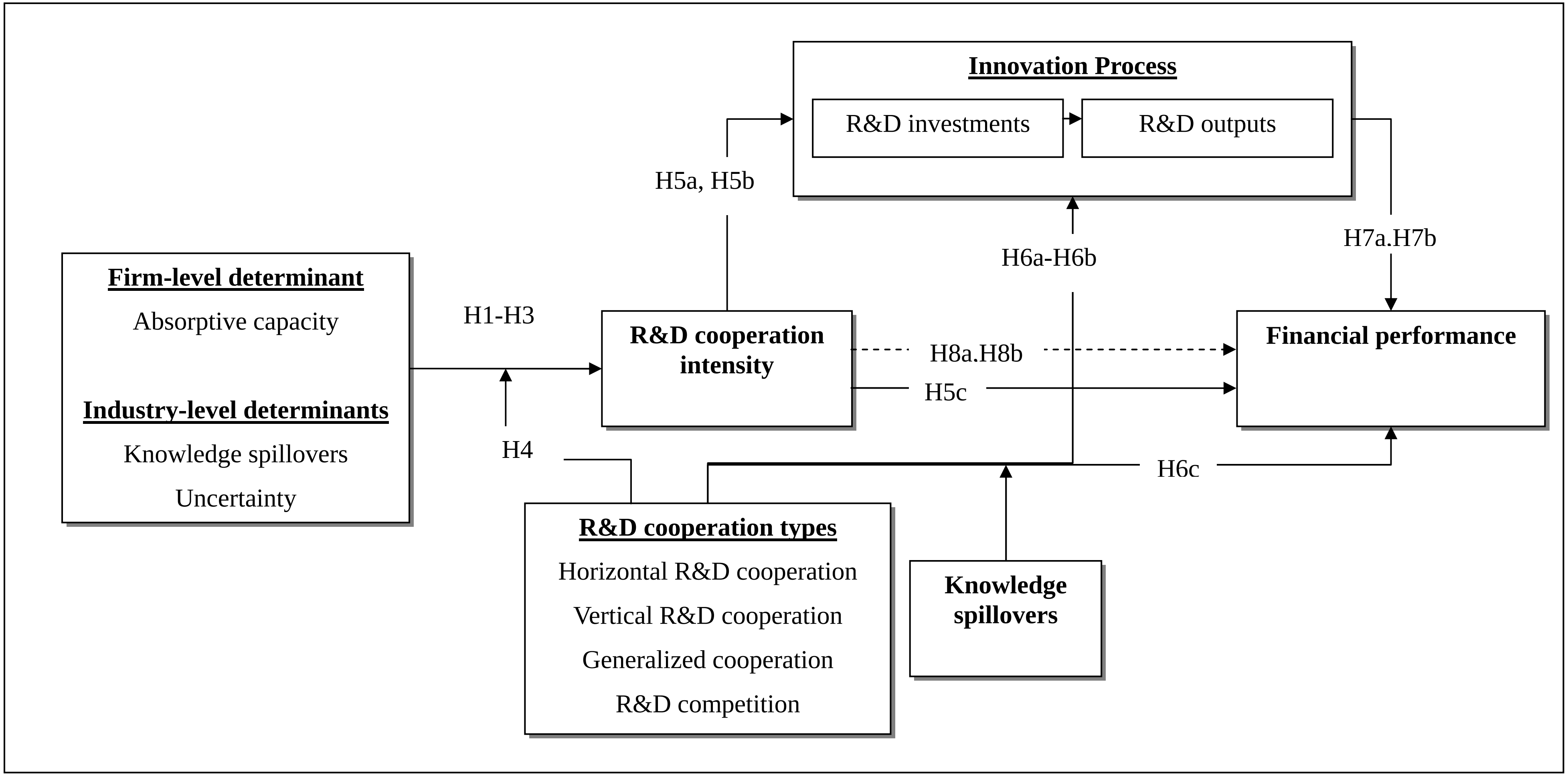

Figure 5: Hypothetical research framework of this study — The R&D cooperation — innovation — financial performance chain

4.2 Research sample and data collection

Hagedoorn (1993), Wang (1994), and Hagedoorn et al. (2000) find that cooperation is even more widespread in higher technological industries. Hence the high-technology industries are representative and ideally situated for R&D cooperation and performance research. These industries also provide a natural environment to test the theoretical model of R&D cooperation. Therefore, I use 604 Taiwan's publicly-traded firms from high-technology industries as a research sample, including semiconductor, optoelectronics, telecommunications, computer component, Computer peripheral, and system and equipment industries.[20] I also interview several managers in this industry to confirm my research setting and empirical test. Financial data, patent data, and R&D cooperation data are collected from the following sources.

(1) Financial data

Financial data (including R&D investment) are drawn from the Taiwan Economic Journal (TEJ) database during 2001-2004.

(2) Patent data

Patent, citation, and claim data of Taiwan's high technology companies are collected from the database of the United States Patent and Trademark Office (USPTO) during 2001-2004.

(3) Cooperation data

To prevent measurement biases, four sources are used to collect R&D collaboration data during 1998 to 2001: the database of the Industrial Technology Development Alliance Program (ITDAP) of the Ministry of Economic Affairs, Department of Industrial Technology in Taiwan, the database of the United States Patent and Trademark Office (USPTO), the database of Taiwan Business groups from China Credit Information service, and collaboration related news from DigitTimes daily.

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[20] Please refer to Appendix C for the definition and classification of these high-technology industries.

4.3 Variable measurement

Dependent Variables

Profit

R&D efforts usually result in product or process improvements (Tsai and Wang 2005). For R&D activity in a profit-making organization, the outcomes are accomplishments such as cost reduction and sales improvement (Brown and Svenson 1988). Thus, this study uses profit, measured as earning before interest and tax, to proxy financial performance.

R&D output

R&D outputs are intangible assets that can be labeled as the firm's "knowledge stock" (Hall, Jaffe, and Trajtenberg 2005). Empirical testing requires an observable proxy for R&D outputs. Pakes and Griliches (1984) emphasize that there is quite a strong relationship between the number of patents and R&D, indicating that patents are good indicators of unobserved R&D outputs. There is also a considerable amount of studies using the number of a firm's patents as a major performance indicator (e.g. Scherer 1982; Griliches 1984; Jaffe 1986; Ernst 2001; Bottazzi and Peri 2003; Feeny and Rogers 2003; Hagedoorn and Cloodt 2003; Lin and Chen 2005; Tsai and Wang 2005). Therefore, in this study I take the number of patents as an indicator of R&D output quantity.

The value of patent counts as a proxy for R&D output is limited by the very large variability in the importance of individual patents, rendering patent counts as a noisy indicator of R&D outputs (e.g. Bottazzi and Peri 2003; Hagedoorn and Cloodt 2003; Hall et al. 2005). Griliches (1990) also points out that the inventions that are patented differ greatly in 'quality'. According to Hall et al. (2005), an increase of one citation per patent is related to an increase of 3—4% in market value. Therefore, more valuable patents are cited more frequently. In addition, claims are the parts of a patent that define the boundaries and legal basis of patent protection. Having more claims allows firms to have legal title to different aspects of invention. Several prior literatures (e.g. Trajtenberg 1989; Deng, Lev, and Narin 1999; Harhoff, Narin, Scherer, and Vopel 1999; Hirschey, Richardson, and Scholz 2001; Lanjouw and Schankerman 2004; Scotchmer 2005) also indicate that patents with higher average citation and claim contain indicators of the invention's worth and firm value. Therefore, I use the number of citations and claims as an indicator of R&D output quality.

I heed Balkin, Markman, and Gomez-Mejia's (2000) recommendation that a composite measure be used to capture broad aspects of innovation activities more accurately. In addition, the correlation between the number of patents, citations, and claims is quite high (from 0.7846 to 0.9622), indicating several problems with multicollinearity, so I use Principal Component Analysis (PCA) to generate the single factor of R&D outputs which explains 94.45% of the observed variation.

R&D investment

The level of R&D investments is the most extensively used proxy for the level of innovative effort. Its advantages are that it is a relatively well understood term and it provides a dollar figure for use in analysis (Rogers 1998). In accordance with previous research (e.g. Shrader 2001; Hall and Bagchi-Sen 2002; Sakakibara 2002; Hernan et al. 2003; Negassi 2004; Huang and Liu 2005; Lin and Chen 2005; Liu, Lin, and Chin 2005; Yu,Chiao, and Chen 2005), this study adopts R&D expenditures to proxy R&D investments.

Independent Variables

R&D cooperation type (Vertical cooperation, Horizontal cooperation, Generalized cooperation, R&D competition)

Survey data are the primary sources for the prior R&D cooperation research (e.g. Kaiser 2002a; Caloghirou et al. 2003; Chang 2003; Belderbos et al. 2004). According to Hagedoorn and Schakenraad (1994), in this study I use archival data and content analysis from 1998 to 2001 to measure the variable of R&D cooperation. Four sources were used to measure each company's R&D collaboration. First, I collect collaboration data from the database of the Industrial Technology Development Alliance Program (ITDAP) of the Ministry of Economic Affairs, Department of Industrial Technology in Taiwan. Second, according to the database of USPTO, if the company has co-assignee(s) for the same patent rights, then I identify these assignees with R&D collaboration relationships. Third, companies that belong to the same business group are regarded as R&D collaborative companies.[21]

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[21] This assumption may not hold because companies that belong to the same business group are not necessary to cooperation on R&D. Therefore, I also exclude this data source and to examine the robustness of the empirical test. The results show that the correlation between R&D cooperation with business group and without business group is over 98%, and the empirical results remain unchanged

Finally, I collect collaboration related news from DigiTimes daily. DigiTimes daily consists of sections devoted to news concerning computers and peripherals, semiconductors, optoelectronics, IT, communications, networking and software, and is the most professional and popular newspaper in Taiwan's high-technology industry.[22] The following key words are used to obtain R&D collaboration and strategy alliance data: collaboration: strategy alliance, joint development, joint research, research alliance, strategic collaboration, and cooperative alliance, etc. There were 30,258 related news items during 1998-2001. Then, I analyze and code the news that relates to my sample companies (604 listed companies in Taiwan's high technology industry). Finally, to make sure that the classification procedure is reliable, I invited two specialists (Scott Lin, the manager of DigiTime daily, and Walter Huang, the business director of ZuKen Taiwan Inc.) to review the code process. I then revised the coding text according to their suggestions.

I use the following principle for constructing the database of R&D cooperation: Firstly, I exclude the R&D cooperation news with possibility. For example,

> "…A company indicates that it will not rule out the possibility of integrating vertically with other key computer component companies. To enhance market competition ability, the related R&D cooperation or strategic alliances are all under discussion. It is still not the right time to make a public announcement…." (April 17, 2001)

Secondly, news content can be used to determine the types of R&D cooperation, including vertical R&D cooperation (cooperation between suppliers or customers), horizontal R&D cooperation (cooperation with competitors), and generalized R&D cooperation (cooperation with competitors and vertical industries simultaneously). For example, the following news item is regarded as vertical R&D cooperation:

> "Lucent and Winbond have agreed to jointly develop stand-alone and embedded flash memory products using CHISEL for a period of two years. It is expected that both Lucent and Winbond will offer products

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after excluding the data of business group.

[22] According to my interview with several practitioners, e.g. Victor Tsan, the general director of Market Intelligence Center, Institute of Information Industry, and Walter Huang, the business direct of Zuken Taiwan Inc, they all agree that DigiTimes is the most reliable professional newspaper in Taiwan high-technology industry.

[24] I appreciate Ph. D. committee members' opinion for the measurement of knowledge spillovers.

> that use the CHISEL technology.” (December 13, 1998)

The following news item is regarded as horizontal R&D cooperation:

> “Accton yesterday confirmed that it will invest about US$15 million in a joint venture with one large American network company to develop an internet audio chip….” (December 6, 1999)

If the same company has both vertical R&D cooperation and horizontal R&D cooperation during the same year, then I define it as generalized R&D cooperation. In addition, I exclude duplicate news, and also consistently apply a single classification principle.

R&D cooperation intensity

Most of the research uses a dummy variable to proxy R&D cooperation (e.g. Hagedoorn and Schakenraad 1994; Shrader 2001; Sakakibara 2002; Caloghirou et al. 2003; Belderbos et al. 2004). However, dummy variables cannot represent the frequency and intensity of R&D cooperation for each firm. Therefore, I measure R&D cooperative activity in two ways. The first measure, *R&D cooperation type*, focuses on the event of cooperation formation, that is, whether a firm engaged in cooperation or not during a given period. Based on prior literature (e.g. Belderbos et al. 2004), the R&D cooperation type variable is taken as 1 indicating that a firm has at least one vertical R&D cooperation (cooperation between suppliers or customers), horizontal R&D cooperation (cooperation with competitors), or generalized R&D cooperation (cooperation with competitors and vertical industries simultaneously) during 1998-2001, and 0 otherwise. No cooperation (R&D competition) is treated as a reference variable. The second variable, *R&D cooperation intensity*, measures the total amount of cooperation undertaken by a firm during a given period, which does reflect the intensity of cooperative activity (Park, Chen, and Gallagher 2002). I follow Stuart’s (2000) and Park et al.’s (2002) approach and use the number of R&D cooperation formed by a firm during 1998-2001 to proxy R&D cooperation intensity.

Absorptive capacity

Zahra and George (2002) highlight four distinct but complementary capabilities that compose a firm’s absorptive capacity: acquisition, assimilation, transformation, and exploitation. To account for differing abilities of firms to internalize other firms’ knowledge, this study follows the idea of Luo (1997) and Zahra and George (2002) by including the share of employees with Ph. D. and master’s degrees to proxy absorptive capacity.

Knowledge spillover

The earliest and simplest formulation of firm i’s knowledge spillovers is given by:

$$SP_i = \sum_{j \neq i}^{N} RD_j \ , \tag{44}$$

where SP_i is the level of spillovers enjoyed by firm i; RD_j is the investments in R&D by firm j; and N denotes the number of firms inside firm i’s industry (Kaiser 2002b). However, it is not necessary that every firm can gain from other firms’ R&D investments. In this study, I argue that the strategy alliance usually includes knowledge sharing and technique exchange with each other. Therefore, knowledge spillovers of firm i are higher if the number of strategy alliance (including sales alliance, production alliance, and joint venture) inside or outside firm i’s industry (horizontal alliance or vertical alliance) is higher:[24,25]

$$SP_i = \sum_{j \neq i}^{N} SA_j \tag{28}$$

Where SA_j is the number of strategy alliance by firm j.

Uncertainty

Uncertainty is the degree of accuracy with which one can predict the future. Where there is less variance, there is more certainty (Tosi, Aldag, Storey 1973). Former literatures use standard deviation or coefficient of variation to measure uncertainty (e.g. Tosi et al 1973; Snyder and Glueck 1982; Kothari 2002). However, these measures do not consider the ordering of the data points and measure only their dispersion from the mean. The measures are unable to detect variation from a time trend. Hence, regression approach is superior to the above measurements. In this study, I apply Dess and Beard’s (1984) approach to measuring uncertainty which is obtained when each dependent variable (sales, employees, and R&D and capital expenditures)

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[25] I have separated knowledge spillovers into vertical spillovers (the number of strategy alliance with suppliers and buyers) and horizontal spillovers (the number of strategy alliance with competitors). However, the correlation between these two spillovers is very high (88.43%), meaning serious problem of multicollinearity. Thus I combine these two variables as knowledge spillovers.

is regressed on time over the period 1998-2001. Four volatility measures are calculated: the standard error of the regression slope coefficient of sales divided by mean value of sales is used as a measure of market volatility; the standard error of the regression slope coefficient of earning before income and tax (EBIT) divided by mean value of EBIT is used as a measure of profit volatility; the standard error of the regression slope coefficient of employees divided by mean value of employees is used as a measure of employment volatility; the standard error of the regression slope coefficient of R&D and capital expenditures divided by mean value of the R&D and capital expenditures is used as a measure of technology volatility. All of these four can refer to market uncertainty. Finally, I use Principal Component Analysis (PCA) to extract the single factor of uncertainty. The principal component derived form PCA explains 73.66% of the observed variation.

Control Variables

To avoid the impact caused by other variables that are absent from my model, this study refers to prior research and chooses firm characteristics (including sales growth, capital structure, and firm size), industry characteristics (industry segments and industry effect) as control variables.

Sales growth

Higher sales means that the profitability of a firm is better. Therefore, I measure sales growth as the change in sales revenue to this period from last period and scale it by net sales revenue from the last period (e.g. Capon, Farley, and Hoenig 1990; Yu et al. 2005; Huang and Liu 2005).

Capital structure

Capital structure reflects the operation risk of a firm and is deemed as the important decisive factor of financial performance. Therefore, I use the ratio of total liabilities to total assets to proxy capital structure (e.g. Capon et al. 1990; Said et al. 2003; Yu et al. 2005; Huang and Liu 2005).

Firm size

The effect of firm size on innovation is tied to the relative advantage of large/small firms during the process of innovation (Mazzucato 2000). Acs and Audretsch (1987) find that large firms tend to hold a relative innovative advantage in industries that are capital-intensive, concentrated, and highly unionized, that produce a differentiated good, while small firms tend to own a relative advantage in industries that are highly innovative and utilize a large component of skilled labor. Research also points out that firm size may have an influence on performance (e.g. Ittner and Larker 1997; Bharadwaj, Bharadwaj, and Konsynski 1999). Therefore, consistent with prior literature, this study uses total asset to proxy firm size (e.g. Mazzucato 2000; Shrader 2001; Kaiser 2002a; Hernan et al. 2003; Matusik and Heeley 2005; Tsai 2005; Tsai and Wang 2005).

Industry segments (Upstream, Midstream, and Downstream)

I divide high-technology industry into three segments, including upstream, midstream, and downstream industry.[26] The classification criteria are according to the high-technology industry reports issued by the Industrial Technology Research Institute (ITRI) and "Electronic Industry Connection Encyclopedia" issued by Get-Fortune Publishing Ltd. Industry segment variables are dummy variables taking the value of one if the firm is in upstream and midstream industry, respectively. Downstream industry is treated as a reference variable.

Industry effect (Semiconductor, Optoelectronics, Telecommunications, Computer component, Computer peripheral, and system and equipment)

Prior literature suggests that sectoral differences can play a role in explaining the various outcomes of innovative performance (e.g. Griliches 1998; Ernst 2001; Hagedoorn and Cloodt 2003). Therefore, to control for industry effects on R&D investments, R&D outputs, and financial performance, I use the industry effect measured as dummy variables. Taiwan's high-technology industries include semiconductor, optoelectronics, telecommunications, computer component, computer peripheral, and system and equipment.[27] Thus, industry effect variables are dummy variables taking the value of one if the firm is in optoelectronics, telecommunications, computer component, computer peripheral, and system and equipment industries, respectively. The semiconductor industry is treated as a reference group.

See Table 11 for the variable measurements of this study.

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[26] In Taiwan, most of the upstream firms are raw materiel and design companies, while most of the manufacturing companies belong to midstream industry. Downstream industry includes application industry that is much closer to final customers. For example, the level of labor division in IC design (upstream), IC manufacturing (midstream), and IC testing and package (downstream) specialization for Taiwan's semiconductor industry is the most comprehensive in the world.

[27] The classification criteria are from the same resources as the variable of industry segments.

Table 11: Variable measurements for this study

Variables	Variable Measurement
Dependent Variable	
Profit	*Earnings before interest and tax*
R&D investment	*R&D expenditures*
R&D output	*The number of patents is used to measure R&D output quantity. The number of citations and claims is used to measure R&D output quality.* Principal Component Analysis (PCA) is used to extract the single factor of R&D outputs.
Independent Variables	
R&D cooperation type[28]	*The R&D cooperation type variable is taken as 1 if a firm has at least one vertical R&D cooperation (cooperation between suppliers or customers), horizontal R&D cooperation (cooperation with competitors), or generalized R&D cooperation (cooperation with competitors and vertical industries simultaneously) during 1998-2001, and 0 otherwise.*
R&D cooperation intensity	*Total number of R&D cooperation formed by a firm during 1998-2001.*
Absorptive capacity	*The ratio of Ph. D. and master degree employees to total employees.*
Knowledge spillover	$SP_i = \sum_{j \neq i}^{N} SA_j$ *where* SP_i *is the level of spillovers enjoyed by firm i;* SA_j *is the number of strategy alliances by firm j; N denotes the number of firms inside firm i's industry.*

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[28] R&D competition is treated as a reference group.

Variables	Variable Measurement
Uncertainty	*Standard error of the regression slope coefficient divided by mean value (sales, profits, employees, and the sum of R&D expenditures and capital investment). Principal Component Analysis (PCA) is used to extract the single factor of uncertainty.*
Control Variables	
Firm characteristic	
Sales growth	*(Net operating sales this period – net operating sales last period) / Net operating sales last period*
Capital structure	*Total Liabilities / Total assets*
Firm size	*Total assets*
Industry characteristic	
Industry segment[29]	
Upstream	*Upstream industry = 1; others = 0.*
Midstream	*Midstream industry = 1; others = 0.*
Industry effect[30]	
Optoelectronics	*Optoelectronics industry = 1; others = 0*
Telecommunications	*Telecommunications industry =1; others = 0*
Computer component	*Computer component industry = 1; others = 0*
Computer peripheral	*Computer peripheral industry =1; others = 0*
System and equipment	*Other industry = 1; others = 0*

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[29] Downstream industry is treated as a reference group.

[30] Semiconductor industry is treated as a reference group.

4.4 Data analysis methods

I use descriptive statistics analysis, correlation analysis, Principal Component Analysis (PCA), Hierarchical Linear Model (HLM), multiple regression analysis, Heckman two-step model, treatment effects model, and Path analysis to test the hypotheses of this study:

(1) Descriptive statistics analysis

To summarize data in a clear and understandable way, I use means, medians, standard deviations, minimums, and maximums to analyze the characteristics of each variable.

(2) Correlation analysis

Correlation analysis is a statistical technique that shows whether and how strongly the pairs of variables are related. I use Pearson’s correlation analysis to gain preliminary evidence on the association among variables.

(3) Principal Component Analysis (PCA)

PCA is a data reduction method, that is, a method for reducing the number of variables. I use PCA to extract the representative factor of R&D outputs and uncertainty.

(4) Hierarchical linear model (HLM)

HLM is a multilevel modeling approach that allows researchers to use couple level variables without losing individual differences. In this study, knowledge spillovers and uncertainty are industry level variables, and absorptive capacity is firm level variable. Therefore, I use HLM to test how factors across different levels interact with one another and jointly determine the intensity of R&D cooperation.

(5) Multiple regression analysis

This study uses Ordinary Least Squares (OLS) to test the relationship between R&D cooperation, R&D investments, R&D outputs, and financial performance.

(6) Heckman two-step model

Observations (companies) that have better performance may be more willing to engage in R&D cooperation with their suppliers, buyers, or competitors. Therefore, I apply the Heckman two-step model[31] in empirical tests to avoid sample selection bias. The estimation starts with a probit model to estimate the probability of whether a firm engages in R&D cooperation or not (the first step). In the second step, an OLS model is estimated to test the impact of R&D cooperation intensity on R&D investments, R&D outputs, and financial performance, in which the fitted values of the first-step estimates are included as Heckman (1979)-type correction terms.

(7) Treatment effects model

In contrast to standard application of Heckman two-step model, I retain the entire sample for the second-step regression and treat the variable of R&D cooperation type as endogenous.

(8) Path analysis

To test the direct and indirect relationship between R&D cooperation, R&D investments, R&D outputs, and financial performance, I use path analysis to examine their relationship.

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[31] Sample selection bias can arise in practice for two reasons: 1. Self selection by the individuals or data units being investigated; 2. Sample selection decisions by analysts or data processors operate in much the same fashion as self selection (Heckman 1979).

Chapter 5: Empirical results

5.1 Fundamental results

Table 12 summarizes the descriptive statistics. 42.5% of Taiwan's high technology firms participate in R&D cooperation. Most of them engage in vertical R&D cooperation (21.8%), followed by generalized R&D cooperation (13.3%) and horizontal R&D cooperation (4.7%). The low percentage of horizontal R&D cooperation means that firms tend to avoid R&D cooperation with their competitors (Miotti and Sachwald 2003). The average number of R&D cooperation events in the sample firms from 1998 to 2001 is 1.67. Average profits are NT$331 million. Eight percent of the employees in the sample firms are highly educated (with a master's or Ph. D. degree). Most of the firms are in midstream industry. (42.7%), followed by downstream industry (29.1%) and upstream industry (28.2%). Regarding Taiwan's high technology industry sector, the largest proportion of the companies is in the computer component industry (28.6%). The smallest proportion is in the telecommunications industry (9.8%). The natural logarithm of profit, R&D investment, sales growth, and firm size is taken to improve normality because these variables' kurtosis is over 10 and is widely dispersed. In addition, to prevent the influence of outliers on empirical results, I exclude the observations that exceed than three standard deviations.

Table 13 contains descriptive statistics for both the firms that undertake cooperative R&D and for those that do not. It also shows the results of the Z-test. The data reveal that among cooperative firms, the average number of R&D cooperation events is 4.2 during 1998-2001. These cooperative firms show higher profits, invest more in R&D and produce more R&D outputs. In general, R&D cooperative firms face high knowledge spillovers and uncertainty, and have a greater firm size and absorptive capacity. Regarding industry sectors, optoelectronics, telecommunications, and computer peripheral industries have a higher percentage of R&D cooperation, while the computer component industry has a higher percentage of R&D competition. In summary, the two sub-samples behave differently with regard to financial performance, R&D investments, R&D outputs, knowledge spillovers, absorptive capacity, uncertainty, firm size, and industry sectors, etc.

The correlation matrix among various variables is presented in Table 14. R&D cooperation type and R&D cooperation intensity are positively and significantly correlated with profit, R&D investment, R&D output, knowledge spillover, absorptive capacity, and uncertainty. I utilize the Variance Inflation Factors (VIF) to further test the problem of multicollinearity among independent variables. All of the VIF values are under 10, indicating that there is no serious multicollinearity (Belsley, Kuh, and Welsch 1980).

Table 12: Descriptive statistics

Variable	N	Mean	Std. Dev.	Min	Max
R&D cooperation type	602	.4252492	.4947919	0	1
Generalized cooperation*	602	.1328904	.3397385	0	1
Vertical cooperation	602	.217608	.4129625	0	1
Horizontal cooperation	602	.0465116	.2107655	0	1
R&D cooperation intensity	602	1.666113	3.986643	0	49
Profit (thousand)	600	331493.7	2733730	-1.71e+07	4.73e+07
R&D investment (thousand)	600	151966.2	586118.5	0	1.06e+07
R&D output	602	-.0243801	1.601991	-.2244772	27.38801
Knowledge spillover	602	94.72591	76.74523	1	324
Uncertainty	602	-.8050133	1.675844	-3.365633	2.284041
Absorptive capacity	596	.0802146	.1087352	0	.7798
Sales growth	586	64.45734	768.4253	-70	14168
Capital structure	599	37.15693	16.31705	0	87
Firm size (thousand)	600	7283775	2.70e+07	117639	4.56e+08
Upstream	602	.282392	.4505374	0	1
Midstream	602	.4269103	.4950404	0	1
Downstream	602	.2906977	.4544619	0	1
Semiconductor	602	.1362126	.3432995	0	1
Optoelectronics	602	.1328904	.3397385	0	1
Telecommunications	602	.0980066	.2975709	0	1
Computer component	602	.2857143	.4521296	0	1
Computer peripheral	602	.2076412	.4059558	0	1
System and equipment	602	.1395349	.346792	0	1

Note:

* 17 sample firms only engaged R&D cooperation with academic institutions. I did not treat academic cooperation as one of the R&D cooperation categories because it is not my research interest in this study.

Table 13: Descriptive statistics for R&D cooperation and R&D competition

Variable	R&D cooperation	R&D competition	Z-value
N	258	346	
R&D cooperation intensity	4.186047	0	-12.4993***
Profit (thousand)	583269.2	109786.4	-2.0912**
R&D investment (thousand)	375954.3	32268.64	-5.7516***
R&D output	.2766713	-.206304	-3.5596***
Knowledge spillover	101.0194	89.90462	-1.7663*
Uncertainty	-.570489	-.9631044	-2.8556***
Absorptive capacity	.1116318	.0577137	-6.1720***
Sales growth	66.21371	62.53529	-0.0574
Capital structure	37.44706	36.87861	-0.4222
Firm size (thousand)	1.62e+07	1808886	-6.0088***
Upstream	.2945736	.2716763	-0.6182
Midstream	.3953488	.4537572	1.4348
Downstream	.3100775	.2745665	-0.9508
Semiconductor	.1589147	.1242775	-1.2164
Optoelectronics	.1782946	.0982659	-2.8851***
Telecommunications	.124031	.0780347	-1.8859*
Computer component	.1782946	.3641618	5.1056***
Computer peripheral	.2364341	.1849711	-1.5448
System and equipment	.124031	.150289	0.9217

Note:

Two-tail test; * significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level

Table 14: Correction matrix among dependent variables and independent variables

	1	2	3	4	5	6	7	8	9	10	11
1. R&D cooperation type	1.0000										
2. R&D cooperation intensity	0.4539***	1.0000									
3. Profit	0.0851**	0.2062***	1.0000								
4. R&D investment	0.2286***	0.7899***	0.1289***	1.0000							
5. R&D output	0.1436***	0.5483***	0.2295***	0.6858***	1.0000						
6. Knowledge spillover	0.0718*	0.0935**	0.0714*	0.0275	-0.0167	1.0000					
7. Uncertainty	0.1156***	0.1133***	-0.0186	0.1383***	0.0503	-0.2505***	1.0000				
8. Absorptive capacity	0.2451***	0.2583***	0.0594	0.2215***	0.1604***	-0.1061***	0.0774**	1.0000			
9. Sales growth	0.0024	-0.0130	-0.0023	-0.0174	-0.0104	-0.0214	0.0358	0.0011	1.0000		
10. Capital structure	0.0172	-0.0048	-0.1014**	-0.0220	-0.0091	0.0633	-0.0309	-0.2553***	-0.0188	1.0000	
11. Firm size	0.2382***	0.6999***	0.5354***	0.7739***	0.5477***	0.0473	0.1216***	0.1048**	-0.0119	0.0072	1.0000

Note:

Two-tail test; * significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

5.2 Hypotheses test

5.2.1 The determinants of R&D cooperation

1. The impact of knowledge spillovers, absorptive capacity, and uncertainty on R&D cooperation

In this section, I test the impact of knowledge spillovers, absorptive capacity, and uncertainty on the intensity of R&D cooperation. Because knowledge spillovers and uncertainty are industry level variables, and absorptive capacity is a firm level variable, I use the Hierarchical Linear Model (HLM) to test hypotheses 1, 2, and 3 in three steps (Bryk and Raudenbus 1992). First, I estimate a null model without variables at either firm-level or industry-level to partition the R&D cooperation intensity variance into within- and between-industry variance components. The models are specified as follows:

Level-1 Model

R&D cooperation intensity = B0 + R

Level-2 Model

B0 = G00 + U0

Then I can calculate the percentage of variance explained by the industry-level variables (Intraclass correlation coefficient, ICC):

$$ICC = \tau_{00} / \left(\tau_{00} + \sigma^2\right)$$

Second, in a firm-level analysis, R&D cooperation intensity is regressed on grand-mean-centered firm-level variables in this step, including absorptive capacity and firm size. The models are specified as follows:

Level-1 Model

R&D cooperation intensity = B0 + B1*(Absorptive capacity)+ B2* (Firm size) + R

Level-2 Model

B0 = G00 + U0

B1 = G10

B2 = G20

If we want to know how well absorptive capacity and firm size explain R&D cooperation intensity, we can compare the within-industry variances in a null model and firm-level model to obtain the proportion of variance explained by firm-level model:

$$R^2_{firm-level} = \frac{\left(Null\, \mathrm{mod}\, el\sigma^2 - Firm - level\, \mathrm{mod}\, el\sigma^2\right)}{Null\, \mathrm{mod}\, el\sigma^2}$$

In the third step, I use the intercept estimates obtained from firm-level analysis as outcome variables and regress on the industry-level variables, including knowledge spillovers and uncertainty (Intercept-as-Outcome model). The models are specified as follows:

Level-1 Model

R&D cooperation intensity = B0 + B1*(Absorptive capacity)+ B2* (Firm size) + R

Level-2 Model

B0 = G00 + G01*(Knowledge spillover) + G02*(Uncertainty) + U0

B1 = G10

B2 = G20

If we want to know how well knowledge spillovers and uncertainty explain R&D cooperation intensity after controlling firm-level variables, we can compare the between-industry variances in firm-level model and adding industry-level model to obtain the proportion of variance explained by adding industry-level model:

$$R^2_{industry-level} = \frac{\left(Firm - level\, \mathrm{mod}\, el\sigma^2 - Adding\ industry - level\, \mathrm{mod}\, el\sigma^2\right)}{Firm - level\, \mathrm{mod}\, el\sigma^2}$$

Examining null model in Table 15, results indicate that 20.18 percent of the variance is explained by industry-level variables, and 79.82 percent of the variance resides within industry. Level-1 variables are added in firm-level model. level-1 predictors are centered around their respective grand mean. Results of this model indicate that firm-level variables explain 32 percent of the within-industry variance. Absorptive capacity has significantly positive relationships with R&D cooperation intensity (Coef. =8.249728; p<0.001). Therefore, hypothesis 1 is supported. In addition, the results show that firm size has a positive and significant effect on R&D cooperation, in the sense that the larger the firm, the greater the propensity to cooperation (Coef. =1.788781; p<0.001), which is consistent with prior literature (e.g. Hagedoorn and Schakenraad 1994; Bayona et al 2001; Belderbos et al. 2004). While the cost of not joining an R&D cooperation may be measured in terms of a lag in the acquisition of new technology, the net benefits of free-riding may surpass those of cooperative status, especially for small companies (Corey 1997).

Adding industry-level variables model is significant. Level 2 variables account for 14 percent of the variance. As report in Table 15, knowledge spillovers demonstrate significant relationships with R&D cooperation intensity after controlling firm-level variables (Coef. =0.007913; p<0.001). However, uncertainty does not has significant relationships with R&D cooperation intensity (Coef.=0.369823; p>0.1). Hence, hypothesis 2 is supported, while hypothesis 3 is not.

2. The interaction between R&D cooperation types and the determinants of R&D cooperation.

I further use the Random Slopes and Intercepts Model[32] to test the interaction between R&D cooperation types and the determinants of R&D cooperation. The models are specified as follows:

Level-1 Model

R&D cooperation intensity = B0 + B1*(Absorptive capacity) + B2*(Horizontal cooperation) + B3*(Vertical cooperation) + B4*(Generalized cooperation) + B5* (Firm size) + R

Level-2 Model

B0 = G00 + G01*(Knowledge spillover) + G02*(Uncertainty) + U0

B1 = G10

B2 = G20 + G21*(Knowledge spillover) + G22*(Uncertainty) + G23* (Absorptive capacity)

B3 = G30 + G31*(Knowledge spillover) + G32*(Uncertainty) + G33* (Absorptive capacity)

B4 = G40 + G41*(Knowledge spillover) + G42*(Uncertainty) + G43*(Absorptive capacity)

B5 = G50

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[32] The Random Slopes and Intercepts Model combines the Intercept-as-Outcomes Model and Slopes-as-Outcomes Model so that both mean differences in intercept and the differences in slope can be evaluated by level-2 variables.

Interestingly, after considering the interaction between R&D cooperation types and the determinants of R&D cooperation, there is no significant result for knowledge spillovers, uncertainty, and absorptive capacity regarding horizontal cooperation and vertical cooperation. However, Table 15 shows, regarding generalized cooperation, that there is an increase in the strength of the relationship between knowledge spillovers and R&D cooperation intensity, and absorptive capacity and R&D cooperation intensity relative to R&D competition (Coef.=0.26752, $p<0.01$; Coef.=19.1129, $p<0.01$, respectively). Therefore, if knowledge spillovers and absorptive capacity are higher, companies are more likely to cooperate with their suppliers, customers, and competitors simultaneously. H4a and H4b are supported.

Table 15: The interaction between R&D cooperation types and the determinants of R&D cooperation

Dependent variable: R&D cooperation intensity				
Independent variable	Null Model	Firm-Level Variables	Adding Industry-Level Variables	Adding Interaction
Level-1				
Intercept	2.048296***	1.931547***	1.320930***	0.544344***
Absorptive capacity		8.249728***	8.426255***	3.959232**
Firm size		1.788781***	1.770733***	1.093871***
Horizontal cooperation				1.678760***
Vertical cooperation				0.440670
Generalized cooperation				1.098134
Level-2				
Knowledge spillover			0.007963***	0.002105*
Uncertainty			0.369823	0.107120
Interaction				
Horizontal cooperation*Absorptive capacity				0.545536
Horizontal cooperation*Uncertainty				-0.109662
Horizontal cooperation*Knowledge spillover				-0.003635
Vertical cooperation*Absorptive capacity				2.815761
Vertical cooperation* Uncertainty				0.178070

Vertical cooperation*Knowledge spillover				0.000499
Generalized cooperation*Absorptive capacity				19.112900***
Generalized cooperation* Uncertainty				1.435124
Generalized cooperation*Knowledge spillover				0.026752***
Within-industry residual variance (σ^2)	18.53	12.58	12.58	10.05
Between-industries variance (τ_{00})	4.68***	1.71***	1.47***	1.05***
$R^2_{\text{within-industry}}$[a]		0.32		
$R^2_{\text{between-industries}}$[b]			0.14	
Model deviance	3380.83	3145.43	3147.02	3017.75

Note:

Companies n=581, Industries=18. Entries are estimations of the fixed effects with robust standard errors.

[a] Proportion of within-industry variance explained by level-1 variables.

[b] Proportion of between-industry variance explained by industry-level variables (after level-1 variables are controlled for).

* significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

5.2.2 The impact of R&D cooperation on R&D investments, R&D outputs, and financial performance

1. The impact of R&D cooperation intensity on R&D investments, R&D outputs, and financial performance

To avoid sample selection bias, I use the Heckman two-step model to test H5a, H5b, and H5c. The first step is to use probit model to examine the factors of R&D cooperation for the whole sample. Therefore, I test H1, H2, and H3 again. The model is as follows:

Model 1 (R&D cooperation type probit regression): Regressing R&D cooperation type on Absorptive capacity, Knowledge spillover, and Uncertainty:

$$\begin{aligned} R\,\&\,D\ cooperation\ type = {} & \beta_0 + \beta_1 absorptive\ capacity + \beta_2 Knowledge\ spillover \\ & + \beta_3 Uncertainty + \beta_4 Firm\ size + \varepsilon \end{aligned}$$

In the second step, I calculate inverse Mill's ratio from the first step to be an adjusted item and use R&D cooperative companies as a research sample to examine the impact of R&D cooperation on R&D investments, R&D outputs, and financial performance. The models are as follows:

Model 2 (R&D investment regression): Regressing R&D investment on R&D cooperation intensity:

$$\begin{aligned} \mathrm{R}\,\&\,D\ investment = {} & \beta_0 + \beta_1 R\,\&\,D\ cooperation\ intensity + \beta_2 Sales\ growth \\ & + \beta_3 Capital\ structure + \beta_4 Firm\ size + \beta_5 Upstream \\ & + \beta_6 Midstream + \beta_7 Optoelectronics + \beta_8 Telecommunications \\ & + \beta_9 Component + \beta_{10} Computer\ peripheral + \beta_{11} Other + \varepsilon \end{aligned}$$

Model 3 (R&D output regression): Regressing R&D output on R&D cooperation intensity:

$$\begin{aligned} \mathrm{R}\,\&\,D\ output = {} & \beta_0 + \beta_1 R\,\&\,D\ cooperation\ intensity + \beta_2 Sales\ growth \\ & + \beta_3 Capital\ structure + \beta_4 Firm\ size + \beta_5 Upstream \\ & + \beta_6 Midstream + \beta_7 Optoelectronics + \beta_8 Telecommunications \\ & + \beta_9 Component + \beta_{10} Computer\ peripheral + \beta_{11} Other + \varepsilon \end{aligned}$$

Model 4 (Profit regression): Regressing Profit on R&D cooperation intensity:

$$\begin{aligned} Profit = {} & \beta_0 + \beta_1 R\&D\ cooperation\ intensity + \beta_2 Sales\ growth + \beta_3 Capital\ structure \\ & + \beta_4 Firm\ size + \beta_5 Upstream + \beta_6 Midstream + \beta_7 Optoelectronics \\ & + \beta_8 Telecommunications + \beta_9 Component + \beta_{10} Computer\ peripheral \\ & + \beta_{11} Other + \varepsilon \end{aligned}$$

In Model 1 of Table 16, empirical results show that the coefficients of absorptive capacity, knowledge spillover, and uncertainty are all positive and significant (Z=6.04, p<0.01l Z=1.73, p<0.1; Z=2.82, p<0.01, respectively). These results show that when absorptive capacity, knowledge spillovers, and uncertainty are higher, companies engage in R&D cooperation more frequently. The empirical results further support H1, H2. However, the result of H3 is contrary to the result of HLM. Because the variables of uncertainty is an industry-level variable and HLM is used to know how factors across different levels interact with one another and jointly determine the intensity of R&D cooperation. Hence, the result of HLM is more robust than that of Probit regression.

The impact of R&D cooperation intensity on R&D investments, R&D outputs, and financial performance is shown in Table 16. The coefficient of R&D cooperation intensity in Model 2 is positive and significant (t=2.49; p<0.05). This means that R&D cooperation has a positive impact on R&D investments, which supports H5a. The coefficient of R&D cooperation intensity in Model 3 is also positive and significant (t=11.03; p<0.01). This means that R&D cooperation has a positive impact on R&D outputs, which supports H5b. Regarding financial performance, the coefficient of R&D cooperation intensity in the profit regression model (Model 4) is positive and significant (t=3.35; p<0.01). This means that R&D cooperation has a positive impact on profit. The result supports H5c.

Table 16: The impact of R&D cooperation intensity on R&D investments, R&D outputs, and financial performance—Heckman two-step model

	Model 1		Model 2		Model 3		Model 4	
	Dependent variable: R&D cooperation type		Dependent variable: R&D investment		Dependent variable: R&D output		Dependent variable: profit	
Independent variables	Coef.	Z-value	Coef.	t-value	Coef.	t-value	Coef.	t-value
R&D cooperation intensity			.1088185	2.49**	.1493304	11.03***	.0048524	3.35***
Absorptive capacity	3.517169	6.04						
Knowledge spillover	.0014179	1.73						
Uncertainty	.1032128	2.82						
Sales growth			.1271074	0.66	.0184954	0.25	.0185296	1.90*
Capital structure			-.0289435	-3.34***	.0012949	0.39	-.002108	-4.93***
Firm size	.5917384	10.34	.1666954	0.69	.0989728	1.07	.0209127	1.70*
Upstream			.5566342	1.48	-.0910848	-0.64	-.0032864	-0.18
Midstream			1.310687	3.99***	.06163	0.49	-.0324389	-1.98
Optoelectronics			-.376435	-0.75	-.4788096	-2.47**	.016557	0.66
Telecommunications			-.2526581	-0.47	-.7351118	-3.54***	.0585871	2.13**
Computer component			-1.940495	-3.55***	-.4905255	-2.37**	.0591023	2.23**
Computer peripheral			.1283916	0.27	-.4730079	-2.63***	.0879492	3.79***
System and equipment			-1.261879	-2.40**	-.5708449	-2.83***	.0339421	1.31
Inverse Mill’s Ratio			-1.554908	-2.30**	.3480231	1.35	.0156767	0.45
_cons	-9.10099	-10.89	9.699255	2.38**	-1.921345	-1.22	16.2967	78.21***
N	596		232		243		237	
Psuedo R2	0.2400		0.4299		0.5325		0.2167	
F-value			15.52***		23.97***		6.44***	

Note: * significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

In order to compare the performance of R&D cooperation vs. R&D competition, I use treatment effects model and retain the entire sample for the second-step regression and treat the variable of R&D cooperation type as endogenous. The models are as follows:

Model 1 (R&D cooperation type probit regression): Regressing R&D cooperation type on Absorptive capacity, Knowledge spillover, and Uncertainty:

$$\begin{aligned} R\ \&\ D\ cooperation\ type = {} & \beta_0 + \beta_1 absorptive\ capacity + \beta_2 Knowledge\ spillover \\ & + \beta_3 Uncerta\,\mathrm{int}\,y + \beta_4 Firm\ size + \varepsilon \end{aligned}$$

Model 2 (R&D investment regression): Regressing R&D investment on R&D cooperation intensity and R&D cooperation type:

$$\begin{aligned} \mathrm{R}\ \&\ D\ investment = {} & \beta_0 + \beta_1 R\ \&\ D\ cooperation\,\mathrm{int}\,ensity + \beta_2 R\ \&\ D\ cooperation\ \mathrm{type} \\ & + \beta_3 Sales\ growth + \beta_4 Capital\ structure + \beta_5 Firm\ size + \beta_6 Upstream \\ & + \beta_7 Midstream + \beta_8 Optoelectronics + \beta_9 Telecommunications \\ & + \beta_{10} Component + \beta_{11} Computer\ \ peripheral + \beta_{12} Other + \varepsilon \end{aligned}$$

Model 3 (R&D output regression): Regressing R&D output on R&D cooperation intensity and R&D cooperation type:

$$\begin{aligned} \mathrm{R}\ \&\ D\ \mathrm{ouptut} = {} & \beta_0 + \beta_1 R\ \&\ D\ cooperation\,\mathrm{int}\,ensity + \beta_2 R\ \&\ D\ cooperation\ \mathrm{type} \\ & + \beta_3 Sales\ growth + \beta_4 Capital\ structure + \beta_5 Firm\ size + \beta_6 Upstream \\ & + \beta_7 Midstream + \beta_8 Optoelectronics + \beta_9 Telecommunications \\ & + \beta_{10} Component + \beta_{11} Computer\ \ peripheral + \beta_{12} Other + \varepsilon \end{aligned}$$

Model 4 (Profit regression): Regressing Profit on R&D cooperation intensity and R&D cooperation type:

$$
\begin{aligned}
\Pr ofit = {} & \beta_0 + \beta_1 R\,\&\,D\ cooperation\ \text{int}ensity + \beta_2 R\,\&\,D\ cooperation\ \text{type} \\
& + \beta_3 Sales\ growth + \beta_4 Capital\ structure + \beta_5 Firm\ size + \beta_6 Upstream \\
& + \beta_7 Midstream + \beta_8 Optoelectronics + \beta_9 Telecommunications \\
& + \beta_{10} Component + \beta_{11} Computer\ peripheral + \beta_{12} Other + \varepsilon
\end{aligned}
$$

Table 17 reports the treatment effects model that control for self-selection using full sample. The first-step probit model reports that higher absorptive capacity, knowledge spillovers, and uncertainty are likely to engage in R&D cooperation (Model 1). In the second step (Model 2, 3 and 4), the coefficient on R&D cooperation intensity is still positive and statistically significant which is consistent with the results of Heckman two-step model. However, the coefficient on R&D cooperation type is insignificant except Model 2 (R&D investment regression). This means that R&D cooperation is not enough for the firms to gain higher R&D outputs and financial performance. R&D cooperation intensity is the main drivers for improving R&D outputs and financial performance.

Table 17: The impact of R&D cooperation intensity on R&D investments, R&D outputs, and financial performance—Treatment effects model

	Model 1		Model 2		Model 3		Model 4	
	Dependent variable: R&D cooperation type		Dependent variable: R&D investment		Dependent variable: R&D output		Dependent variable: profit	
Independent variables	Coef.	Z-value	Coef.	t-value	Coef.	t-value	Coef.	t-value
R&D cooperation intensity			.1215369	1.93**	.0559059	9.97***	.0032288	4.56***
R&D cooperation type			3.946434	3.08***	-.0656694	-0.65	.021107	1.23
Absorptive capacity	3.569024	6.24***						
Knowledge spillover	.002089	2.55**						
Uncertainty	.1076634	2.86***						
Sales growth			.0636759	0.28	.0070297	0.42	.0118905	4.12***
Capital structure			-.0428587	-4.71***	.0009179	1.32	-.000607	-5.06***
Firm size	.5752795	10.31***	.1011202	0.40	.0423711	2.15**	.0079005	2.32**
Upstream			.8093722	2.14**	.0331422	1.14	.0015167	0.31
Midstream			2.043718	5.87***	.0288706	1.08	.000042	0.01
Optoelectronics			.2357682	0.41	-.0699464	-1.60	.0170329	2.26**
Telecommunications			-.0024564	-0.00	-.1211725	-2.53**	.0211142	2.56**
Computer component			-.9822309	-1.83*	-.1061002	-2.57**	.028062	3.97***
Computer peripheral			.2146275	0.41	-.037088	-0.93	.0300923	4.37***
System and equipment			-.3566659	-0.65	-.103397	-2.44**	.0197959	2.74***
Inverse Mill’s Ratio			-1.863144	-2.44**	-.0266216	-0.45	-.0176462	-1.74*
_cons	-9.09785	-11.09***	6.720394	1.97**	-.8201615	-3.12***	16.4908	363.20***
N	598		581		576		569	
Psuedo R2	0.2544		0.2522		0.3354		0.2110	
F-value			16.05***		23.32***		12.68***	

Note: * significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

2. The impact of different R&D cooperation types on R&D investments, R&D outputs, and financial performance

I further test the impact of different R&D cooperation types on R&D investments, R&D outputs, and financial performance. I also consider the impact of interaction between different R&D cooperation and knowledge spillovers. The models are as follows:

Model 1 (R&D investment regression): Regressing R&D investment on Vertical cooperation, Horizontal cooperation, and Generalized cooperation:[33]

$$\begin{aligned} \mathrm{R}\ \&\ D\ \textit{investment} = {} & \beta_0 + \beta_1 \textit{Vertical cooperation} + \beta_2 \textit{Horizontal cooperation} \\ & + \beta_3 \textit{Gernalized cooperation} + \beta_4 \textit{Sales growth} + \beta_5 \textit{Capital structure} \\ & + \beta_6 \textit{Firm size} + \beta_7 \textit{Upstream} + \beta_8 \textit{Midstream} + \beta_9 \textit{Optoelectronics} \\ & + \beta_{10} \textit{Telecommunications} + \beta_{11} \textit{Component} + \beta_{12} \textit{Computer peripheral} \\ & + \beta_{13} \textit{Other} + \varepsilon \end{aligned}$$

Model 2 (R&D investment regression): Regressing R&D investment on Vertical cooperation, Horizontal cooperation, Generalized cooperation, and the interaction with Knowledge spillover:

$$\begin{aligned} \mathrm{R}\ \&\ D\ \textit{investment} = {} & \beta_0 + \beta_1 \textit{Vertical cooperation} + \beta_2 \textit{Horizontal cooperation} \\ & + \beta_3 \textit{Gerneralized cooperation} + \beta_4 \textit{Knowledge spillover} \\ & + \beta_5 \textit{Vertical cooperation} * \textit{Knowledge spillover} \\ & + \beta_6 \textit{Horizontal cooperation} * \textit{Knowledge spillover} \\ & + \beta_7 \textit{Gerneralized cooperation} * \textit{Knowledge spillover} \\ & + \beta_8 \textit{Sales growth} + \beta_9 \textit{Capital structure} + \beta_{10} \textit{Firm size} + \beta_{11} \textit{Upstream} \\ & + \beta_{12} \textit{Midstream} + \beta_{13} \textit{Optoelectronics} + \beta_{14} \textit{Telecommunications} \\ & + \beta_{15} \textit{Component} + \beta_{16} \textit{Computer peripheral} + \beta_{17} \textit{Other} + \varepsilon \end{aligned}$$

Model 3 (R&D output regression): Regressing R&D output on Vertical cooperation, Horizontal cooperation, and Generalized cooperation:

$$\begin{aligned} \mathrm{R}\ \&\ D\ \mathrm{output} = {} & \beta_0 + \beta_1 \textit{Vertical cooperation} + \beta_2 \textit{Horizontal cooperation} \\ & + \beta_3 \textit{Gernalized cooperation} + \beta_4 \textit{Sales growth} + \beta_5 \textit{Capital structure} \\ & + \beta_6 \textit{Firm size} + \beta_7 \textit{Upstream} + \beta_8 \textit{Midstream} + \beta_9 \textit{Optoelectronics} \\ & + \beta_{10} \textit{Telecommunications} + \beta_{11} \textit{Component} + \beta_{12} \textit{Computer peripheral} \\ & + \beta_{13} \textit{Other} + \varepsilon \end{aligned}$$

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[33] The variable of R&D competition is used as a reference variable.

Model 4 (R&D output regression): Regressing R&D output on Vertical cooperation, Horizontal cooperation, Generalized cooperation, and the interaction with Knowledge spillover:

$$\begin{aligned}\mathrm{R\,\&}\,D\,\mathrm{output} = {} & \beta_0 + \beta_1 Vertical\ cooperation + \beta_2 Horizontal\ cooperation \\ & + \beta_3 Gerneralized\ cooperation + \beta_4 Knowledge\ spillover \\ & + \beta_5 Vertical\ cooperation * Knowledge\ spillover \\ & + \beta_6 Horizontal\ cooperation * Knowledge\ spillover \\ & + \beta_7 Gerneralized\ cooperation * Knowledge\ spillover \\ & + \beta_8 Sales\ growth + \beta_9 Capital\ structure + \beta_{10} Firm\ size + \beta_{11} Upstream \\ & + \beta_{12} Midstream + \beta_{13} Optoelectronics + \beta_{14} Telecommunications \\ & + \beta_{15} Component + \beta_{16} Computer\ peripheral + \beta_{17} Other + \varepsilon\end{aligned}$$

Model 5 (Profit regression): Regressing Profit on Vertical cooperation, Horizontal cooperation, and Generalized cooperation:

$$\begin{aligned}\mathrm{Profit} = {} & \beta_0 + \beta_1 Vertical\ cooperation + \beta_2 Horizontal\ cooperation \\ & + \beta_3 Gernalized\ cooperation + \beta_4 Sales\ growth + \beta_5 Capital\ structure \\ & + \beta_6 Firm\ size + \beta_7 Upstream + \beta_8 Midstream + \beta_9 Optoelectronics \\ & + \beta_{10} Telecommunications + \beta_{11} Component + \beta_{12} Computer\ peripheral \\ & + \beta_{13} Other + \varepsilon\end{aligned}$$

Model 6 (Profit regression): Regressing Profit on Vertical cooperation, Horizontal cooperation, Generalized cooperation, and the interaction with Knowledge spillover:

$$\begin{aligned}\mathrm{Pr}\,ofit = {} & \beta_0 + \beta_1 Vertical\ cooperation + \beta_2 Horizontal\ cooperation \\ & + \beta_3 Gerneralized\ cooperation + \beta_4 Knowledge\ spillover \\ & + \beta_5 Vertical\ cooperation * Knowledge\ spillover \\ & + \beta_6 Horizontal\ cooperation * Knowledge\ spillover \\ & + \beta_7 Gerneralized\ cooperation * Knowledge\ spillover \\ & + \beta_8 Sales\ growth + \beta_9 Capital\ structure + \beta_{10} Firm\ size + \beta_{11} Upstream \\ & + \beta_{12} Midstream + \beta_{13} Optoelectronics + \beta_{14} Telecommunications \\ & + \beta_{15} Component + \beta_{16} Computer\ peripheral + \beta_{17} Other + \varepsilon\end{aligned}$$

Table 18 presents the impact of different R&D cooperation types on R&D investments, R&D outputs, and financial performance. Models 1, 3, and 5 show the estimation results with the base models. The results show that vertical cooperation and generalized cooperation significantly and positively affect R&D investments (t=3.14, t<0.01; t=2.25, t<0.05). In addition, generalized cooperation also leads to higher R&D outputs and profits (t=4.26, t<0.01; t=2.38; t<0.05). In Models 2, 4, and 6, I add knowledge spillovers and the interaction between R&D cooperation and knowledge spillovers in the regressions. The findings provide very similar results as above. It is found that Vertical cooperation * Knowledge spillover and Generalized cooperation*Knowledge spillover have positive effects on R&D investments. Although the coefficient of Vertical cooperation*Knowledge spillover (0.0125045) is larger than that of Generalized cooperation*Knowledge spillover (0.0090275), the difference is not significant (F=0.32, p=0.5727). Therefore, vertical cooperation and generalized cooperation both invest more in R&D relative to horizontal cooperation and R&D competition when knowledge spillovers are higher, and H6a is moderately supported. In Models 4 and 6, I find that the coefficients of Generalized cooperation*Knowledge spillover both have positive effects on R&D outputs and profits (t=2.69, p<0.01; t=5.91, p<0.01). These findings indicate that when knowledge spillovers are higher, generalized cooperation can lead to higher R&D outputs and profits relative to other R&D cooperation types. Thus H6b and H6c are supported.

Table 18: The impact of different R&D cooperation types on R&D investments, R&D outputs, and financial performance

	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6	
	Dependent variable: R&D investment		Dependent variable: R&D investment		Dependent variable: R&D output[34]		Dependent variable: R&D output		Dependent variable: Profit		Dependent variable: Profit	
Independent variables	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value
Vertical cooperation	1.222772	3.14***	.4131625	0.74	.0100367	0.58	-.0040158	-0.16	-.0013308	-0.23	-.0056685	-0.71
Horizontal cooperation	-.6806009	-0.96	-1.125567	-0.98	-.0381425	-1.22	-.0311551	-0.61	-.0074627	-0.72	-.0132695	-0.81
Generalized cooperation	1.154383	2.25**	.0457696	0.06	.0980286	4.26***	.0261674	0.74	.018125	2.38**	-.033706	-2.96***
Knowledge spillover			-.0108314	-3.01***			-.0001082	-0.67			-.0000204	-0.40
Vertical cooperation * Knowledge spillover			.0090275	2.08**			.0001871	0.95			.0000704	1.12
Horizontal cooperation * Knowledge spillover			.0055933	0.63			-.0000209	-0.05			.0000813	0.64
Generalized cooperation * Knowledge spillover			.0125045	2.15**			.0006911	2.69***			.0004981	5.91***
Sales growth	-.0880232	-0.39	-.0507862	-0.23	.0035592	0.35	.003193	0.32	.0148265	4.42***	.0144372	4.42***
Capital structure	-.0506867	-5.44***	-.0503852	-5.41***	.0001217	0.29	.0002	0.48	-.0006266	-4.51***	-.0005764	-4.25***
Firm size	.8214437	6.28***	.7759058	5.90***	.0399771	6.43***	.0366618	5.80***	.0145043	7.03***	.0128751	6.36***
Upstream	.7875584	2.01**	.4800901	1.11	.0128476	0.73	.0170792	0.89	.0004926	0.09	.0061544	1.00

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[34]

Midstream	1.897476	5.38***	1.880061	5.23***	.0167572	1.06	.0220489	1.37	-.0053422	-1.01	-.0008259	-0.16
Optoelectronics	.0466146	0.08	.0016619	0.00	.000599	0.02	-.0006121	-0.02	.0182017	2.09**	.0150794	1.77*
Telecommunications	-.0845574	-0.13	.0402893	0.06	-.042567	-1.47	-.0452526	-1.55	.0227114	2.36**	.0178307	1.88*
Computer component	-1.536795	-3.11***	-1.664756	-3.36***	-.0529776	-2.33**	-.0587904	-2.59***	.0269065	3.61***	.0218431	2.99***
Computer peripheral	.0707791	0.13	.8287599	1.23	.0044577	0.18	-.0051804	-0.17	.0371416	4.68***	.0234297	2.37**
System and equipment	-.5895006	-1.06	-.559017	-1.00	-.0460872	-1.84*	-.0497643	-1.98*	.0196246	2.38**	.0153534	1.90*
_cons	-1.276931	-0.58	.1498993	0.07	-.7673383	-7.53***	-.7112588	-6.82***	16.39586	484.21***	16.42248	489.11***
N	571		571		555		555		558		556	
Adj. R2	0.2526		0.2620		0.1939		0.1991		0.1699		0.1902	
F-value	15.82***		12.91***		11.25***		9.10***		9.77***		8.67***	

Note: * significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

3. The direct and indirect impact of R&D cooperation intensity on R&D investments, R&D outputs, and financial performance

To understand the direct and indirect impact of R&D cooperation intensity on R&D investments, R&D outputs, and financial performance, I further use path analysis to examine their relationship. The models are as follows:

Model 1: Regressing Profit on R&D cooperation intensity:

$$\begin{aligned} \mathrm{Pr}\mathit{ofit} = {} & \beta_0 + \beta_1 R\,\&\,D\ cooperation\ \mathrm{int}\mathit{ensity} + \beta_2 Sales\ growth \\ & + \beta_3 Capital\ structure + \beta_4 Firm\ size + \beta_5 Upstream \\ & + \beta_6 Midstream + \beta_7 Optoelectronics + \beta_8 Telecommunications \\ & + \beta_9 Component + \beta_{10} Computer\ peripheral + \beta_{11} Other + \varepsilon \end{aligned}$$

Model 2: Regressing R&D investment on R&D cooperation intensity:

$$\begin{aligned} \mathrm{R}\,\&\,D\ investment = {} & \beta_0 + \beta_1 R\,\&\,D\ cooperation\ \mathrm{int}\mathit{ensity} + \beta_2 Sales\ growth \\ & + \beta_3 Capital\ structure + \beta_4 Firm\ size + \beta_5 Upstream \\ & + \beta_6 Midstream + \beta_7 Optoelectronics + \beta_8 Telecommunications \\ & + \beta_9 Component + \beta_{10} Computer\ peripheral + \beta_{11} Other + \varepsilon \end{aligned}$$

Model 3: Regressing R&D output on R&D cooperation intensity and R&D investment:

$$\begin{aligned} R\,\&\,D\ output = {} & \beta_0 + \beta_1 R\,\&\,D\ cooperation\ \mathrm{int}\mathit{ensity} + \beta_2 R\,\&\,D\ investment \\ & + \beta_3 Sales\ growth + \beta_4 Capital\ structure + \beta_5 Firm\ size + \beta_6 Upstream \\ & + \beta_7 Midstream + \beta_8 Optoelectronics + \beta_9 Telecommunications \\ & + \beta_{10} Component + \beta_{11} Computer\ peripheral + \beta_{12} Other + \varepsilon \end{aligned}$$

Model 4: Regressing Profit on R&D investment:

$$\begin{aligned} \mathrm{Pr}\mathit{ofit} = {} & \beta_0 + \beta_1 R\,\&\,D\ investment + \beta_2 Sales\ growth + \beta_3 Capital\ structure + \beta_4 Firm\ size \\ & + \beta_5 Upstream + \beta_6 Midstream + \beta_7 Optoelectronics + \beta_8 Telecommunications \\ & + \beta_9 Component + \beta_{10} Computer\ peripheral + \beta_{11} Other + \varepsilon \end{aligned}$$

Model 5: Regressing Profit on R&D output:

$$\begin{aligned} \mathrm{Pr}\mathit{ofit} = {} & \beta_0 + \beta_1 R\,\&\,D\ output + \beta_2 Sales\ growth + \beta_3 Capital\ structure + \beta_4 Firm\ size \\ & + \beta_5 Upstream + \beta_6 Midstream + \beta_7 Optoelectronics + \beta_8 Telecommunications \\ & + \beta_9 Component + \beta_{10} Computer\ peripheral + \beta_{11} Other + \varepsilon \end{aligned}$$

Model 6: Regressing Profit on R&D cooperation intensity and R&D investment:

$$\begin{aligned}\mathrm{Pr}\mathit{ofit} = {} & \beta_0 + \beta_1 R\,\&\,D\,\mathit{cooperation}\,\mathrm{int}\mathit{ensity} + \beta_2 R\,\&\,D\,\mathit{investment} + \beta_3 \mathit{Sales\ growth} \\ & + \beta_4 \mathit{Capital\ structure} + \beta_5 \mathit{Firm\ size} + \beta_6 \mathit{Upstream} + \beta_7 \mathit{Midstream} + \beta_8 \mathit{Optoelectronics} \\ & + \beta_9 \mathit{Telecommunications} + \beta_{10} \mathit{Component} + \beta_{11} \mathit{Computer\ peripheral} + \beta_{12} \mathit{Other} + \varepsilon\end{aligned}$$

Model 7: Regressing Profit on R&D cooperation intensity and R&D output:

$$\begin{aligned}\mathrm{Pr}\mathit{ofit} = {} & \beta_0 + \beta_1 R\,\&\,D\,\mathit{cooperation}\,\mathrm{int}\mathit{ensity} + \beta_3 R\,\&\,D\,\mathit{output} + \beta_3 \mathit{Sales\ growth} \\ & + \beta_4 \mathit{Capital\ Structure} + \beta_5 \mathit{Firm\ size} + \beta_6 \mathit{Upstream} + \beta_7 \mathit{Midstream} + \beta_8 \mathit{Optoelectronics} \\ & + \beta_9 \mathit{Telecommunications} + \beta_{10} \mathit{Component} + \beta_{11} \mathit{Computer\ peripheral} + \beta_{12} \mathit{Other} + \varepsilon\end{aligned}$$

Model 8: Regressing Profit on R&D cooperation intensity, R&D investments, and R&D output:

$$\begin{aligned}\mathrm{Pr}\mathit{ofit} = {} & \beta_0 + \beta_1 R\,\&\,D\,\mathit{cooperation}\,\mathrm{int}\mathit{ensity} + \beta_2 R\,\&\,D\,\mathrm{investment} + \beta_3 R\,\&\,D\,\mathit{output} \\ & + \beta_4 \mathit{Sales\ growth} + \beta_5 \mathit{Capital\ structure} + \beta_6 \mathit{Firm\ size} + \beta_7 \mathit{Upstream} + \beta_8 \mathit{Midstream} \\ & + \beta_9 \mathit{Optoelectronics} + \beta_{10} \mathit{Telecommunications} + \beta_{11} \mathit{Component} + \beta_{12} \mathit{Computer\ peripheral} \\ & + \beta_{13} \mathit{Other} + \varepsilon\end{aligned}$$

Table 19 shows the path analysis between R&D cooperation intensity, R&D investments, R&D outputs, and financial performance in 2001. I find that R&D cooperation intensity has a direct effect on Profit (t=6.92, p<0.01), R&D investment (t=2.60, p<0.01), and R&D output (t=17.30, p<0.01) in Model 1, 2 and 3, which are consistent with the results of Heckman two-step model and treatment effects model. R&D investment has no direct effect on Profit (t=0.37, p=0.713) in Model 4. Therefore, H7a is not supported. In addition, the coefficient of R&D cooperation intensity becomes slightly larger (The coefficient of R&D cooperation intensity is changed from 0.311 in Model 1 to 0.313 in Model 6) after controlling for the effect of R&D investments on financial performance (t=6.92, p<0.01) in Model 6. Hence, H8a is not supported which indicate that the impact of R&D cooperation intensity on financial performance is not mediated by R&D investments. In contrast, R&D output has a positive impact on profit (t=10.55, p<0.01) in Model 5, which supports H7b. Once I control for the effect of R&D outputs on financial performance, the direct effect of R&D cooperation intensity on profit no longer exists (t=1.34, p=0.181) (Model 7). Together, these findings support H8b's prediction that the effect of R&D cooperation on financial performance is mediated by R&D outputs. See Figure 6 for the path between R&D cooperation, R&D investments, R&D outputs, and financial performance.

Table 19: The path analysis between R&D cooperation intensity, R&D investments, R&D outputs, and financial performance

	Model 1		Model 2		Model 3	
	Dependent variable: Profit		Dependent variable: R&D investment		Dependent variable: R&D output	
Independent variables:	Coef.	t-value	Coef.	t-value	Coef.	t-value
R&D cooperation intensity	.310924	6.92***	.1143941	2.60***	.6550353	17.30***
R&D investment					-.0522751	-1.45
R&D output						
Sales growth	.1135411	2.89***	-.0214036	-0.56	.0196114	0.60
Capital structure	-.1986721	-5.00***	-.2022589	-5.19***	-.0304236	-0.89
Firm size	.1587066	3.39***	.247595	5.40***	.0032276	0.08
Upstream	-.0058575	-0.13	.1022043	2.23**	-.0343485	-0.88
Midstream	-.0534298	-1.15	.2284298	5.01***	.0544386	1.37
Optoelectronics	.0243313	0.47	.030012	0.59	-.1084808	-2.49**
Telecommunications	.0947205	1.91*	.0233555	0.48	-.1197046	-2.88***
Computer component	.1935287	3.19***	-.1702806	-2.86***	-.0912834	-1.78*
Computer peripheral	.1988898	3.49***	.0163349	0.29	-.1201103	-2.52**
System and equipment	.0823636	1.58	-.0435842	-0.85	-.1025022	-2.34**
N	577		577		577	
Adj. R2	0.1985		0.2282		0.4378	

Note: * significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

Table 19: The path analysis between R&D cooperation intensity, R&D investments, R&D outputs, and financial performance (cont.)

	Model 4		Model 5		Model 6		Model 7		Model 8	
	Dependent variable: Profit		Dependent variable: Profit		Dependent variable: Profit		Dependent variable: Profit		Dependent variable: Profit	
Independent variables:	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value
R&D cooperation intensity					.3127386	6.92***	.0706144	1.34	.0700509	1.32
R&D investment	.0163585	0.37			-.0158633	-0.37			.0035044	0.09
R&D output			.4077024	10.55***			.3702451	7.76***	.3704956	7.75***
Sales growth	.1154766	2.82***	.1053268	2.81***	.1132016	2.88***	.1058658	2.83***	.1059356	2.83***
Capital structure	-.209904	-4.96***	-.1927574	-5.09***	-.2018805	-4.96***	-.1913225	-5.06***	-.1906087	-4.92***
Firm size	.3189568	7.24***	.1872832	4.64***	.1626343	3.39***	.1623037	3.65***	.1614384	3.54***
Upstream	.0153995	0.32	.0137599	0.31	-.0042362	-0.09	.008838	0.20	.0084897	0.19
Midstream	-.0390159	-0.79	-.0680368	-1.54	-.0498062	-1.05	-.0691643	-1.56	-.0699755	-1.54
Optoelectronics	-.0170982	-0.32	.0630654	1.27	.0248074	0.48	.0650767	1.31	.064999	1.31
Telecommunications	.0788313	1.53	.1416988	2.99***	.095091	1.92**	.1394926	2.94***	.139441	2.94***
Computer component	.1293679	2.05**	.2170861	3.76***	.1908275	3.12***	.2240302	3.87***	.2246476	3.85***
Computer peripheral	.1641517	2.78***	.2430428	4.46***	.199149	3.49***	.2436762	4.47***	.2436493	4.47***
System and equipment	.06866	1.26	.1210652	2.43**	.0816722	1.56	.119471	2.40**	.1196488	2.39**
N	577		577		577		577		577	
Adj. R2	0.1307		0.2735		0.1987		0.2758		0.2758	

Note: * significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

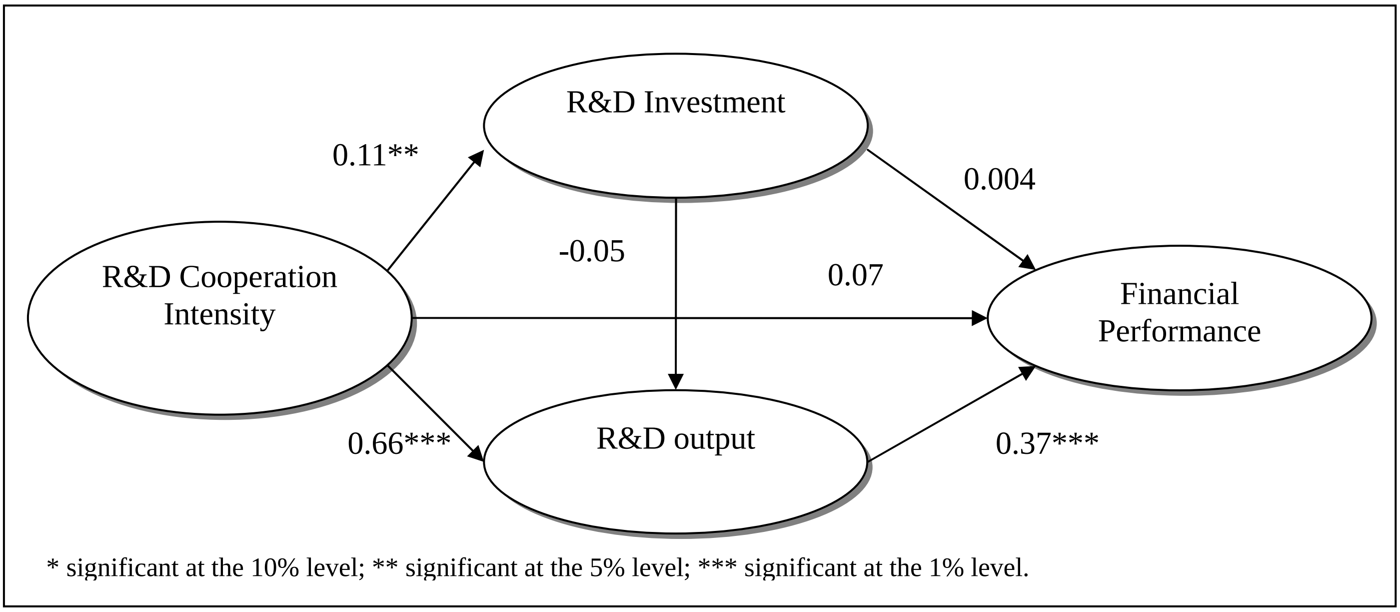

Figure 6: The path between R&D cooperation intensity, R&D investments, R&D outputs, and financial performance

5.3 Robustness test

5.3.1 Sensitivity analysis for R&D investments, R&D outputs, and financial performance

In order to test the reliability of empirical results, I use alternative variables to proxy R&D investments, R&D outputs, and financial performance. Firstly, in accordance with previous research (e.g. Bharadwaj et al. 1999; Shrader 2001; Hall and Bagchi-Sen 2002; Sakakibara 2002, Hernan et al. 2003; Negassi 2004; Lin and Chen 2005; Huang and Liu 2005 Yu et al. 2005), this study adopts R&D intensity, measured as the ratio of R&D expenditures to net operating sales, to proxy R&D investments. Secondly, according to the U.S. patent law, a patent can be classified into two categories: utility patent and design patent. Utility patent protects the way an invention works. Design patent protects only the appearance of an article. The legal effects of these two patents are also different in terms of the protection period: 20 years for an utility patent and 14 years for a design patent. Apparently, the technical level and commercial value of utility patents is much higher than that of design patents. Therefore, in addition to prior indicators of R&D output quantity and R&D output quality, I add the ratio of utility patents to the total number of patents as another indicator of R&D output quality. I also employ PCA to extract the single factor of R&D

outputs. The first principal components derived form PCA explains 71.36% of the observed variation. Thirdly, regarding the measurement of financial performance, return on assets (ROA) is still usually used to measure the profitability of business and value of intellectual capital (e.g. Chen and Lee 1995; Ghosh 2002; Wang and Chang 2004; Chang, Wang, and Lee 2007). Therefore, this research selects ROA as the alternative measure of financial performance.

According to Table 20, R&D cooperation intensity does positively affect R&D intensity ($t=3.37$, $p<0.01$), revised R&D outputs ($t=10.58$, $p<0.01$), and ROA ($t=1.93$, $p<0.01$). Therefore, using alternative variables to proxy R&D investments, R&D outputs, and financial performance does not influence the empirical results of H5a, H5b, and H5c. I further test the direct and indirect impact of R&D cooperation on financial performance. Table 21 presents the results of the path analysis. The results show that R&D cooperation intensity strongly and positively affects Profit, R&D investment, and R&D output ($t=3.17$, $p<0.01$; $t=4.14$, $p<0.01$; $t=4.32$, $p<0.01$, respectively) in Model 1, 2, and 3. After controlling for the effect of R&D output, the indirect effect of R&D cooperation intensity on Profit becomes weaker (The coefficient of R&D cooperation intensity is decreased from 0.148 in Model 1 to 0.084 in Model 7; $t=23.3168$, $p<0.01$). However, the indirect effect of R&D cooperation intensity on Profit even becomes larger (The coefficient of R&D cooperation intensity is increased from 0.148 in Model 1 to 0.165 in Model 6) after controlling for the effect of R&D investments. Therefore, the effect of R&D cooperation intensity on financial performance is partially mediated[35] by R&D outputs, which support H8b, but not H8a. See Figure 7 for the path between R&D cooperation, R&D investments, R&D outputs, and financial performance.

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[35] Partial mediation is the case in which the influence of independent variable on dependent variable is reduced in absolute size but is still different from zero when the mediator is controlled (Baron and Kenny 1986).

Table 20: The impact of R&D cooperation on R&D intensity, revised R&D outputs, and ROA

	Dependent variable: R&D intensity		Dependent variable: Revised R&D output		Dependent variable: ROA	
Independent variables	Coef.	t-value	Coef.	t-value	Coef.	t-value
R&D cooperation intensity	.1842669	3.37***	.1508537	10.58***	.0063707	1.93**
Sales growth	.0364077	0.09	.0200428	0.25	.0303025	1.59
Capital structure	-.0597306	-3.36***	.0008818	0.25	-.0031011	-3.67***
Firm size	-2.512616	-5.33***	.1114927	1.14	.080573	3.30***
Upstream	3.047725	4.05***	-.0234762	-0.16	.032934	0.94
Midstream	2.741949	4.10***	.1214906	0.91	-.0277725	-0.88
Optoelectronics	-3.23299	-3.16***	-.4615067	-2.26**	-.0280772	-0.56
Telecommunications	-2.429386	-2.19**	-.7724183	-3.53***	.1120632	2.09**
Computer component	-5.244903	-4.83***	-.6033481	-2.77***	.0271288	0.51
Computer peripheral	-4.927096	-5.19***	-.4457981	-2.35**	.0674206	1.45
System and equipment	-4.432142	-4.02***	-.6432048	-3.02***	.0306908	0.60
Inverse Mill's Ratio	-5.246254	-3.86***	.1656409	0.61	.0645132	0.81
_cons	49.94671	6.21***	-1.936825	-1.17	18.91624	44.77***
N	243		242		234	
Adj. R2	0.5495		0.4410		0.2144	
F-value	25.60***		16.85***		6.30***	

Note: * significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

Table 21: The path analysis between R&D cooperation, R&D investments, revised R&D outputs, and ROA

	Model 1		Model 2		Model 3	
	Dependent variable: profit		Dependent variable: R&D investment		Dependent variable: R&D output	
Independent variables:	Coef.	t-value	Coef.	t-value	Coef.	t-value
R&D cooperation intensity	.1475835	3.17***	.1757015	4.14***	.2013758	4.32***
R&D investment					.0793629	1.75*
R&D output						
Sales growth	.1512691	3.70***	-.0105603	-0.28	.0685797	1.70*
Capital structure	-.1537271	-3.72***	-.2546104	-6.77***	.0054689	0.13
Firm size	.2021085	4.16***	-.2188579	-4.95***	.2431269	4.97***
Upstream	.0067645	0.14	.1846414	4.18***	.0027858	0.06
Midstream	-.0708291	-1.47	.1214374	2.77***	.0671973	1.41
Optoelectronics	.0112296	0.21	-.1055706	-2.16**	-.082277	-1.55
Telecommunications	.1191731	2.31**	-.1279602	-2.73***	-.0713978	-1.40
Computer component	.1815476	2.88***	-.3954867	-6.91***	-.0144013	-0.22
Computer peripheral	.1960108	3.31***	-.2328849	-4.32***	-.0565082	-0.95
System and equipment	.0806264	1.49	-.1807044	-3.66***	-.0459423	-0.85
N	579		579		579	
Adj. R2	0.1279		0.2784		0.1557	

Note: * significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

Table 21: The path analysis between R&D cooperation, R&D investments, revised R&D outputs, and ROA (cont.)

	Model 4		Model 5		Model 6		Model 7		Model 8	
	Dependent variable: Profit		Dependent variable: Profit		Dependent variable: Profit		Dependent variable: Profit		Dependent variable: Profit	
Independent variables:	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value
R&D cooperation intensity					.1647677	3.49***	.084461	1.86*	.1040791	2.27**
R&D investment	-.0702352	-1.53			-.0978031	-2.13**			-.1217207	-2.76***
R&D output			.3077618	7.67***			.2931566	7.19***	.3013698	7.41***
Sales growth	.1507137	3.66***	.1305155	3.31***	.1502363	3.68***	.1314102	3.34***	.1295684	3.32***
Capital structure	-.175664	-4.06***	-.1512528	-3.81***	-.1786288	-4.17***	-.1494066	-3.77***	-.1802769	-4.40***
Firm size	.2716154	6.38***	.1757869	4.14***	.1807035	3.65***	.1359261	2.86***	.1074324	2.22**
Upstream	.0333086	0.67	.0083001	0.18	.024823	0.51	.001652	0.04	.0239834	0.51
Midstream	-.0573577	-1.17	-.091963	-1.98***	-.0589522	-1.22	-.0933538	-2.02**	-.0792034	-1.71*
Optoelectronics	-.0108311	-0.20	.0316829	0.61	.0009045	0.02	.0378059	0.73	.0257003	0.50
Telecommunications	.1088882	2.09**	.1436122	2.90***	.1066582	2.06**	.1430809	2.89***	.1281753	2.59***
Computer component	.1247544	1.90*	.1808857	3.01***	.1428678	2.19**	.1949708	3.23***	.1472079	2.36**
Computer peripheral	.170764	2.82***	.2145697	3.77***	.1732339	2.89***	.2179948	3.83***	.1902638	3.31***
System and equipment	.0653737	1.18	.0978772	1.88**	.0629529	1.15	.0982989	1.89*	.0767986	1.47
N	579		579		579		579		579	
Adj. R2	0.1162		0.1960		0.1348		0.2009		0.2115	

Note: * significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

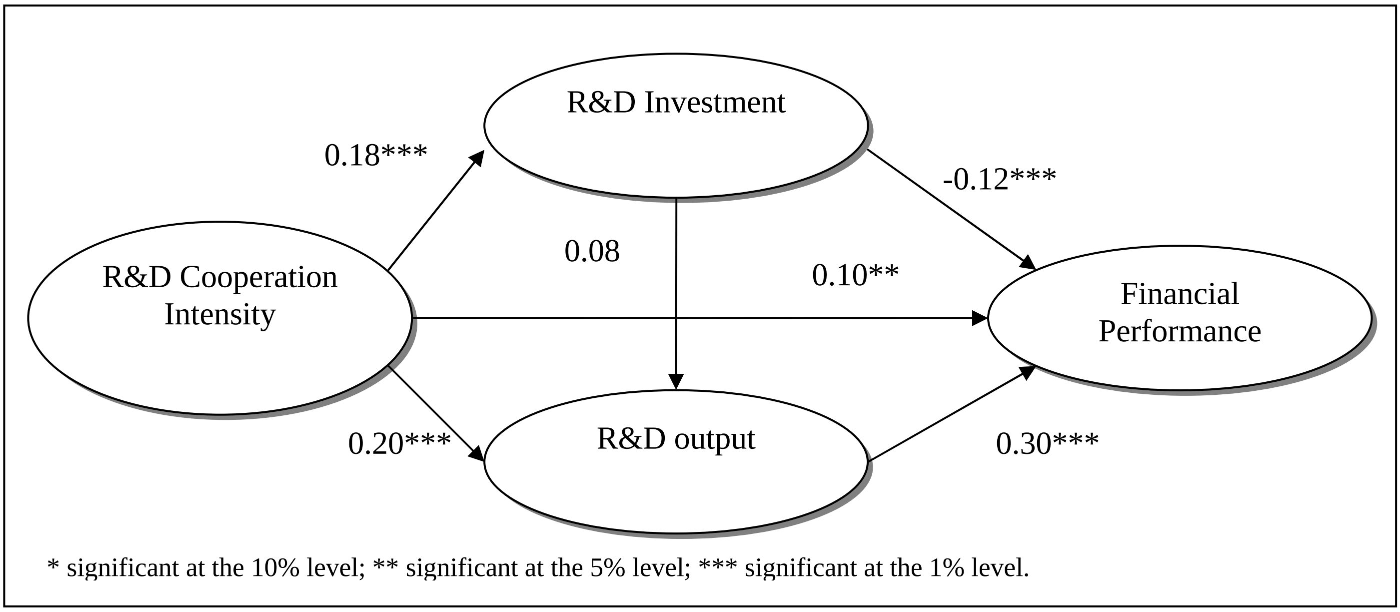


Figure 7: The path between R&D cooperation intensity, R&D investments, R&D outputs, and financial performance

5.3.2 Time-lagged effect analysis

Existing cross-sectional analyses that neglect the lagged effects of R&D cooperation intensity, R&D investments, and R&D outputs on financial performance may be problematic. Lin and Chen (2005) state that short-term economics measures are unable to reflect the influence of corporate R&D strategy if empirical data are cross sectional and limited within a short time of period. They indicate that the impact of R&D on economics measures often has a time-lag of more than 2 years. Ernst (2001) also argues that patent applications lead to sales increases with a time-lag of 2 to 3 years. Therefore, I apply path analysis to further test the lagged effects of R&D cooperation on R&D investments, R&D outputs, and financial performance during the period of 2002 (t+1) - 2004 (t+3). The models are as follows:

Model 1: Regressing $\mathrm{Profit}_{t+1\sim t+3}$ on R&D cooperation intensity:

$$\begin{aligned}\mathrm{Profit}_{t+1\sim t+3} = {} & \beta_0 + \beta_1 R\,\&\,D\ cooperation\ intensity + \beta_2 Sales\ growth_{t+1\sim t+3} \\ & + \beta_3 Capital\ structure_{t+1\sim t+3} + \beta_4 Firm\ size_{t+1\sim t+3} + \beta_5 Upstream \\ & + \beta_6 Midstream + \beta_7 Optoelectronics + \beta_8 Telecommunications \\ & + \beta_9 Component + \beta_{10} Computer\ peripheral + \beta_{11} Other + \varepsilon\end{aligned}$$

Model 2: Regressing R&D investment$_{t+1\sim t+3}$ on R&D cooperation intensity:

$$\begin{aligned} R\,\&\,D\ investment_{t+1\sim t+3} = {} & \beta_0 + \beta_1 R\,\&\,D\ cooperation\ intensity + \beta_2 Sales\ growth_{t+1\sim t+3} \\ & + \beta_3 Capital\ structure_{t+1\sim t+3} + \beta_4 Firm\ size_{t+1\sim t+3} + \beta_5 Upstream \\ & + \beta_6 Midstream + \beta_7 Optoelectronics + \beta_8 Telecommunications \\ & + \beta_9 Component + \beta_{10} Computer\ peripheral + \beta_{11} Other + \varepsilon \end{aligned}$$

Model 3: Regressing R&D output$_{t+1\sim t+3}$ on R&D cooperation intensity and R&D investment:

$$\begin{aligned} R\,\&\,D\ output_{t+1\sim t+3} = {} & \beta_0 + \beta_1 R\,\&\,D\ cooperation\ intensity + \beta_2 R\,\&\,D\ investment_t \\ & + \beta_3 Sales\ growth_{t+1\sim t+3} + \beta_4 Capital\ structure_{t+1\sim t+3} \\ & + \beta_5 Firm\ size_{t+1\sim t+3} + \beta_6 Upstream + \beta_7 Midstream \\ & + \beta_8 Optoelectronics + \beta_9 Telecommunications \\ & + \beta_{10} Component + \beta_{11} Computer\ peripheral + \beta_{12} Other + \varepsilon \end{aligned}$$

Model 4: Regressing Profit$_{t+1\sim t+3}$ on R&D investment:

$$\begin{aligned} Profit_{t+1\sim t+3} = {} & \beta_0 + \beta_1 R\,\&\,D\ investment_t + \beta_2 Sales\ growth_{t+1\sim t+3} + \beta_3 Capital\ structure_{t+1\sim t+3} \\ & + \beta_4 Firm\ size_{t+1\sim t+3} + \beta_5 Upstream + \beta_6 Midstream + \beta_7 Optoelectronics \\ & + \beta_8 Telecommunications + \beta_9 Component + \beta_{10} Computer\ peripheral \\ & + \beta_{111} Other + \varepsilon \end{aligned}$$

Model 5: Regressing Profit$_{t+1\sim t+3}$ on R&D output:

$$\begin{aligned} Profit_{t+1\sim t+3} = {} & \beta_0 + \beta_1 R\,\&\,D\ output_t + \beta_2 Sales\ growth_{t+1\sim t+3} + \beta_3 Capital\ structure_{t+1\sim t+3} \\ & + \beta_4 Firm\ size_{t+1\sim t+3} + \beta_5 Upstream + \beta_6 Midstream + \beta_7 Optoelectronics \\ & + \beta_8 Telecommunications + \beta_9 Component + \beta_{10} Computer\ peripheral \\ & + \beta_{11} Other + \varepsilon \end{aligned}$$

Model 6: Regressing Profit$_{t+1\sim t+3}$ on R&D cooperation intensity and R&D investment:

$$\begin{aligned} Profit_{t+1\sim t+3} = {} & \beta_0 + \beta_1 R\,\&\,D\ cooperation\ intensity + \beta_2 R\,\&\,D\ investment_t \\ & + \beta_3 Sales\ growth_{t+1\sim t+3} + \beta_4 Capital\ structure_{t+1\sim t+3} + \beta_5 Firm\ size_{t+1\sim t+3} \\ & + \beta_6 Upstream + \beta_7 Midstream + \beta_8 Optoelectronics + \beta_9 Telecommunications \\ & + \beta_{10} Component + \beta_{11} Computer\ peripheral + \beta_{12} Other + \varepsilon \end{aligned}$$

Model 7: Regressing Profit$_{t+1\sim t+3}$ on R&D cooperation intensity and R&D output:

$$\begin{aligned} \Pr ofit_{t+1\sim t+3} = {} & \beta_0 + \beta_1 R\,\&\,D\ cooperation\ \mathrm{int}ensity + \beta_2 R\,\&\,D\ output_t \\ & + \beta_3 Sales\ growth_{t+1\sim t+3} + \beta_4 Capital\ structure_{t+1\sim t+3} + \beta_5 Firm\ size_{t+1\sim t+3} \\ & + \beta_6 Upstream + \beta_7 Midstream + \beta_8 Optoelectronics \\ & + \beta_9 Telecommunications + \beta_{10} Component + \beta_{11} Computer\ \ peripheral \\ & + \beta_{12} Other + \varepsilon \end{aligned}$$

Model 8: Regressing Profit$_{t+1\sim t+3}$ on R&D cooperation intensity, R&D investment, and R&D output:

$$\begin{aligned} \Pr ofit_{t+1\sim t+3} = {} & \beta_0 + \beta_1 R\,\&\,D\ cooperation\ \mathrm{int}ensity + \beta_2 R\,\&\,D\ investment_t + \beta_3 R\,\&\,D\ output_t \\ & + \beta_4 Sales\ growth_{t+1\sim t+3} + \beta_5 Capital\ structure_{t+1\sim t+3} + \beta_6 Firm\ size_{t+1\sim t+3} \\ & + \beta_7 Upstream + \beta_8 Midstream + \beta_9 Optoelectronics + \beta_{10} Telecommunications \\ & + \beta_{11} Component + \beta_{12} Computer\ \ peripheral + \beta_{13} Other + \varepsilon \end{aligned}$$

Table 22, 23 and 24 provide the results of path analysis with the time-lagged effect of R&D cooperation intensity, R&D investments, and R&D outputs on financial performance. The coefficients on R&D cooperation are all positive and significant for all lagged effect models (Model 1, 2, and 3). Thus H5a, H5b, and H5c are further supported. R&D output still has a positive impact on profit for all Model 5, while R&D investment has no direct effect on Profit in all Model 4. Therefore, H7b is supported, but H7a is not. Once I control for the effect of R&D outputs on financial performance, the coefficients of R&D cooperation intensity on profit becomes much smaller in all lagged effect model (The coefficient of R&D cooperation intensity is decreased from 0.206 in Model 1 to 0.069 in Model 7 for one-year lagged model, t=54.5390, p<0.01; 0.245 to 0.124 for two-year lagged model, t=51.5443, p<0.01; 0.274 to 0.222 for three-year lagged model, t=21.7458, t<0.01). Therefore, these results again support H8b's prediction that the effect of R&D cooperation on financial performance is mediated by R&D outputs. However, the coefficients of R&D cooperation intensity still remain unchanged or even become larger (The coefficient of R&D cooperation intensity is changed from 0.206 in Model 1 to 0.203 in Model 6 for one-year lagged model, t=0.7769, p=0.4374; 0.245 to 0.249 for two-year lagged model; 0.274 to 0.278 for three-year lagged model) after controlling for the effect of R&D investments on financial performance. Hence, H8a is not supported which indicate that the impact of R&D cooperation intensity on financial performance is not mediated by R&D investments. This justifies that R&D outputs explain a larger portion of performance than R&D investments and are a superior leading indicator of future financial performance (e.g. Jaffe 1986; Narin and Noma 1987; Deng et al. 1997; Werner and Souder 1997; Ernst 2001; Hirschey et al 2001; Cukier 2005; Hall et al. 2005; Scotchmer 2005; Tsai and Wang 2005). See Figures 8, 9, and 10 for the time-lagged path between R&D cooperation intensity, R&D investments, R&D outputs, and financial performance.

Table 22: The path analysis between R&D cooperation intensity, R&D investments, R&D outputs, and financial performance (One-year lagged model)

	Model 1		Model 2		Model 3	
	Dependent variable: Profit$_{2002}$		Dependent variable: R&D investment$_{2002}$		Dependent variable: R&D output$_{2002}$	
Independent variables:	Coef.	t-value	Coef.	t-value	Coef.	t-value
R&D cooperation intensity	.2055718	4.30***	.1416735	3.02***	.2236149	4.40***
R&D investment$_{2001}$					.030042	0.67
R&D output$_{2001}$						
Capital structure$_{2002}$	.1040717	2.74***	-.0145913	-0.39	.0518743	1.29
Sales growth$_{2002}$	-.1312972	-3.35***	-.1755982	-4.57***	-.0011948	-0.03
Firm size$_{2002}$	.2901122	5.80***	.2580936	5.26***	.1594957	2.95***
Upstream	-.0268653	-0.59	.0559293	1.25	.0030101	0.06
Midstream	-.0483916	-1.06	.1894584	4.24***	.0484638	0.99
Optoelectronics	.0681345	1.35	-.0053953	-0.11	-.0456653	-0.86
Telecommunications	.1194649	2.52**	-.0616865	-1.33	-.0333532	-0.66
Computer component	.2036955	3.47***	-.2586809	-4.49***	.0568963	0.90
Computer peripheral	.2362288	4.28***	-.038519	-0.71	-.0110956	-0.19
System and equipment	.1308065	2.60***	-.0630689	-1.28	.0071531	0.13
N	591		591		591	
Adj. R2	0.2160		0.2456		0.1273	

Note: * significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

Table 22: The path analysis between R&D cooperation intensity, R&D investments, R&D outputs, and financial performance (One-year lagged model) (cont.)

	Model 4		Model 5		Model 6		Model 7		Model 8	
	Dependent variable: Profit$_{2002}$		Dependent variable: R&D investment$_{2002}$		Dependent variable: Profit$_{2002}$		Dependent variable: Profit$_{2002}$		Dependent variable: Profit$_{2002}$	
Independent variables:	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value
R&D cooperation intensity					.2034012	4.22***	.0689908	1.83*	.0693557	1.83*
R&D investment$_{2001}$	.0376029	0.88			.0153209	0.36			-.0026878	-0.08
R&D output$_{2001}$			.6096806	20.28***			.5993785	19.64***	.5994482	19.62***
Capital structure$_{2002}$	.0989571	2.57***	.0708274	2.40**	.1042953	2.75***	.0732421	2.49**	.0731993	2.48**
Sales growth$_{2002}$	-.1422334	-3.53***	-.1331897	-4.40***	-.1286069	-3.22***	-.1274192	-4.20***	-.1278907	-4.14***
Firm size$_{2002}$	.4090182	9.56***	.2309465	7.19***	.286158	5.58***	.1898665	4.85***	.1905486	4.76***
Upstream	-.0076681	-0.17	-.022636	-0.64	-.0277222	-0.61	-.0296766	-0.84	-.0295266	-0.83
Midstream	-.0450113	-0.96	-.0779131	-2.20**	-.0512942	-1.11	-.0808512	-2.29**	-.0803458	-2.24**
Optoelectronics	.0494268	0.97	.0897809	2.30**	.0682171	1.35	.0956024	2.45**	.0955911	2.44**
Telecommunications	.121789	2.52**	.1409311	3.82***	.12041	2.53**	.1405669	3.82***	.1404035	3.81***
Computer component	.1755073	2.92***	.1611264	3.58***	.2076587	3.48***	.1742511	3.83***	.1735524	3.74***
Computer peripheral	.221781	3.97***	.2384087	5.58***	.236819	4.29***	.2435728	5.70***	.2434702	5.69***
System and equipment	.1334258	2.61***	.127683	3.27***	.1317728	2.61***	.1276547	3.27***	.1274848	3.26***
N	591		591		591		591		591	
Adj. R2	0.1921		0.5271		0.2162		0.5298		0.5298	

Note: * significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

Table 23: The path analysis between R&D cooperation intensity, R&D investments, R&D outputs, and financial performance (Two-year lagged model)

	Model 1		Model 2		Model 3	
	Dependent variable: Profit$_{2003}$		Dependent variable: R&D investment$_{2003}$		Dependent variable: R&D output$_{2003}$	
Independent variables:	Coef.	t-value	Coef.	t-value	Coef.	t-value
R&D cooperation intensity	.2451476	5.47***	.1605468	3.43***	.2058905	4.09***
R&D investment$_{2001}$					.0344372	0.78
R&D output$_{2001}$						
Capital structure$_{2003}$	.0804072	2.28**	.125414	3.40***	.0051657	0.13
Sales growth$_{2003}$	-.1354655	-3.73***	-.1810908	-4.77***	.0061384	0.15
Firm size$_{2003}$	.3634683	7.74***	.1976471	4.02***	.2222172	4.20***
Upstream	-.0204757	-0.48	.0346766	0.78	.002035	0.04
Midstream	-.0347794	-0.82	.1882846	4.24	.060242	1.26
Optoelectronics	.092218	1.97*	.024145	0.49	-.062716	-1.20
Telecommunications	.0664313	1.49	.0134405	0.29	-.0465934	-0.94
Computer component	.1531854	2.79***	-.1996018	-3.48***	.0231223	0.38
Computer peripheral	.1669296	3.24***	.0156542	0.29	-.0428352	-0.75
System and equipment	.1012047	2.14**	-.0404762	-0.82	-.0038424	-0.07
N	591		591		591	
Adj. R2	0.3163		0.2522		0.1560	

Note: * significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

Table 23: The path analysis between R&D cooperation intensity, R&D investments, R&D outputs, and financial performance (Two-year lagged model) (cont.)

	Model 4		Model 5		Model 6		Model 7		Model 8	
	Dependent variable: Profit$_{2003}$		Dependent variable: Profit$_{2003}$		Dependent variable: Profit$_{2003}$		Dependent variable: Profit$_{2003}$		Dependent variable: Profit$_{2003}$	
Independent variables:	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value
R&D cooperation intensity					.248967	5.50***	.1243808	3.54***	.1310853	3.70***
R&D investment$_{2001}$	.0070287	0.17			-.02379	-0.60			-.0435069	-1.42
R&D output$_{2001}$			.5889773	20.49***			.5712198	19.76***	.5725459	19.81***
Capital structure$_{2003}$	.065415	1.80*	.0678456	2.47**	.0833908	2.34**	.0749895	2.75***	.0804333	2.93**
Sales growth$_{2003}$	-.1607258	-4.26***	-.148524	-5.28***	-.1397737	-3.77***	-.1354096	-4.82***	-.1432882	-5.01***
Firm size$_{2003}$	.5203776	13.09***	.3068306	10.00***	.3681704	7.73***	.2326455	6.30***	.2409408	6.45***
Upstream	.0003244	0.01	-.011975	-0.36	-.0196507	-0.46	-.0223203	-0.68	-.0208159	-0.64
Midstream	-.0228753	-0.52	-.0675408	-2.04**	-.0303001	-0.70	-.0728946	-2.22**	-.0647914	-1.94*
Optoelectronics	.0706304	1.47	.118079	3.23***	.0927924	1.98**	.1275677	3.51***	.1287002	3.55***
Telecommunications	.0710679	1.55	.0959399	2.75***	.0667511	1.49	.092782	2.69***	.093428	2.71***
Computer component	.1127835	2.00**	.1229499	2.90***	.1484368	2.68***	.1439039	3.39***	.1351983	3.16***
Computer peripheral	.1523195	2.88***	.1846732	4.59***	.167302	3.24***	.19109	4.79***	.1918271	4.81***
System and equipment	.1074174	2.21**	.1072193	2.90***	.1002417	2.11**	.1041958	2.84***	.1024417	2.80***
N	591		591		591		591		591	
Adj. R2	0.2810		0.5832		0.3168		0.5920		0.5934	

Note: * significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

Table 24: The path analysis between R&D cooperation intensity, R&D investments, R&D outputs, and financial performance (Three-year lagged model)

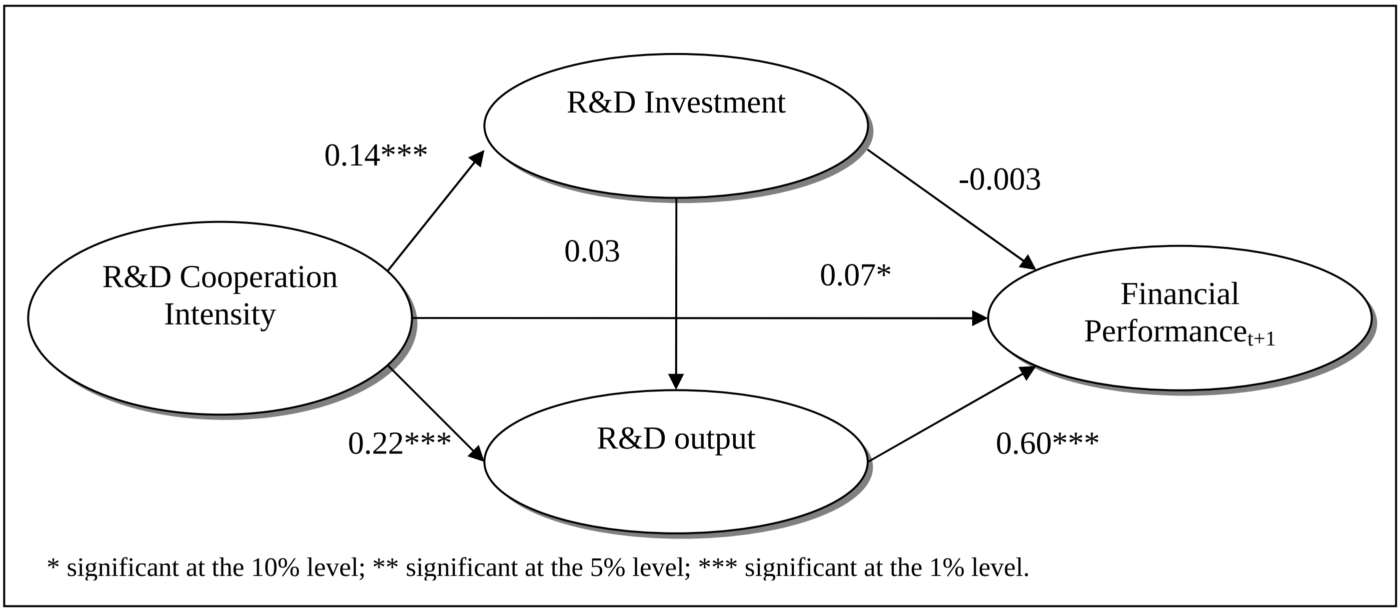
	Model 1		Model 2		Model 3	
	Dependent variable: Profit$_{2004}$		Dependent variable: R&D investment$_{2004}$		Dependent variable: R&D output$_{2004}$	
Independent variables:	Coef.	t-value	Coef.	t-value	Coef.	t-value
R&D cooperation intensity	.2739623	6.65***	.1711348	3.67***	.200969	4.28***
R&D investment$_{2001}$					.0279647	0.67
R&D output$_{2001}$						
Capital structure$_{2004}$	.1791359	5.27***	.0081381	0.21	.0299327	0.78
Sales growth$_{2004}$	-.1216223	-3.56***	-.1720889	-4.44***	-.017132	-0.44
Firm size$_{2004}$	.3700922	8.51***	.1607931	3.26***	.3059684	6.19***
Upstream	-.0401578	-1.00	.046747	1.03	.007665	0.17
Midstream	-.0417754	-1.04	.1906113	4.18***	.0528157	1.15
Optoelectronics	-.0403301	-0.91	.0860108	1.70*	-.1188879	-2.36**
Telecommunications	-.0221491	-0.52	.0027137	0.06	-.1111999	-2.33**
Computer component	-.0281847	-0.54	-.1672513	-2.84***	-.1054863	-1.79*
Computer peripheral	-.0277133	-0.56	.0379752	0.68	-.0902195	-1.63
System and equipment	-.0108552	-0.24	-.003125	-0.06	-.0751049	-1.48
N	587		587		587	
Adj. R2	0.3879		0.2147		0.2243	

Note: * significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

Table 24: The path analysis between R&D cooperation intensity, R&D investments, R&D outputs, and financial performance (Three-year lagged model) (cont.)

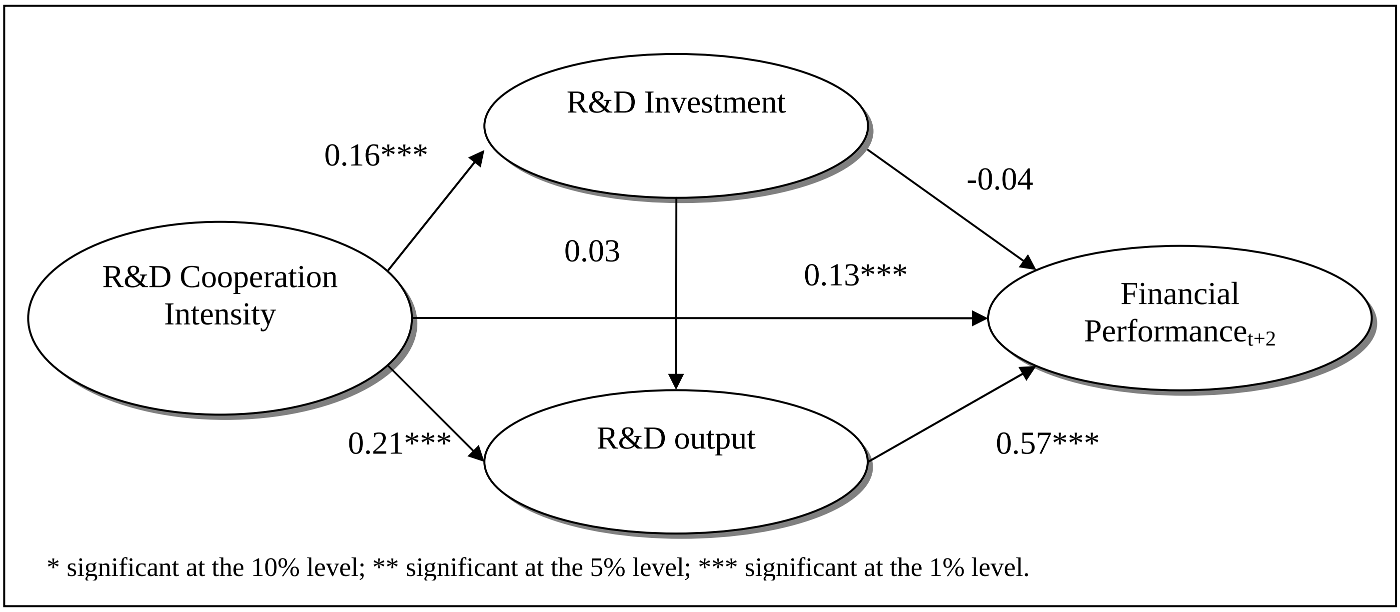
	Model 4		Model 5		Model 6		Model 7		Model 8	
	Dependent variable: Profit$_{2004}$		Dependent variable: Profit$_{2004}$		Dependent variable: Profit$_{2004}$		Dependent variable: Profit$_{2004}$		Dependent variable: Profit$_{2004}$	
Independent variables:	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value
R&D cooperation intensity					.2784324	6.68***	.2222996	5.53***	.2277828	5.61***
R&D investment$_{2001}$	.0110868	0.29			-.0261201	-0.71			-.0331679	-0.94
R&D output$_{2001}$			.2868404	8.00***			.2510887	7.06***	.252027	7.09***
Capital structure$_{2004}$	.1432275	4.12***	.1421867	4.31***	.1793484	5.28***	.171563	5.26***	.1718046	5.26***
Sales growth$_{2004}$	-.1502814	-4.19***	-.139477	-4.18***	-.1261173	-3.62***	-.1161123	-3.54***	-.1217996	-3.65***
Firm size$_{2004}$	.5359057	14.10***	.4134468	10.84***	.3742921	8.52***	.292138	6.76***	.2971798	6.83***
Upstream	-.0164654	-0.40	-.0236039	-0.60	-.0389367	-0.97	-.0424106	-1.10	-.0408685	-1.06
Midstream	-.0270345	-0.64	-.0451385	-1.14	-.0367966	-0.90	-.0563753	-1.46	-.0501076	-1.28
Optoelectronics	-.0689181	-1.50	-.0287506	-0.65	-.0380835	-0.85	-.0110826	-0.26	-.0081205	-0.19
Telecommunications	-.0159404	-0.36	.0146547	0.35	-.0220783	-0.52	.0057528	0.14	.0059471	0.15
Computer component	-.0728065	-1.35	-.0333036	-0.65	-.0325533	-0.62	-.0005239	-0.01	-.0059679	-0.12
Computer peripheral	-.045471	-0.89	-.0158361	-0.33	-.0267214	-0.54	-.0053269	-0.11	-.0039837	-0.08
System and equipment	-.0033253	-0.07	.0166346	0.38	-.0109368	-0.24	.0080247	0.19	.0079916	0.19
N	587		587		587		587		587	
Adj. R2	0.3409		0.4068		0.3884		0.4368		0.4377	

Note: * significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.



* significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

Figure 8: The path between R&D cooperation intensity, R&D investments, R&D outputs, and financial performance (One-year lag)



* significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

Figure 9: The path between R&D cooperation intensity, R&D investments, R&D outputs, and financial performance (Two-year lag)

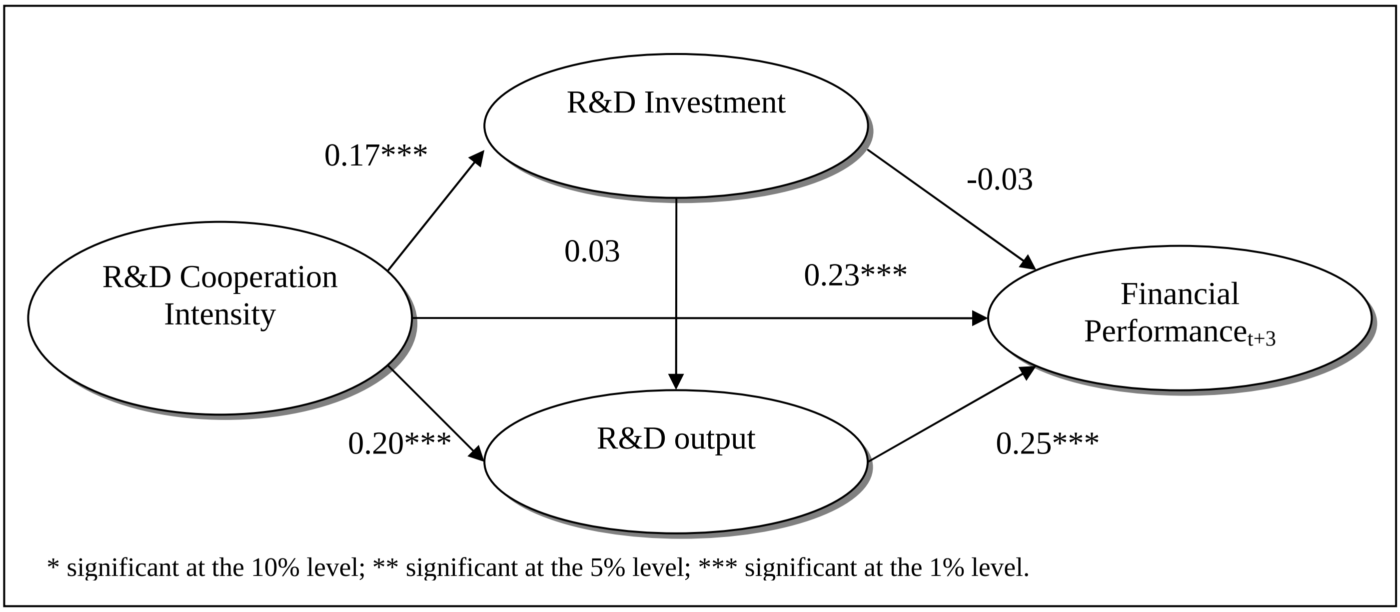


Figure 10: The path between R&D cooperation intensity, R&D investments, R&D outputs, and financial performance (Three-year lag)

5.3.3 Industry analysis

According to my interview, R&D period and performance is very different among different products. For example, it may only take one year to improve a memory chip, but 3-5 years may be required to invent large hardware. The length of the patent granting procedure is also influenced by institutional circumstances (Ernst 2001). Finally, different industries face different technology complexity and product markets. For instance, the semiconductor industry does not have products in the market place relative to the computer peripheral industry. Therefore, industry differences may play a very important role in the relationship between R&D cooperation, R&D investments, R&D outputs, and financial performance. To consider the disturbance arising from industry differences, this analysis separates the sample of high-technology industry into six sub-industries according to the characteristics of products: semiconductor, optoelectronics, telecommunications, computer component, computer peripheral, and system and equipment industries (including software, information system, and electronic equipment industry). Table 25 shows the descriptive statistics of these industries.

According to the analysis, the computer component industry has the most firms among six industries (28.5%), but has the least percentage of R&D cooperation (26.7%) and the least number of R&D cooperation events (0.622). On average, the semiconductor industry has the highest R&D investments, R&D outputs, absorptive capacity, and largest firm size. Most of the semiconductor firms are in an upstream industry (54.8%) while most of the firms of optoelectronics (46.8%), telecommunications (59.3%), computer component (52.3%), and computer peripheral (50%) industries are in a midstream segment.

Table 25: The descriptive statistics of sub-industries

Variables	Semiconductor	Optoelectronics	Telecommunications	Computer component	Computer peripheral	System and equipment
N	84	80	59	172	125	84
R&D cooperation type	.4756098	.5696203	.5423729	.2674419	.483871	.3809524
R&D cooperation intensity	3.073171	1.78481	2.20339	.622093	1.741935	1.142857
Profit (thousand)	-320856.3	149797.7	1460391	288801.8	576063.9	149980.9
R&D investment	417988.2	159682.4	176350	52398.73	161489.6	38174.57
R&D output	.4414037	-.0938835	-.1741875	-.0289392	-.0881625	-.2178195
Knowledge spillover	50.59756	57.24051	102.2542	61.06395	199.7419	79.34524
Absorptive capacity	.1806442	.0925523	.0948646	.0369198	.0628343	.076099
Uncertainty	.1587312	.2292901	-.2625014	-2.322589	-1.392393	.8818693
Sales growth	5.95	190.6486	82.41071	6.982353	14.225	187.0476
Capital structure	30.78049	37.82278	33.34483	40.11696	41.19512	33.11905
Firm size	1.31e+07	9175295	1.35e+07	3784093	7319260	1589802
Upstream	.5487805	.2911392	.1016949	.2674419	.1612903	.3571429
Midstream	.195122	.4683544	.5932203	.5232558	.5	.1904762
Downstream	.2560976	.2405063	.3050847	.2093023	.3387097	.452381

The findings of the regression of R&D cooperation intensity on R&D investment are displayed in Table 26. It appears that R&D cooperation intensity of all sub-industries has a positive influence on R&D investments except for the computer component and the computer peripheral industry. This is perhaps because R&D cooperation in the computer component and the computer peripheral industry induces a cost sharing effect and eliminates wasteful duplication, which in turn counteracts the encouraging effect of R&D cooperation on R&D investments.

In R&D output regression (Table 27), the model of system and equipment industry does not reach a significant level (F=0.53). Hence, I will not further discuss this model. On the other hand, semiconductor, optoelectronics, telecommunications, computer component, and computer peripheral industries all show positive signs for R&D cooperation intensity (t=5.57, p<0.01; t=3.17, p<0.01; t=2.47, p<0.05; t=12.55, p<0.01; t=5.62, p<0.01, respectively), which are consistent with the results of the Heckman two-step model.

With regard to financial performance, Table 28 reveals mixed results. The model of the optoelectronics industry does not reach a significant level (F=1.56). Therefore, I do not further discuss this model. The R&D cooperation intensity variable of semiconductor, telecommunications, computer component, and computer peripheral industries is significant and has a positive sign (t=2.38, p<0.05; t=2.43, p<0.05; t=5.97, p<0.01; t=5.12, p<0.01, respectively). However, the coefficient of R&D cooperation intensity in system and equipment industry is not significant (t=-0.77, p=0.446). The most probable reason is that R&D cooperation has a time-lagged effect on financial performance. Lin and Chen (2005) argue that the impact of R&D activity on performance often has a lag time of more than 2 to 3 years. Ernst (2001) also shows that patent applications lead to performance increases with a lag time of 2 to 3 years after the priority year. As mentioned earlier, the innovation process and innovation period are very different among products. In system and equipment industry, 80% of the firms are related to information systems and electronic equipment, which requires a longer R&D period to generate R&D outputs and profits, according to the interview.

I therefore test the time-lagged effect of R&D cooperation on future R&D outputs and profits for system and equipment industry. The results show that the coefficients of R&D cooperation intensity for system and equipment industry become positive and significant with a lag of one year (The estimated results of the lagged effect are not displayed here). Therefore, in summary, I find that the impact of R&D cooperation on R&D investments, R&D outputs, and financial performance differs across different industry sectors. In semiconductor, and telecommunication industries, R&D cooperation induces higher R&D investments and creates greater R&D outputs and financial performance. For computer component and computer peripheral industries, R&D cooperation creates synergy among R&D cooperative partners, and also leads to higher R&D outputs and profits. However, in system and equipment industry, the time-lagged effects influence the relationship between R&D cooperation, R&D outputs, and financial performance.

Table 26: R&D investment regression model for sub-industries

Dependent variable: R&D output

Independent variables	Semicon-ductor		Optoelec-tronics		Telecom-munications		Computer component		Computer peripheral		System and equipment	
	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value
R&D cooperation intensity	.1254901	5.68***	.1400886	2.88***	.123091	2.00**	.0082681	0.04	.1520477	1.25	.5873397	1.84*
Sales growth	-.0128286	-0.12	-.1901222	-1.31	.3019222	1.78*	-.0631391	-0.10	-.5181371	-1.16	-.7104141	-1.29
Capital structure	.0041585	0.59	.0041398	0.45	-.0183388	-2.15**	-.0279127	-1.41	-.0507974	-3.64***	-.0711026	-2.40**
Firm size	.5545549	6.70***	.5739332	4.89***	.6177863	3.83***	1.034375	3.21***	1.033247	3.96***	.4253183	0.77
Upstream	1.133748	4.06***	.523589	1.75*	.7097205	1.55	-1.949161	-2.29**	2.762436	3.79***	-.0797067	-0.09
Midstream	.2214048	0.76	-.3042692	-1.03	.4761304	1.56	1.71017	2.16**	2.398168	4.49***	2.036644	1.84*
_cons	2.001513	1.42	2.876642	1.65*	.6917285	0.30	-5.808616	-1.04	-2.520367	-0.55	7.378075	0.91
N	72		70		51		170		116		80	
Adj. R2	0.7778		0.6255		0.6405		0.2078		0.4113		0.1525	
F-value	42.43***		20.21***		15.85***		8.39***		14.39***		3.37***	

Note:

1. * significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level
2. The figures in parentheses are the t value.

Table 27: R&D output regression model for sub-industries

Dependent variable: R&D investment												
Independent variables	Semiconductor		Optoelectronics		Telecommunications		Computer component		Computer peripheral		System and equipment	
	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value
R&D cooperation intensity	.1578392	5.57***	.0244593	3.17***	.0129333	2.47**	.176439	12.55***	.0225754	5.62***	.0000429	0.08
Sales growth	.0337454	0.24	-.0192956	-0.81	.0394195	2.60**	.0356024	0.95	.016184	0.52	-.0002018	-0.14
Capital structure	-.0029499	-0.34	.0014294	1.06	.0004256	0.59	.0009717	0.86	-.0010872	-1.10	-.000053	-0.70
Firm size	.1287845	1.26	.0293714	1.59	-.015818	-1.23	-.0156189	-0.83	.0380142	2.62**	.0015214	1.07
Upstream	-.2783341	-0.85	.0399376	0.84	-.0371308	-0.82	-.0070719	-0.15	.0793668	1.48	.0024438	1.02
Midstream	.1047683	0.30	-.0093647	-0.21	-.0182153	-0.70	.0368225	0.81	.0348963	0.92	.0004218	0.15
_cons	-2.046973	-1.18	-.5999735	-2.13**	-.1704714	-0.91	-.2634452	-0.80	-.7880259	-2.81***	-.2419821	-11.49***
N	80		72		54		168		118		81	
Adj. R2	0.4945		0.3609		0.1435		0.5282		0.3459		-0.0369	
F-value	13.88***		7.68***		2.48**		32.15***		11.31***		0.53	

Note:

1. * significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level

2. The figures in parentheses are the t value.

Table 28: Profit regression model for sub-industries

Dependent variable: Profit

Independent variables	Semiconductor		Optoelectronics		Telecommunications		Computer component		Computer peripheral		System and equipment	
	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value
R&D cooperation intensity	.0055714	2.38**	.0014048	0.59	.0090026	2.43**	.0080376	5.97***	.0092737	5.12***	-.0002732	-0.77
Sales growth	.0195461	1.79*	.0055629	1.37	.0165818	1.72*	.0106859	2.96***	.0292287	4.74***	.0034733	3.45***
Capital structure	-.001612	-2.47**	-.0003549	-1.47	-.0007432	-1.61	-.0001168	-1.08	-.0005635	-2.88***	-.0000522	-1.01
Firm size	-.0163019	-2.12**	.0039564	1.04	.008013	0.96	.0099852	5.53***	.0194333	5.40***	.0082938	7.35***
Upstream	-.0276198	-1.11	-.0074938	-0.92	.0187502	0.72	-.000971	-0.21	-.0027393	-0.27	.0008071	0.49
Midstream	-.0167665	-0.62	-.0114276	-1.49	.0012782	0.08	.003408	0.78	-.0080583	-1.08	.0025269	1.26
_cons	16.85967	128.77***	16.59815	293.49***	16.4878	136.99***	16.47657	520.87***	16.28313	256.48***	16.533	1007.14***
N	76		66		54		168		117		81	
Adj. R2	0.1620		0.0493		0.2271		04226		0.5996		0.4279	
F-value	3.42***		1.56		3.60***		2.37**		29.96***		10.97***	

Note:

1. * significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level

2. The figures in parentheses are the t value.

5.3.4 Other analysis

R&D output is the combination of count variables (including the number of patents, citations, and claims) which adhere to the Poisson distribution. Therefore, I also run poisson regression model and negative binomial regression model. The results remain the same as OLS regression model.

In this study companies that belong to the same business group are regarded as R&D collaborative companies. However, this assumption may not hold because companies that belong to the same business group are not necessary to cooperation on R&D. Therefore, I also exclude this data source and to examine the robustness of the empirical test. The results show that the correlation between R&D cooperation with business group and without business group is over 98%, and the empirical results remain unchanged after excluding the data of business group.

Chapter 6: Conclusions

6.1 Conclusions and implications

Innovation is complex, costly, and risky and incurs externalities. R&D cooperation is deemed as a proper mechanism to encourage firms to innovate (Kamien et al. 1992). The purposes of this dissertation are to extend the prior theoretical and empirical studies to establish a research framework of the R&D cooperation—innovation—financial performance chain. I apply the two-industry, n-firm Cournot competition models to examine theoretically the relationship between R&D cooperation, R&D investments, R&D outputs, and financial performance. I then use Taiwan's high-technology industry as a research sample and empirically test my research hypotheses.

Empirical results and implications are summarized as follows:

1. The determinants of R&D cooperation

I find that firm-level factor (absorptive capacity) and industry-level factor (knowledge spillovers) specified in this study explain a moderate amount of the variance in R&D cooperation intensity. The empirical results show that absorptive capacity has a positive impact on the frequency of R&D cooperation. Prior research also indicates that external knowledge is not 'manna from heaven', and firms need an absorptive capacity to assimilate and exploit knowledge (e.g. Kamien and Zang 2000). Therefore, to engage in R&D cooperation and learn from other innovators, companies should encourage employees to strengthen their abilities. The empirical results also support the argument that an increase in knowledge spillovers, especially in high-technology industry, tends to increase frequency to collaborate in R&D. Based on prior research, when large knowledge spillovers exist, it is impossible for the innovator to appropriate all of the benefits from an innovation (e.g. Miyagiwa and Ohno 2002). Thus companies are more willing to cooperate in R&D because externality problems can be internalized (e.g. Goel 1995; Veugelers 1998). For example, when knowledge spillovers are high, R&D outputs are easily copied by other manufacturers. Therefore, a company has an incentive to carry on R&D cooperation, such as the cooperation between Sony vs. Samsung, and Sharp vs. LG on CFL-LCD.

Under high uncertainty, firms may be more likely to engage in R&D cooperation because of the benefits such as pooling risk and uncertainty (Choi 1993). Firms use partnerships to reduce risk and uncertainty when collaborating with competitors as well as with suppliers and buyers (Caloghirou et al. 2003). However, inconsistent with prior literature, the empirical results do not support the hypothesis. I suspect that Taiwan high technology companies may adopt different strategy from western companies, i.e. engaging in R&D activity independently, under high environment uncertainty. For example, GIGABYTE and ASUS have called off the joint venture on March 22, 2007. GIGABYTE explained the confusion of clients and suppliers, together with the uncertainty of both internal and external environment has lead to this decision. R&D cooperation may also exist nonlinear relationships under different scenarios of uncertainty. Additionally, the reason for the lack of association between uncertainty and R&D cooperation intensity may be that the uncertainty measure is improper and does not capture the real definition of this construct. Therefore, future research should measure the accuracy and consistency of uncertainty in conjunction with the intensity of R&D cooperation.

The results also show that if R&D cooperative firms have a greater absorptive capacity, they are more likely to cooperate with suppliers, customers, and competitors simultaneously. For example, MediaTek Inc. and Global Mixed-mode technology Inc. are both the leader in graphics processing and power management, respectively. They cooperate to establish SOC and also cooperate with the upstream EDA tool suppliers and downstream wafer manufacturing and packaging/testing companies to insure the yield rate of the products. Finally, they cooperate with BenQ to integrate their chips with BenQ’s products. Companies with lower absorptive capacity have fewer chances to engage in this type of research alliance. Moreover, when firms face higher knowledge spillovers, R&D cooperative firms increase their propensity to engage in generalized cooperation to internalize spillover externalities. Therefore, the ability of knowledge sharing is the main reason of forming network organization and generalized R&D cooperation is preferred over other cooperative models.

2. The impact of R&D cooperation on R&D investments, R&D outputs, and financial performance

R&D cooperation is a proper mechanism that can restore firms’ incentives to engage in R&D. Through cooperation in R&D, the externality problem can be internalized, which will have a positive impact on R&D levels and profitability when spillovers are high (e.g. Goel 1995; Veugelers 1998). Prior research also indicates that R&D cooperation accelerates the speed of innovation with less risk (e.g. Jacquemin 1988; Kamien 1992). Taking R&D cooperation between suppliers and customers as an example, for encouraging downstream manufacturers to accept and provide more complete products or techniques, the suppliers have the incentive to invest more R&D to produce more R&D outputs and financial performance. In this study, the empirical results confirm that R&D cooperation does encourage Taiwan's high-technology firms to invest more resources on R&D, and also leads to higher R&D outputs and financial performance.

Empirical results show that generalized cooperation can lead to higher R&D outputs and profits relative to other R&D cooperation types when knowledge spillovers are higher. Therefore, according to this finding, R&D cooperation does not mean higher R&D outputs and financial performance. In this study, only generalized cooperation can exert the full advantage of network organization and is regarded as a preferable type of R&D cooperation under high knowledge spillover. In addition, compared with horizontal cooperation, vertical and generalized cooperation leads to higher R&D investments. Atallah (2002) states that horizontal R&D cooperation is involuntary and undesirable because innovative firms have to face their competitors. Therefore, horizontal cooperative companies may not be willing to invest too much in R&D relative to vertical cooperation and generalized cooperation. The technique is usually the key that the companies win the battle, and is the resource that the enterprises protect intentionally. Without having enough trust, how does everyone guarantee to frankly and earnestly cooperate with each other, and not steal techniques from each other? Therefore, a trust relation based on long-term business interaction is the foundation of knowledge sharing.

The impact of R&D cooperation on financial performance is mediated by R&D outputs, but not by R&D investments in all time periods. Taking CHI Research as an example, it is a worldwide leader in intellectual property consulting and has developed a patent index[36] that evaluates firms' potential value. Having a higher patent index can indicate that a company is more innovative, with the possibility of

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[36] Patent index includes the number of patents a company holds, the number of citations by later patent applications (citation index), references a patent makes to scientific papers, the median age of patents cited in an application (technology cycle time), etc.

greater future profits. Based on CHI's system, its pick outperformed the Nasdaq composite index in 7 of 10 years and the Standard & Poor's 500 stock index in 8 of 10 years over the 1990-1999 period (Barker 2002). This supports that R&D outputs explain a larger portion of performance than R&D investments and are a superior leading indicator of future financial performance (e.g. Jaffe 1986; Narin and Noma 1987; Deng et al. 1997; Werner and Souder 1997; Ernst 2001; Hirschey et al 2001; Cukier 2005; Hall et al. 2005; Scotchmer 2005; Tsai and Wang 2005). Finally, I also find that the impact of R&D cooperation on R&D investments, R&D outputs, and financial performance differs across different industry sectors.

Table 29 summarizes the conclusions and implication of this study:

Table 29: Summary of conclusions and implications

Research topic 1: The determinants of R&D cooperation		
Research hypotheses	**Empirical results**	**Implications**
H1: The greater the absorptive capacity, the greater the intensity will be for engaging in R&D cooperation.	Support	The empirical results show that absorptive capacity has a positive impact on the frequency of R&D cooperation. Prior research also indicates that external knowledge is not 'manna from heaven', and firms need an absorptive capacity to assimilate and exploit knowledge (Kamien and Zang 2000). Therefore, in order to engage in R&D cooperation, companies should strengthen employees' ability to learn from others, which supports the theory of absorptive capacity proposed by Cohen and Levinthal (1989).
H2: The greater the knowledge spillovers, the greater the intensity will be for engaging in R&D cooperation.	Support	When knowledge spillovers are high, R&D outputs are easily copied by other manufacturers. Company has an incentive to carry on R&D cooperation, such as the cooperation between Sony vs. Samsung, and Sharp vs. LG on CFL-LCD. The empirical results support the argument that an increase in knowledge spillovers tends to increase intensity to collaborate in R&D, especially in the high-technology industry.

H3: The greater the uncertainty, the greater the intensity will be for engaging in R&D cooperation.	Not Support	Prior research shows that firms are more likely to engage in R&D cooperation under high uncertainty because of the benefits such as pooling risk and uncertainty (Choi 1993). Firms use partnerships to reduce risk and uncertainty when collaborating with competitors as well as with suppliers and buyers (Caloghirou et al. 2003). However, inconsistent with prior literature, the empirical results do not support the hypothesis. Taiwan high technology companies may adopt different strategy from western companies under high environment uncertainty. R&D cooperation may also exist nonlinear relationships under different scenarios of uncertainty. Therefore, future research should focus more on this issue.
H4a: The greater the absorptive capacity, the greater the intensity will be for engaging in generalized R&D cooperation relative to other cooperation types.	Support	The results show that if R&D cooperative firms have a greater absorptive capacity, they are more likely and able to cooperate with suppliers, customers, and competitors simultaneously. For example, MediaTek Inc. and Global Mixed-mode technology Inc. are both the leader in graphics processing and power management, respectively. They cooperate to establish SOC and also cooperate with the upstream EDA tool suppliers and downstream wafer manufacturing and packaging/testing companies to insure the yield rate of the products. Finally, they cooperate with BenQ to integrate their chips with BenQ's products. Companies with lower absorptive capacity have fewer chances to engage in this type of research alliance. Therefore, the ability of knowledge sharing is the main reason of forming network organization.

H4b: The greater the knowledge spillovers, the greater the intensity will be for engaging in generalized R&D cooperation relative to other cooperation types.	Support	When firms face higher knowledge spillovers, R&D cooperative firms increase their propensity to engage in generalized cooperation to internalize most of the competitive externalities, compared with other cooperation types. To exert the full advantage of network organization, generalized cooperation relation should be formed. Therefore, generalized R&D cooperation is preferred over other cooperative models.
H4c: The greater the uncertainty, the greater the intensity will be for engaging in generalized R&D cooperation relative to other cooperation types.	Not Support	Contrary to prior research, uncertainty has no specific relationships with different types of R&D cooperation. The possible explanation might be that Taiwan high technology companies adopt different strategy from western companies under high environment uncertainty. R&D cooperation may also exist nonlinear relationships under different scenarios of uncertainty.
Research topic 2: The impact of R&D cooperation on R&D investments, R&D outputs, and financial performance		
Research hypotheses	**Empirical results**	**Implications**
H5a: Higher R&D cooperation intensity leads to higher R&D investments.	Support	R&D cooperation is a proper mechanism that can restore firms' incentives to engage in R&D. Through cooperation in R&D, the externality problem can be internalized, which will have a positive impact on R&D levels when spillovers are high (e.g. Goel 1995; Veugelers 1998). In addition, for encouraging downstream manufacturers to accept and provide more complete products or techniques, the suppliers have the incentive to invest more R&D.

H5b: Higher R&D cooperation intensity leads to higher R&D outputs.	Support	Research results show that R&D cooperation leads to significantly higher R&D outputs. Prior research also indicates that R&D cooperation not only accelerates the speed of innovation with less risk, but also produces synergetic effects through the combination of new information, teams of specialists, and expertise (e.g. Jacquemin 1988; Kamien 1992).
H5c: Higher R&D cooperation intensity leads to higher financial performance.	Support	The leaking of firms’ knowledge to competitors has a negative impact on the firms’ own profitability, thus reducing the incentives for investing in R&D (e.g. Spence 1984; Veugelers 1998). Previous literature indicates that R&D cooperation has a positive impact on profitability when spillovers are high (e.g. Goel 1995; Veugelers 1998). In this study, the empirical results confirm that R&D cooperation does lead to higher financial performance for Taiwan’s high-technology firms.
H6a: Generalized R&D cooperation leads to higher R&D investments relative to other cooperation types if knowledge spillovers are “large” (7h+5v>2).	Moderate support	Compared with horizontal cooperation, vertical and generalized cooperation leads to higher R&D investments. Atallah (2002) states that horizontal R&D cooperation is involuntary and undesirable because innovative firms have to face their competitors. Therefore, horizontal cooperative companies are not willing to invest too much in R&D relative to vertical cooperation and generalized cooperation. Without having enough trust, however, it is hard for companies to frankly and earnestly cooperate with each other.
H6b: Generalized R&D cooperation leads to higher R&D outputs relative to other cooperation types if	Support	Empirical results show that generalized cooperation can lead to higher R&D outputs relative to other R&D cooperation types when knowledge spillovers are higher. This further confirms that generalized cooperation is a preferable type of R&D cooperation to

knowledge spillovers are “large” (7h+5v>2).		others under high knowledge spillovers.
H6c: Generalized R&D cooperation leads to higher financial performance relative to other cooperation types if knowledge spillovers are “large” (7h+5v>2).	Support	Empirical results show that generalized cooperation can lead to higher profits relative to other R&D cooperation types when knowledge spillovers are higher. Therefore, according to this finding, R&D cooperation does not mean higher financial performance. In this study, generalized cooperation is regarded as a preferable type of R&D cooperation under high knowledge spillovers, and R&D cooperation types do matter to the performance of R&D cooperation.
H7a: R&D investments are positively related with financial performance.	Not support	1. From the theory of industrial organization, society exists at an optimal R&D level. Increasing R&D investments will definitely increase discovery probability, but will also increase the industry’s aggregate R&D cost associated with R&D duplication (Shy 1996). Therefore, persistently investing in R&D may not definitely bring benefit to a company. Huang and Liu’s (2005) research also support this argument. 2. Simply investing in R&D alone is not enough to achieve breakthrough performance and sustain a competitive advantage. The ability to innovate and generate R&D outputs determines the profitability of the company.
H7b: R&D outputs are positively related with financial performance.	Support	
H8a: The impact of R&D cooperation intensity on financial performance is	Not support	The impact of R&D cooperation on financial performance is mediated by R&D outputs, but not R&D investments in all time periods. Taking CHI research as an example, it uses the patent index to evaluate firms’ potential value and suggests that having

mediated by R&D investments.		a higher patent index can indicate that a company is more innovative, with the possibility of greater future profits (Barker 2002). This justifies that R&D outputs explain a larger portion of performance than R&D investments and are a superior leading indicator of future financial performance (e.g. Jaffe 1986; Narin and Noma 1987; Deng et al. 1997; Werner and Souder 1997; Ernst 2001; Hirschey et al 2001; Cukier 2005; Hall et al. 2005; Scotchmer 2005; Tsai and Wang 2005).
H8a: The impact of R&D cooperation intensity on financial performance is mediated by R&D outputs.	Support	

6.2 Research limitations

Model limitation

(1) The limitation of D' Aspremont and Jacquemin (1988) and Kamien et al. (1992) is that R&D is treated as being deterministic — that is, without considering technical uncertainty. Therefore, if a firm is willing to invest in R&D, it can then obtain a certain cost reduction (Martin 2002). This limitation also exists in my model.

(2) Under the consideration of reputation, opportunistic behavior will result in the permanent punishment of retreating from the R&D consortium. However, companies without continued strategic relationships probably would be more tempted to engage in corporate espionage. In this study, I do not consider "information asymmetry" in the model setting.[37]

Variable measurement limitation

(1) Both formal and informal cooperation are forms of R&D cooperation. However, I cannot obtain informal cooperation data from public information because of business confidentiality

(2) Patent data have an inherent measurement limitation, because not all inventions

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[37] The standard models for R&D cooperation always assume "information symmetry" because the models will be too complex if they consider "information asymmetry" problem (Vonortas 1994; Geroski 1995; Steurs 1995; Harhoff 1996; Kaiser and Licht 1998; Petit and Tolwinski 1999; Inkmann 2000; Atallah 2002; Atallah 2004; Milliou 2004; Ishill 2004; Atallah 2005). Even in D'Aspremont and Jacquemin's (1988) original horizontal cooperation model, it is still hard to incorporate "information asymmetry" assumption. I deeply appreciate Rabah Amir for providing helpful opinions.

are patentable, and not all patentable inventions are patented (e.g. Basberg 1987; Griliches 1990; Ernst 2001; Hall et al. 2005). Therefore, using patent data may not capture the overall R&D outputs. In addition, citations to a given patent typically keep coming over long periods of time (Hall et al. 2005), but I only include them until the last date of the available data (May 27, 2006).

(3) Since the financial data represent sales and profits for the entire firm, it is difficult to segregate just the R&D aspects (e.g. Narin and Noma 1987). Therefore, there is a major problem in defining the R&D aspects of a firm's performance.

(4) Dess and Beard (1984) classify environmental dimensions into three categories: environmental munificence (capacity), environmental complexity (homogeneity-heterogeneity, concentration-dispersion), and environmental dynamism (stability-instability, turbulence). I only measure uncertainty based on the dimension of environmental dynamism.

6.3 Future research

1. "Information asymmetry" is an important assumption for contemporary theory. Under "information asymmetry", R&D partners may conduct opportunistic behavior in an R&D cooperation relationship. Although there is a high degree of difficulty in modeling, future researchers should try to incorporate this assumption into the model of R&D cooperation.

2. To prevent imitation by other competitors, some companies would rather not apply for the patent to avoid the leak of technique in advance. Moreover, some invention can- not apply for patent, and the patent also has to be commercialized to create performance for the company. Therefore, researchers can adopt more representative measures, such as the shares of new product sales to total sales, to trace the relationship between R&D outputs and financial performance.

3. In this study I collect R&D cooperation data from 1998-2001. Future research should cover a longer time period and more recent data in R&D cooperation research.

4. The research shows the importance of institutions, such as the Industrial Technology Research Institute (ITRI), in encouraging technological development and diffusion in Taiwan through collaborative projects (e.g. Hagedoorn et al. 2000; Mathews 2002). The survey of the annual world competitiveness yearbook also

shows that Taiwan is assessed to do comparatively well in the extent to which firms collaborate with universities (e.g. Sakakibara and Dodgson 2003). Hence collaborating with universities or institutions is more likely to be chosen as a route that exhibits faster technological and product developments. It would be interesting to include university laboratories and government agencies as one of the R&D cooperation types, and examine the impact of academic R&D cooperation on R&D investments, R&D outputs, and financial performance.

5. Most of the R&D cooperation studies relate to North America, Japan, and Europe (e.g. Veugelers 1998; Hagedoorn et al. 2000; Man and Duysters 2005). Taiwan is deemed a core innovator in the world. However, Taiwan has received little attention because of the problem of difficult data collection. In addition, the empirical evidence that exists to test the differences among countries is scarce (e.g. Man and Duysters 2005). Therefore, the comparison between Taiwan and other countries will be a promising avenue for R&D cooperation study.
6. R&D cooperation behavior is a complex phenomenon. Different industries have different R&D patterns and engage in different types of R&D cooperation. Accordingly, the impacts of R&D cooperation on financial performance will be different, too. Future researchers still need to do more qualitative research, such as case study and field study, to better understand the essence and dynamic behavior of R&D cooperation.

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Appendix A: Simulation results

TableA1: R&D investments with three firms R&D cooperation and R&D competition (a=100, b=1, c=1, d=1, γ =70, n=3)

		R&D competition					Vertical cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	11.265	8.334	5.8417	3.7972	2.2058	16.723*	14.466*	12.357*	10.402*	8.6057*
	0.25	14.02	10.709	7.8415	5.4281	3.4743	23.589*	20.888*	18.329*	15.919*	13.666*
	0.5	17.149	13.438	10.179	7.382	5.0524	31.883*	28.719*	25.691*	22.807*	20.075*
	0.75	20.681	16.55	12.879	9.6796	6.9577	41.773*	38.124*	34.604*	31.22*	27.983*
	1	24.652	20.075	15.969	12.346	9.2117	53.474*	49.312*	45.269*	41.355*	37.581*

		Horizontal cooperation					Generalized cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	2.1902	3.4359	4.9719	6.8066*	8.9499*	8.4839	13.363*	19.432*	26.76*	35.43*
	0.25	4.9719	6.8066	8.9499*	11.414*	14.212*	19.432*	26.76*	35.43*	45.54*	57.213*
	0.5	8.9499	11.414	14.212*	17.361*	20.878*	35.43*	45.54*	57.213*	70.588*	85.835*
	0.75	14.212	17.361*	20.878*	24.784*	29.102*	57.213*	70.588*	85.835*	103.15*	122.77*
	1	20.878	24.784*	29.102*	33.859*	39.084*	85.835*	103.15*	122.77*	144.96*	170.06*

[a] If R&D cooperation results in higher R&D investments than R&D competition, the R&D investment level is followed by an asterisk (*).

TableA2: R&D outputs with three firms R&D cooperation and R&D competition (a=100, b=1, c=1, d=1, γ =70, n=3)

		R&D competition					Vertical cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	0.8016	0.6887	0.5754	0.4618	0.3481	0.9776*	0.9092*	0.8403*	0.771*	0.7013*
	0.25	0.8935	0.7798	0.6657	0.5513	0.4369	1.161*	1.0925*	1.0234*	0.9538*	0.8837*
	0.5	0.9874	0.8727	0.7576	0.6422	0.5269	1.3498*	1.281*	1.2116*	1.1416*	1.071*
	0.75	1.0835	0.9676	0.8512	0.7348	0.6183	1.545*	1.476*	1.4062*	1.3357*	1.2645*
	1	1.182	1.0647	0.947	0.8292	0.7114	1.748*	1.6786*	1.6084*	1.5373*	1.4654*

		Horizontal cooperation					Generalized cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	0.3469	0.4345	0.5227	0.6115*	0.7013*	0.6963	0.8738*	1.0538*	1.2366*	1.4229*
	0.25	0.5227	0.6115	0.7013*	0.7919*	0.8837*	1.0538*	1.2366*	1.4229*	1.6132*	1.8081*
	0.5	0.7013	0.7919	0.8837*	0.9767*	1.071*	1.4229*	1.6132*	1.8081*	2.0084*	2.2147*
	0.75	0.8837	0.9767*	1.071*	1.1669*	1.2645*	1.8081*	2.0084*	2.2147*	2.4278*	2.6486*
	1	1.071	1.1669*	1.2645*	1.364*	1.4654*	2.2147*	2.4278*	2.6486*	2.8781*	3.1173*

[a] If R&D cooperation results in higher R&D outputs than R&D competition, the R&D output level is followed by an asterisk (*).

TableA3: Profits with three firms R&D cooperation and R&D competition (a=100, b=1, c=1, d=1, γ =70, n=3)

		R&D competition					Vertical cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	1920	1924.6	1926.5	1925.9	1922.7	1922.6*	1930.5*	1936.9*	1941.9*	1945.3*
	0.25	1939.2	1942.7	1943.5	1941.7	1937.3	1947.4*	1956.2*	1963.4*	1969.1*	1973.3*
	0.5	1962.1	1964.4	1964.1	1961.1	1955.5	1979.1*	1988.8*	1996.9*	2003.5*	2008.5*
	0.75	1988.7	1989.9	1988.4	1984.1	1977.2	2018.2*	2028.9*	2038*	2045.5*	2051.3*
	1	2019.5	2019.4	2016.6	2011.1	2002.8	2065.4*	2077.2*	2087.3*	2095.8*	2102.6*

		Horizontal cooperation					Generalized cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	1909.1	1915.9	1924.3	1934.3*	1945.9*	1917.8	1929.6*	1944.2*	1961.7*	1982.3*
	0.25	1924.3	1934.3	1945.9*	1959.2*	1974.3*	1944.2*	1961.7*	1982.3*	2006.1*	2033.2*
	0.5	1945.9	1959.2	1974.3*	1991.1*	2009.9*	1982.3*	2006.1*	2033.2*	2064*	2098.7*
	0.75	1974.3	1991.1*	2009.9*	2030.6*	2053.3*	2033.2*	2064*	2098.7*	2137.5*	2180.9*
	1	2009.9	2030.6*	2053.3*	2078.1*	2105.3*	2098.7*	2137.5*	2180.9*	2229.2*	2283*

[a] If R&D cooperation results in higher profits than R&D competition, the profit level is followed by an asterisk (*).

TableA4: R&D investments with five firms R&D cooperation and R&D competition (a=100, b=1, c=1, d=1, γ =70, n=5)

		R&D competition					Vertical cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	7.4001	4.726	2.6209	1.1233	0.2522	7.9584*	5.6507*	3.7045*	2.1514*	1.0128*
	0.25	8.2441	5.3699	3.0829	1.4198	0.3968	9.624*	7.0388*	4.8197*	3.0006*	1.6046*
	0.5	9.1648	6.0755	3.5946	1.7571	0.5762	11.522*	8.6366*	6.1236*	4.0198*	2.3504*
	0.75	10.17	6.8489	4.1605	2.1381	0.7921	13.686*	10.472*	7.6392*	5.2278*	3.2649*
	1	11.27	7.6969	4.7855	2.5664	1.0467	16.154*	12.578*	9.3951*	6.6481*	4.3669*

		Horizontal cooperation					Generalized cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	0.2497	1.0063	2.292	4.1455*	6.624*	0.9932	4.0314	9.2969*	17.117*	28.002*
	0.25	1.2769	2.7003	4.7039*	7.35*	10.724*	5.1289	10.996*	19.526*	31.285*	47.112*
	0.5	3.1447	5.3023	8.1213*	11.694*	16.141*	12.861*	22.136*	34.82*	51.838*	74.548*
	0.75	5.9419	8.9396*	12.718*	17.407*	23.179*	24.957*	38.624*	56.916*	81.333*	114.11*
	1	9.8065	13.799*	18.741*	24.815*	32.264*	42.715*	62.374*	88.635*	123.98*	172.25*

[a] If R&D cooperation results in higher R&D investments than R&D competition, the R&D investment level is followed by an asterisk (*).

TableA5: R&D outputs with five firms R&D cooperation and R&D competition (a=100, b=1, c=1, d=1, γ =70, n=5)

		R&D competition					Vertical cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	0.6503	0.5197	0.3869	0.2532	0.1196	0.6744*	0.5682*	0.4601*	0.3506*	0.2406*
	0.25	0.6863	0.5539	0.4196	0.2846	0.15	0.7416*	0.6342*	0.5248*	0.4141*	0.3028*
	0.5	0.7236	0.5891	0.4531	0.3165	0.1807	0.8114*	0.7025*	0.5915*	0.4793*	0.3665*
	0.75	0.7623	0.6255	0.4874	0.3491	0.2119	0.8843*	0.7736*	0.6607*	0.5466*	0.4319*
	1	0.8024	0.663	0.5226	0.3824	0.2436	0.9608*	0.8478*	0.7327*	0.6164*	0.4995*

		Horizontal cooperation					Generalized cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	0.119	0.2388	0.3604	0.4847*	0.6127*	0.2382	0.48	0.7289*	0.989*	1.265*
	0.25	0.269	0.3912	0.5163*	0.6454*	0.7796*	0.5414	0.7927*	1.0563*	1.3371*	1.6408*
	0.5	0.4222	0.5482	0.6784*	0.8141*	0.9564*	0.8573*	1.1247*	1.4106*	1.7211*	2.0639*
	0.75	0.5803	0.7118*	0.849*	0.9932*	1.1461*	1.1942*	1.4856*	1.8034*	2.1558*	2.5536*
	1	0.7455	0.8843*	1.0306*	1.1859*	1.3522*	1.5623*	1.8879*	2.2505*	2.6617*	3.1374*

[a] If R&D cooperation results in higher R&D outputs than R&D competition, the R&D output level is followed by an asterisk (*).

TableA6: Profits with five firms R&D cooperation and R&D competition (a=100, b=1, c=1, d=1, γ =70, n=5)

		R&D competition					Vertical cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	1309.7	1321.7	1326.2	1323.1	1312.6	1310*	1323.7*	1331.4*	1332.9*	1328.3*
	0.25	1333.1	1341.8	1342.7	1335.9	1321.5	1335.6*	1347.7*	1353.6*	1353.2*	1346.4*
	0.5	1359.3	1364.4	1361.5	1350.9	1332.6	1366.2*	1376.7*	1380.7*	1378.2*	1369.2*
	0.75	1388.4	1389.8	1383	1368.2	1345.9	1402.2*	1410.9*	1413*	1408.2*	1396.8*
	1	1420.8	1418.1	1407.1	1388.1	1361.5	1444.2*	1451.1*	1451*	1443.8*	1429.8*

		Horizontal cooperation					Generalized cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	1299.9	1309	1324.4	1346.5*	1375.7*	1302.6	1319.9	1349.8*	1393.4*	1452.8*
	0.25	1312.2	1329.3	1353.1*	1384.2*	1423.3*	1326.2	1359.3*	1406.7*	1470.5*	1554.2*
	0.5	1334.6	1360.1	1393.2*	1434.5*	1485.1*	1369.7*	1421*	1489.4*	1578.7*	1694.1*
	0.75	1367.7	1402.7*	1446.2*	1499.4*	1563.6*	1436.3*	1509.6*	1604.9*	1727.9*	1887.1*
	1	1412.7	1458.6*	1514.3*	1581.6*	1662.4*	1531.2*	1632.8*	1763.9*	1933.9*	2156.7*

[a] If R&D cooperation results in higher profits than R&D competition, the profit level is followed by an asterisk (*).

TableA7: R&D investments with ten firms R&D cooperation and R&D competition (a=100, b=1, c=1, d=1, γ =70, n=10)

		R&D competition					Vertical cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	3.1218	1.8942	0.9531	0.3272	0.0285	3.1819*	2.051*	1.1475*	0.4975*	0.1148*
	0.25	3.3467	2.0496	1.0522	0.381	0.0448	3.5724*	2.3479*	1.3595*	0.6329*	0.181*
	0.5	3.5887	2.2165	1.159	0.44	0.0648	4.004*	2.6772*	1.5968*	0.7884*	0.2637*
	0.75	3.8493	2.3958	1.2739	0.5044	0.0889	4.4821*	3.0428*	1.8623*	0.9657*	0.3638*
	1	4.1306	2.589	1.3978	0.5746	0.117	5.013*	3.4493*	2.1591*	1.1671*	0.4828*

		Horizontal cooperation					Generalized cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	0.0283	0.3014	0.8774	1.786*	3.076*	0.1131	1.2135	3.5912*	7.5017*	13.396*
	0.25	0.3501	0.9612	1.9094*	3.2457*	5.0458*	1.4113	3.9437*	8.0481*	14.203*	23.204*
	0.5	1.0492	2.0376	3.4211*	5.2788*	7.724*	4.3155*	8.6194*	15.044*	24.431*	38.19*
	0.75	2.1706	3.6024*	5.519*	8.0384*	11.329*	9.2166*	15.921*	25.71*	40.081*	61.636*
	1	3.7896	5.7666*	8.3623*	11.752*	16.188*	16.835*	27.045*	42.058*	64.65*	99.962*

[a] If R&D cooperation results in higher R&D investments than R&D competition, the R&D investment level is followed by an asterisk (*).

TableA8: R&D outputs with ten firms R&D cooperation and R&D competition (a=100, b=1, c=1, d=1, γ =70, n=10)

		R&D competition					Vertical cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	0.4224	0.329	0.2334	0.1367	0.0403	0.4264*	0.3423*	0.2561*	0.1686*	0.081*
	0.25	0.4373	0.3422	0.2452	0.1475	0.0505	0.4518*	0.3663*	0.2787*	0.1902*	0.1017*
	0.5	0.4528	0.3559	0.2573	0.1585	0.0608	0.4783*	0.3911*	0.3021*	0.2122*	0.1227*
	0.75	0.469	0.37	0.2698	0.1697	0.0712	0.5061*	0.417*	0.3262*	0.2349*	0.1442*
	1	0.4858	0.3846	0.2826	0.1812	0.0817	0.5352*	0.444*	0.3513*	0.2582*	0.1661*

		Horizontal cooperation					Generalized cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	0.0402	0.1311	0.2237	0.3191*	0.4188*	0.0804	0.2633	0.453*	0.6547*	0.8749*
	0.25	0.1413	0.2341	0.3299*	0.4302*	0.5364*	0.284	0.4747*	0.6782*	0.9009*	1.1515*
	0.5	0.2446	0.3408	0.4416*	0.5486*	0.6636*	0.4966	0.7018*	0.9272*	1.1815*	1.4773*
	0.75	0.3518	0.4532*	0.5609*	0.677*	0.8037*	0.7257*	0.9538*	1.2121*	1.5134*	1.8767*
	1	0.4648	0.5734*	0.6905*	0.8185*	0.9607*	0.9808*	1.2432*	1.5503*	1.9221*	2.39*

[a] If R&D cooperation results in higher R&D outputs than R&D competition, the R&D output level is followed by an asterisk (*).

TableA9: Profits with ten firms R&D cooperation and R&D competition (a=100, b=1, c=1, d=1, γ =70, n=10)

		R&D competition					Vertical cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	792.24	803.39	807.39	804.1	793.64	792.27*	804.01*	809.32*	808.02*	800.16*
	0.25	810.1	817.97	818.41	811.44	797.32	810.8*	820.07*	822.64*	818.44*	807.62*
	0.5	829.45	833.82	830.54	819.73	801.85	831.74*	838.38*	838.06*	830.8*	816.87*
	0.75	850.4	851.05	843.82	829.02	807.25	855.32*	859.14*	855.74*	845.23*	828.02*
	1	873.1	869.75	858.35	839.36	813.56	881.82*	882.6*	875.86*	861.88*	841.16*

		Horizontal cooperation					Generalized cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	787.79	793.87	806.6	826.48*	854.31*	788.39	800.3	825.72*	866.66*	926.62*
	0.25	794.95	808.44	829.16*	857.94*	895.99*	802.43	829.45*	872.3*	934.68*	1022.6*
	0.5	810.38	831.95	861.68*	900.86*	951.27*	833.38*	878.18*	943.04*	1034.3*	1162.4*
	0.75	834.83	865.54*	905.87*	957.67*	1023.6*	884.3*	951.74*	1046.5*	1179.5*	1369.3*
	1	869.52	911.01*	964.24*	1031.9*	1117.9*	960.76*	1059.1*	1197.4*	1395.1*	1687.3*

[a] If R&D cooperation results in higher profits than R&D competition, the profit level is followed by an asterisk (*).

TableA10: R&D investments with twenty firms R&D cooperation and R&D competition (a=100, b=1, c=1, d=1, γ =70, n=20)

		R&D competition					Vertical cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	1.0288	0.6078	0.2893	0.0859	0.0025	1.0338*	0.6306*	0.3187*	0.11*	0.0099*
	0.25	1.081	0.6399	0.3073	0.0942	0.0038	1.113*	0.685*	0.3531*	0.1286*	0.0155*
	0.5	1.1366	0.674	0.3262	0.103	0.0056	1.1988*	0.7438*	0.3904*	0.149*	0.0224*
	0.75	1.1959	0.7101	0.3462	0.1123	0.0076	1.2919*	0.8074*	0.4308*	0.1714*	0.0308*
	1	1.2592	0.7485	0.3674	0.1222	0.01	1.3931*	0.8764*	0.4745*	0.1959*	0.0406*

		Horizontal cooperation					Generalized cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	0.0024	0.0813	0.2764	0.6008*	1.0776*	0.0098	0.3278	1.1351*	2.5463*	4.7794*
	0.25	0.0886	0.2901	0.6218*	1.1075*	1.7838*	0.3574	1.193*	2.6408*	4.926*	8.4514*
	0.5	0.3041	0.6433	1.1379*	1.8257*	2.7632*	1.2525*	2.7376*	5.076*	8.683*	14.316*
	0.75	0.6652	1.1689*	1.8682*	2.8209*	4.1144*	2.8368*	5.2294*	8.9201*	14.692*	24.056*
	1	1.2004	1.9114*	2.8795*	4.1942*	5.9922*	5.3864*	9.1628*	15.077*	24.697*	41.339*

[a] If R&D cooperation results in higher R&D investments than R&D competition, the R&D investment level is followed by an asterisk (*).

TableA11: R&D outputs with twenty firms R&D cooperation and R&D competition (a=100, b=1, c=1, d=1, γ =70, n=20)

		R&D competition					Vertical cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	0.2425	0.1864	0.1286	0.0701	0.0118	0.2431*	0.1898*	0.135*	0.0793*	0.0237*
	0.25	0.2485	0.1912	0.1325	0.0734	0.0148	0.2522*	0.1978*	0.1421*	0.0857*	0.0297*
	0.5	0.2549	0.1962	0.1365	0.0767	0.0178	0.2617*	0.2062*	0.1494*	0.0923*	0.0358*
	0.75	0.2614	0.2014	0.1407	0.0801	0.0208	0.2717*	0.2148*	0.1569*	0.099*	0.0419*
	1	0.2682	0.2068	0.1449	0.0836	0.0238	0.2821*	0.2238*	0.1647*	0.1058*	0.0482*

		Horizontal cooperation					Generalized cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	0.0118	0.0682	0.1256	0.1852*	0.2481*	0.0236	0.1369	0.2547*	0.3814*	0.5226*
	0.25	0.0711	0.1287	0.1884*	0.2515*	0.3192*	0.1429	0.2611*	0.3885*	0.5306*	0.6949*
	0.5	0.1318	0.1917	0.2549*	0.3229*	0.3972*	0.2675*	0.3955*	0.5386*	0.7044*	0.9045*
	0.75	0.1949	0.2584*	0.3266*	0.4014*	0.4847*	0.4026*	0.5466*	0.7139*	0.9163*	1.1724*
	1	0.2618	0.3304*	0.4055*	0.4894*	0.585*	0.5548*	0.7236*	0.9282*	1.188*	1.5369*

[a] If R&D cooperation results in higher R&D outputs than R&D competition, the R&D output level is followed by an asterisk (*).

TableA12: Profits with twenty firms R&D cooperation and R&D competition (a=100, b=1, c=1, d=1, γ =70, n=20)

		R&D competition					Vertical cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	436.18	443.8	446.47	444.05	436.67	436.18*	443.97*	447.06*	445.3*	438.78*
	0.25	447.33	452.66	452.81	447.79	437.86	447.51*	453.28*	454.13*	450.03*	441.18*
	0.5	459.19	462.06	459.57	451.86	439.32	459.85*	463.45*	461.94*	455.4*	444.13*
	0.75	471.83	472.06	466.78	456.27	441.05	473.3*	474.57*	470.55*	461.43*	447.67*
	1	485.3	482.69	474.45	461.02	443.06	487.97*	486.71*	480*	468.17*	451.8*

		Horizontal cooperation					Generalized cooperation				
		h					h				
		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
v	0	434.67	438.01	446.21	459.68*	479.14*	434.77	441.4	458.01*	486.35*	529.7*
	0.25	438.32	446.78	460.55*	480.35*	507.32*	442.02	459.19*	488.22*	532.49*	597.87*
	0.5	447.37	461.43	481.58*	508.97*	545.3*	460.4*	490.13*	535.34*	602.06*	701.01*
	0.75	462.33	482.83*	510.64*	547.5*	595.99*	492.09*	538.24*	606.34*	707.43*	862.07*
	1	484.1	512.33*	549.74*	598.93*	663.86*	541.21*	610.71*	713.99*	872.33*	1129.1*

[a] If R&D cooperation results in higher profits than R&D competition, the profit level is followed by an asterisk (*).

Appendix B: Proofs of the proposition

Proofs of Proposition 1.

Proof that $x_{GC} > x_{HC}$.

$$X_{GC} - X_{HC} = \frac{20(A+B)Z}{9\Gamma - 20(A+B)^2} - \frac{10(A-B)Z}{9\Gamma - 10(A+B)^2}$$

The sign of the numerator is the sign of $\frac{9\gamma}{2b}$, which is positive, and the denominator is the product of the denominators of X_{GC} and X_{HC}, which are both positive.

Proof that $x_{VC} > x_{NC}$.

$$X_{VC} - X_{NC} = \frac{4(4A+B)Z}{9\Gamma - 4(4A+B)(A+B)} - \frac{(11A-B)Z}{9\Gamma - (A+B)(11A-B)}$$

The sign of the numerator is the sign of $(1+h+2v)$, which is positive, and the denominator is the product of the denominators of X_{GC} and X_{HC}, which are both positive.

Proof that $x_{VC} > x_{HC} if (h < 1)$.

$$X_{VC} - X_{HC} = \frac{4(4A+B)Z}{9\Gamma - 4(4A+B)(A+B)} - \frac{10(A+B)Z}{9\Gamma - 10(A+B)^2}$$

The sign of the numerator is the sign of $(1-h)$, and the denominator is the product of the denominators of X_{GC} and X_{HC}, which are both positive.

Proof that $x_{HC} > x_{NC} if (23h + 10v > 13)$.

$$X_{HC} - X_{NC} = \frac{10(A+B)Z}{9\Gamma - 10(A+B)^2} - \frac{(11A-B)Z}{9\Gamma - (A+B)(11A-B)}$$

The sign of the numerator is the sign of $(23h + 10v - 13)$, and the denominator is the product of the denominators of X_{GC} and X_{HC}, which are both positive.

Proof that $x_{GC} > x_{VC}\, if\, (7h + 5v > 2)$.

$$X_{GC} - X_{VC} = \frac{20(A+B)Z}{9\Gamma - 20(A+B)^2} - \frac{4(4A+B)Z}{9\Gamma - 4(4A+B)(A+B)}$$

The sign of the numerator is the sign of $(7h + 5v - 2)$, and the denominator is the product of the denominators of X_{GC} and X_{HC}, which are both positive.

Proof that $x_{GC} > x_{NC}\, if\, (11h + 10v > 1)$.

$$X_{GC} - X_{NC} = \frac{20(A+B)Z}{9\Gamma - 20(A+B)^2} - \frac{(11A-B)Z}{9\Gamma - (A+B)(11A-B)}$$

The sign of the numerator is the sign of $(11h + 10v - 1)$, and the denominator is the product of the denominators of X_{GC} and X_{HC}, which are both positive.

Appendix C: The definition and classification of high-technology industries

1. Semiconductor industry:

A semiconductor is a solid whose electrical conductivity can be controlled over a wide range, either permanently or dynamically. Semiconductor industry is the engine of drive technology, and is segmented into four main product categories: memory, microprocessors, commodity integrated circuit, and complex SOC (system on a chip). Taiwanese semiconductor industry's estimated production value reached US$33.2 billion in 2005.

2. Optoelectronics industry:

Optoelectronics is the study and application of electronic devices that interact with light. The total production value of Taiwan's optoelectronics industry was US$38.8 billion in 2006. the display industry generated US$25.2 billion, or 64.6 percent, followed by the optoelectronics storage industry (US$7.2 billion or 18.6 percent), and the optoelectronics input devices (US$2.6 billion or 7 percent), according to photonics industry and Technology Development Association (PITDA).

3. Telecommunications industry:

Telecommunications is the extension of communication over a distance. Telecommunications industry is primarily engaged in operating, maintaining, and/or providing access to facilities for the transmission of voice, data, text, sound, and video. Since the liberalization of the telecommunications sector, communications services have expanded steadily, reaching an estimated production value of US$15.4 billion in 2005, with the wireless segment contributing two-third and wired broadband networks the remainder of the total.

4. Computer component industry:

The range of computer component is widespread, including mobile phone components, NB/PC components, TFT components, semiconductors components, and optoelectronics components. Components can be classified according to their function, including active components, passive components, mechanical components, and functional components. According to the Industry and Technology Intelligence Services (ITIS), the electronic components industry was valued at US$20.7 billion in

2006, and was fueled mainly by IT product applications.

5. Computer peripheral industry:

A peripheral is a piece of computer hardware that is added to a host computer in order to expand its abilities. Computer peripheral industry includes computers, memory cards, card readers, industrial computers, POS, electronic consumption, redundant array of independent disks (RAID), and thermal module, etc.

6. System and equipment industry:

Other industries that are not covered by above industries are classified in this categories, including information system, information software, 3c distributors, and electronic equipment industries, etc.

Appendix D: Interview summary

This dissertation aims to discuss the relationship between R&D cooperation, R&D investments, R&D outputs, and financial performance. At first I analytically examine the impact of R&D cooperation on R&D investments, R&D outputs, and financial performance. Then I use high-technology industry to empirically test research hypotheses. However, theoretical and empirical research on R&D cooperation is difficult because it is a complex phenomenon. Having so much constantly going on in the real world, theoretical and empirical researchers can easily overlook or misread important variables. Therefore, in this appendix I interview two high-technology companies to supplement the findings of this study. In the first part, I describe the research subject. Then I raise some research questions and summarize the interview content.

1. Research subject

Corporation A is a multinational computer technology corporation headquartered in New York, USA. With almost 330,000 employees worldwide, the company is one of the world's largest computer companies with a continuous history dating back to the 19th century. Corporation A manufactures and sells computer hardware, software, infrastructure services, hosting services and consulting services in areas ranging from mainframe computers to nanotechnology. It has engineers and consultants in over 170 countries and has eight laboratories worldwide. According to the US Patent and Trademark Office (USPTO), Corporation A earned about 3,000 patents in 2005, more than any other company for the thirteenth consecutive year.

Corporation B is a Japanese multinational corporation, specializing in engineering consulting and electronic design automation (EDA). Established in 1976, it is listed on the Tokyo Stock Exchange; market capitalization is estimated as USD300 million as of March 2006. Corporation B's software is primarily used for designing printed circuit boards (PCB) and Multi-Chip Modules, or MCMs. Corporation B is the only major EDA company which specializes in PCB design software. Corporation B also provides engineering consultancy services to customers and partners worldwide. I list the fundamental summary of these two interviewed companies as Table C1:

Table D1: The fundamental summary of two interviewed companies

Company	Corporate A	Corporate B
Industry	Computer	EDA
Interview person	Enterprise storage server manager	Director (In charge of Taiwan subsidiary)
Products	Computer hardware, software, infrastructure services, hosting services and consulting services	EDA design tools
Listed or not	Listed company	Listed company
Firm size	Fortune 500 company with 330,000 employees worldwide	Sales: US$ 150 Million/2005 Employees: 1,000 people

2. Interview questions and interview summary

(1) Why does R&D activity need cooperation?

Company	Interview summary
Corporate A	R&D activity is a very complex and risky activity. Even a large-scale integrated circuit company can not monopolize the product innovation completely. Different kinds of companies can freely invest in R&D for new techniques. Therefore, R&D cooperation strategy is adopted widely because the innovation of products and techniques is the primary strategy that maintains the company’s existence. For example, we cooperate with Hitachi for hard disk drives. In this cooperation we focus on R&D and Hitachi focuses on manufacturing because they provide a large-scale economy. The profit of the hard disk drive sector increases from 3% to 8% due to this cooperation.
Corporate B	R&D is a process of cooperation. Each R&D behavior of products of the high-tech industry almost repeats a lot of horizontal and vertical cooperation, because each high-technology company is just the certain part of the high-technology industry chain. Few companies can be independent from

	this industry chain and complete development and design alone. For example, every company has to sell products to their customers, so the specification of the products has to be discussed through both parties. At the same time, the company also has to consider the support ability of the upstream suppliers. This process is the relationship of R&D cooperation. The business behavior of the high-technology industry is accomplished primarily through integrated activity. In addition, the strength, the method, and the frequency of cooperation would be different because of the different characteristics of industries.
Conclusion	R&D activity is very complex, risky, and costly. Few companies can complete R&D independently, even a very large-scale company. Most of the R&D activity is accomplished through cooperation with other companies in the industry chain.

(2) Why is R&D cooperation a widespread phenomenon in high-technology industry?

Company	Interview summary
Corporate A	Interoperability and building standards are very important for the high technology industry. Therefore, R&D cooperation is a popular phenomenon for the high technology industry to make compatible products. For example: we make a compatible server with HP, EMC, and help Lenovo to design a new PC. We also cooperate with Motorola on chips, but they are competitors in the market. It is a very common situation.
Corporate B	The high-technology company usually tries to cooperate with different companies to look for more beneficial results. For example, if the IC design company can cooperate with more system companies in the product R&D process and decide the specification and function, the products will be adopted by customers (system companies) with higher probability.
Conclusion	R&D cooperation is a widespread phenomenon for the high technology industry because high technology companies need to make compatible products and look for more beneficial results.

(3) In this study, R&D cooperation types include vertical cooperation, horizontal cooperation, and generalized cooperation. Which kind of R&D cooperation is more important for the high technology industry?

Company	Interview summary
Corporate A	All cooperation types are important. For example, we cooperate with Motorola on chips, but they are competitors in the market. It is a very common situation.
Corporate B	Vertical cooperation, horizontal cooperation, and generalized cooperation are very widespread phenomena in the high-technology industry. Vertical cooperation would be more closed to the profit of the company relative to horizontal cooperation. The proportion of vertical cooperation and horizontal cooperation would be different because of different industries. For example, IC design industry emphasizes system on chip (SOC). SOC is an idea of integrating all components of a computer or other electronic system into a single integrated circuit (chip). However, a single company can -not own all the techniques in the system, so it has to obtain techniques or complete a product together through cooperation with other companies. In the meantime it has to cooperate with the upstream EDA tool suppliers and downstream wafer manufacturing and packaging/testing companies to insure the yield rate of the products. More importantly, IC design company should have to cooperate with downstream system customers to insure the sales performance of products. Opposite to IC design industry, system assembling companies pay more attention to vertical cooperation. For example, notebook OEM companies emphasize the cooperation between suppliers and customers. They have to cooperate with upstream computer component suppliers to insure the specification and yield rate of the components, and rely on the upstream computer component suppliers' help to complete system design. Besides, when the product is more special, the relationship of vertical R&D cooperation is closer. Therefore, vertical cooperation, horizontal cooperation, and generalized cooperation are all important to high-technology industry.

Conclusion	According to interviews, vertical cooperation, horizontal cooperation, and generalized cooperation are all very popular in the high-technology industry. The cooperation types would be different due to different industry characteristics.

(4) Under the condition of information asymmetry, companies may engage in dishonest behavior. Is it a widespread phenomenon in R&D cooperative activities?

Company	Interview summary
Corporate A	I believe that it goes both ways. In my experience there are a lot of instances of corporate espionage — we have a series of security procedures to prevent leaking of sensitive information. At the same time, we have a lot of procedures to handle licensed material belonging to other companies in order to prevent the accidental violation of trade secrets. In other words, we do not engage in corporate espionage and take serious steps to protect its partners as well. That is part of the corporate culture here. But, that is certainly not true of the industry as a whole. Currently there are a number of high profile lawsuits of technology companies suing each other over trade secrets and patent violations. There are also a number of lawsuits over one company recruiting people from another company in hopes of gaining inside information. It happens all the time. So, I believe that the importance of strategic relationships and alliances requires companies to behave in a moral manner, but companies without continued strategic relationships probably would be more tempted to engage in corporate espionage.
Corporate B	In spite of vertical cooperation or horizontal cooperation, the background of cooperation is mostly because both parties have the techniques or specialties that the other party does not have. Opportunistic behavior is related to the property of cooperation results, the scale of both parties, and industry characteristics. However, due to the intensive competition and the profit-oriented technology industry, in general, it is difficult to find cooperation without accompanying opportunistic behavior.

Conclusion	Under the consideration of reputation, opportunistic behavior will result in the permanent punishment of being required to retreat from the R&D consortium. However, companies without continued strategic relationships probably would be more tempted to engage in corporate espionage.

(5) Is time-lagged effect an important issue in R&D cooperation research and practice?

Company	Interview summary
Corporate A	Yes. But it is very hard to determine time lag. It depends on the characteristics of products and R&D types. For large machines or fundamental change, it may take 3-5 years. For memory chips or incremental change, it may only take one year. It also depends on the market environment.
Corporate B	Horizontal and vertical cooperation are happening repeatedly and it is hard to identify each influence. Besides, the life cycle of products is getting shorter and shorter. Based on the consideration of reality, the time period of R&D cooperation does not usually last too long. Therefore, the influence of time-lagged effect becomes smaller and smaller. It is long enough to consider the test of three-year lagged effect in this study.]
Conclusion	Due to the complexity of R&D cooperation, it is hard to identify the time-lagged effect of R&D cooperation. In addition, the life cycle of products is getting shorter, and the issue of time-lagged effect is not so important nowadays.