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COMPETITION AND INNOVATION
– MICROECONOMETRIC EVIDENCE USING FINNISH DATA

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Abstract: The relationship between product market competition (PMC) and innovative activity has attracted the attention of many economists lately. In this study we elaborate the theory of Aghion *et al.* (1997, 2001) of an inverted-U relationship between competition and innovations. We provide a theoretical prediction of a complementary relationship between the incentive effects of PMC and R&D subsidies. We empirically test our complementarity prediction and that of an inverted-U relationship using Finnish firm level data. Our results suggest that the inverted-U relationship is fairly robust to all our innovation measures. We also find that the inverted-U relationship tends to be steeper when also direct R&D subsidies are considered. This result suggests that there exists complementarity between competition and R&D subsidies.

Key words: Product market competition, Innovation, R&D subsidies

JEL codes: O0, O30, O31, L10

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Tiivistelmä: Toimialojen kilpailullisuuden ja innovaatiotoiminnan välinen suhde on viime aikoina ollut vilkkaasti esillä taloustieteellisessä keskustelussa. Aghion *et al.* (1997, 2001) osoittavat että kilpailun ja innovaatioiden välillä vallitsee käänteisen U-käyrän muotoinen suhde. Laajennamme tässä tutkimuksessa ko. mallia ja osoitamme, että toimialojen kilpailullisuuden ja suorien tutkimus- ja kehitysavustusten (t&k-avustusten) välillä esiintyy komplementaarisuutta. Teoreettisia tuloksia testataan sitten suomalaisella yritystason aineistolla. Empiiristen tulokset osoittavat, että toimialojen kilpailullisuuden ja innovaatioiden välinen käänteisen U-käyrän muotoinen suhde on varsin vahva kaikille innovaatiomittareillamme. Empiiriset tulokset viittaavat siihen, että käänteinen U-käyrä kilpailun ja innovaatioiden välillä jyrkkenee, kun suorat t&k-tuet otetaan tarkasteluun mukaan. Tätä tulosta voidaan pitää osoituksena tietyn asteen komplementaarisuudesta kilpailun ja t&k-tukien välillä.

Asiasanat: Kilpailullisuus, Innovaatiot, T&k-tuet

JEL koodit: O0, O30, O31, L10

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Executive summary

The relationship between product market competition (PMC) and innovative activity has recently attracted the attention of many economists. Several significant contributions to both the Industrial Organization (IO) literature and the recent endogenous growth theory have dealt with the issue of the effects of product market competition on incentives to innovate. Although the standard IO theory as well as the early endogenous growth models predict a negative relationship between competition and innovation, the empirical findings of e.g. Blundell *et al.* (1995, 1999) and Nickell (1996) have raised the possibility of a positive correlation between product market competition and productivity growth within a firm or an industry. These empirical works have led to a new strand of literature where the disciplining effects of competition are introduced into the Schumpeterian paradigm of endogenous growth theory. Interactions between the disciplining effect of product market competition and that of good corporate governance have also been considered in a few studies.

The reconciliation of the Schumpeterian growth paradigm with the evidence of a positive relationship between product market competition and innovation has revitalized endogenous growth theory and lead to implications for policy that point to a need for reorganization of the R&D policy in most industrialized countries. Until recently, R&D policy has focused largely on public intervention in the form of subsidies to private R&D activity. The shared view between theorists and politicians has been that technological advances result from purposive R&D activity. The driving force of innovation is seen to be the reward in the form of post-innovation monopoly power that accrues to an innovator. R&D policy has focused on subsidizing private R&D activity and creating incentives through the protection of intellectual property rights, in order to secure the post-innovation monopoly rents. Although, according to the classical Schumpeterian view, economic rent created via market power is necessary for growth, the general view in economics is that monopoly power causes static (allocative) and dynamic (productive) inefficiencies, which result in a welfare loss (Motta, 2003).

In their elegant model, Aghion *et al.* (1992) show that growth is achieved through quality improvements of the existing technology resulting from a stochastic innovation process. Technological progress always contains a destructive side in that a new innovation implies a switch of monopoly power to an entrant. This implies a rather unrealistic market situation, where competing technologies cannot coexist, as the new innovation always make the old technology obsolete. Another point of criticism to the Schumpeterian paradigm is that the leapfrogging assumption (i.e. the monopolist market being overtaken by an entrant) fits poorly into the reality of many turbulent high-tech industries, where innovations contain tacit knowledge. The increasing amount of tacit knowledge attached to the technology makes imitation complicated and thus it is impossible for an entrant to sidestep the monopolist without breaking even.

In line with the above mentioned recent empirical findings of a positive relationship between productivity growth and product market competition, a more gradualist approach to technological progress has been presented in recent theoretical works by Aghion, Harris and Vickers (1997) and Aghion, Harris, Howitt and Vickers (2001). The leapfrogging approach is replaced by assuming "step-by-step" technological progress. That is, a firm that is lagging behind the technological leader in the industry must catch up with the leader before becoming a leader itself. In contrast to earlier Schumpeterian models competing technologies can coexist and the successful follower in the market intensifies the technology competition between the firms. In the striving for profits the firms are forced to reduce production costs by adopting more efficient production technologies. This creates incentives to innovate in the sense that an innovating firm could capture profits from the rival. Intense competition does not even allow the leader to rest on its laurels, because of the risk of being challenged by the follower.

In this paper, we extend the model of Aghion *et al.* (1997, 2001). First, we study how tax financed direct public R&D subsidies affect firms' dynamically optimal R&D decisions. Second, given the optimal R&D decisions of the firms, we study the interaction between the effectiveness of direct R&D subsidies and market structure. The theory of Aghion *et al.* (1997, 2001), and the extension developed in this paper, give rise to two main predictions. First, the relationship between product market competition and innovation has an inverted-U shape. Second, due to the complementarity between the incentive effects of intensified product market competition and an R&D subsidy, R&D subsidies tend to only steepen the inverted-U shape relationship; at extremely low and extremely high degrees of competition R&D subsidies may not have the desired effect of boosting innovative activity. On the contrary, at moderate levels of competition, firms receiving public R&D subsidies may innovate more than those not receiving any public aid.

Given these two rather straightforward theoretical predictions, we proceed to test the two predictions with Finnish firm level data. For this purpose, we have compiled a unique data set of Finnish firms, covering patenting activity, R&D information, R&D subsidies and accounting data.

In the empirical part of the paper, we find relatively strong evidence in favor of the inverted-U shape hypothesis in the Finnish data. Moreover, we find some evidence of complementarity between product market competition[1] and R&D subsidies. Namely, our results suggest that the inverted-U relationship tends to be steeper when also R&D subsidies are considered. However, this result should be interpreted with some caution, given that the direct effect of an R&D subsidy on our different measures of innovation was found to be negative, indicating that R&D subsidies on average tend to reduce the probability of innovating. A further finding is that in-

[1] Our measure for product market competition is the Lerner index or price cost margin which is constructed by calculating operating profit over value.of gross output.

dustries with more dispersed technology levels tend to innovate less than industries with more equal levels of technology across the firms. This result is also in line with the model of Aghion *et al.* (1997, 2001), which suggests that competition has a stronger impact on innovation for industries that are closer in technology space.

Regarding policy implications, our results quite strongly suggest that within-industry product market competition should be taken into consideration in designing public interventions to R&D activity. On one hand, our theoretical results suggest that the greatest additionality would be achieved in industries with moderate levels of competition. On the other hand, selective R&D subsidy schemes for middle-range productivity firms are a form of public intervention that might foster innovation. In order to increase the competitiveness of the industry, followers (i.e. companies lagging behind the leaders) should be encouraged to challenge the leader and thus intensify the competition. This form of subsidy should be directed at the middle-range-productivity firms as the least productive firms will be exposed to the selection effect. In other words, the risk of subsidizing the least productive firms is very high, as they might be enforced to quickly exit the market. Thus it can be argued that it is irresponsible to tax payers to subsidize the least efficient firms in the market, as the return on such investment is quite insecure. The selective R&D subsidy scheme can be criticized on the grounds that it does not offer a *juste retour* to industry leaders, who arguably still pay the highest corporate taxes. Thus, it would be difficult to justify such a policy.

A moderate version of the former public intervention is to encourage R&D joint ventures between large and small companies. As R&D costs for developing successful innovations are high and the time frames of innovations are short, it has become almost impossible for small entrants to compete with leaders in many industries. Joint ventures are one solution for small firms to overcome the thresholds of critical mass in many industries. For example, in the biotech industry, there are only a few companies in the world that can cover the critical mass for developing a successful concept. It is thus extremely important to get companies to work together in research consortia via publicly subsidized joint venture schemes. This holds especially for small countries, where the absolute mass of research is limited. In Finland, Tekes has developed instruments especially designed to promote national and international networking. The grants awarded to large companies are conditional on some degree of networking or other type of cooperation e.g. with subcontractors. This may importantly facilitate the knowledge spillovers between firms. Yet, one may recognice that in some case co-operation may reduce competition, when rival companies are working in close co-operation in the R&D projects.

Tiivistelmä

Innovatiivisuuden korostaminen taloudellisen kasvun lähteenä on vaikuttanut oleellisesti kehittyneiden maiden talouspolitiikkaan: inhimillisen pääoman ja koulutuksen merkitystä korostetaan, samoin elinikäistä oppimista ja innovaatiojärjestelmän tärkeyttä osana laajempaa kansantalouden instituutioiden verkostoa. Yhteiskunnallisessa keskustelussa törmää nykyään yhä useammin myös käsitteeseen osaamisperusteinen yhteiskunta. Suomeakin pidetään ja halutaan kehittää edelleen tiedon ja osaamisen yhteiskuntana. Jopa EU:n komissio on asettanut keskeiseksi tavoitteeksi Euroopan luotsaamisen 10 vuodessa yhdeksi maailman kilpailukykyisimmistä osaamisperusteisista yhteiskunnista maailmassa. Mutta miten tähän päästään ja mikä on julkisen toiminnan rooli tässä pyrkimyksessä, ei ole lainkaan itsestään selvää.

Perinteisesti, julkisen t&k –politiikan takana on ajatus, että yritykset voivat allokoida liian paljon, tai liian vähän resursseja uuden tiedon tuottamiseen. Tämä voi johtua erilaisista markkinoiden epätäydellisyyksistä kuten rahoitusmarkkinoiden toimimattomuudesta, mutta myös tiedon julkishyödykkeen ominaisuuksista tuotannontekijänä. Tieto muistuttaa julkista hyödykettä siinä mielessä, että sen toistamiseen ei liity kustannuksia.

Toisin kuin julkista hyödykettä tietoa pystytään kuitenkin sulkemaan pois muiden käytöstä esimerkiksi patentein tai rajoittamalla muuten tiedon leviämistä. Markkinoiden toimiessa epätäydellisesti, patentit varmistavat ainakin väliaikaisesti monopoliaseman jonkin tuotteen tai tuotantotavan suhteen. Ns. schumpeteriläisen näkemyksen mukaan monopolivoitot toimivat puolestaan innovaatiotoiminnan kannustimena, koska niiden avulla voidaan korvata teknologian kehittämisestä aiheutuvia kustannuksia. Tämän seurauksena tutkimus- ja kehitystoiminnan (t&k –toiminnan) tukemisessa on perinteisesti korostettu suoria t&k –avustuksia ja patenttipolitiikkaa. Koko kansantalouden tasolla innovaatioiden yleiseen käyttöön päästäminen ja imitoinnin mahdollistaminen olisi suuri, mutta samalla voitto-

jen aleneminen johtaisi lopulta myös t&k-toiminnan lamaantumiseen. Kaikkia kilpailua lisääviä tekijöitä, kuten esimerkiksi patenttisuojan liberalisointia pidetään taloudellisen kasvun kannalta haitallisena. Siten esimerkiksi innovaatioiden omistusoikeuksien suojeleminen patenttien muodossa on perinteisen schumpeteriläisen teorian kannalta oleellinen osa pitkän aikavälin kasvua edistävää politiikkaa: uusien innovaatioiden patenttisuojan avulla varmistetaan että yritysten innovaatiohalukkuus pysyy korkeana monopolivoittojen vuoksi.

Talousteoreettisissa malleissa tähän johtopäätökseen tullaan ensisijassa siitä syystä, että tuotekehityksen kärjessä olevien yritysten oletetaan kilpailun kiristyessä lopettavan innovoinnin. Tämä oletus lienee varsin epärealistinen ja kuvaa huonosti kilpailuasetelmia teknologiamarkkinoilla. Näkemys kilpailun haitallisuudesta on myös ristiriidassa klassisen talousteorian kanssa, jonka mukaan kilpailu on terveellistä taloudelle tehokkuussyistä. Esimerkiksi Michael Porterin (1990) teorian mukaan kilpailu kannustaa yrityksiä differentioimaan tuotteita ja tehostamaan toimintatapoja johtavan markkina aseman säilyttämiseksi ja kustannustehokkuuden lisäämiseksi. Samaan johtopäätökseen ovat tulleet Geroski (1994), Nickell (1996) ja Blundell, Griffith ja Van Reenen (1999) empiirisissä tutkimuksissaan, joiden tulokset viittaavat positiiviseen korrelaatioon kilpailun ja yritysten innovatiivisuuden välillä.

Uudet näkemykset kilpailun, yritysten innovoinnin ja tätä kautta tuottavuuden välisestä riippuvuudesta korostavat innovaatioiden ja kilpailun käänteisen U-käyrän muotoista suhdetta (Aghion, Harris and Vickers (1997) and Aghion, Harris, Howitt and Vickers (2001)). Käsillä olevassa työssä keskeisen mielenkiinnon kohteena ovat juuri kyseiset mallit.

Kuten schumpeteriläisissäkin malleissa, näissä malleissa voitontavoittelu pakottaa yritykset innovoimaan: tuotekehityksen tavoitteena on tuoda markkinoille laadullisesti parempia tuotteita kuin kilpailija ja siten saavuttaa monopoliasema. Schumpeteriläisistä malleista poiketen, rinnakkaiset teknologiat voivat kuitenkin kilpailla keskenään teknologiajohtajuudesta ja siten kilpailla ainakin väliaikaisesta monopoliasemasta. Samanaikaiset kilpailevat teknologiat luovat lisäkannustimia innovoinnille ja tehokkaampien tuotantoprosessien suunnittelulle. Yritykset eivät voi kuitenkaan vapaasti imitoida markkinoilla jo olevaa teknologiaa ja vain aivan uusinta teknologiaa pystytään suojelemaan patenteilla. Tämä johtaa kilpailutilanteeseen, jossa yritykset voivat olla tasoissa (tasapelitilanne) tai tilanteessa, jossa jokin yritys on teknologiajohtaja-asemassa suhteessa toisiin yrityksiin.

Näissä malleissa, kilpailun kiristymisen vaikutus tuotekehittelyyn on erilainen tasapelitilanteissa ja tilanteissa, missä yritysten teknologinen taso eroaa toisistaan (seuraaja-johtaja tilanne) Tasapelitilanteessa olevan yrityksen motiivina tuotekehittelylle on pyrkimys erilaistaa yritysten välistä kilpailutilannetta. Tällöin kilpailun kiristyminen itse asiassa kannustaa yrityksiä lisäämään tuotekehittelyä. Tätä voidaan perustella sillä, että kun kilpailu kiristyy tasapelitilanteessa, myös voitot vähenevät. Yritykset pyrkivät tällöin "pakenemaan"kilpailutilannetta tuotekehityksen avulla. Tätä kilpailun innovaatioita lisäävää vaikutusta voidaan kutsua kilpailun pakenemisvaikutukseksi.

Tilanteessa, jossa yritysten teknologinen osaaminen eroaa toisistaan, kiristyvä kilpailu puolestaan vähentää seuraajan kannustimia innovoida. Tämä johtuu siitä, että tasapelitilanteen saavuttaminen sisältää pienempiä voitonmahdollisuuksia kuin aikaisemmin: kiristyvä kilpailu hidastaa seuraajan tuotekehitystoimintaa. Kilpailun innovaatioita heikentävä vaikutus on siten schumpeteriläisen mallin mukainen. Kilpailun kiristymisen kokonaisvaikutus innovointeihin ja talouden kasvuun seuraa lopulta ns. koostumisvaikutuksesta. Sen voidaan ajatella kuvaavan talouden eri toimialojen kilpailutilanteiden muuttumista. Esimerkiksi innovaatioiden omistusoikeuksien löysääminen saattaa nopeuttaa innovaatioiden keskimääräistä syntymistahtia lisäämällä niiden toimialojen osuutta taloudessa, missä yritykset ovat tasapelitilanteessa. Tämä tarkoittaa myös sitä että, säännöstelypolitiikka (joka vaikuttaa kilpailuun) ja patenttien suojelu omistusoikeuksilla (joka vaikuttaa mahdollisuuksiin imitoida) eivät vaikuta pelkästään suoraan yritysten kannustimiin innovoida, vaan myös epäsuorasti kyseisen koostumisvaikutuksen kautta. Kun nämä edellä mainitut vaikutukset huomioidaan, kilpailun kiristymisen ja innovaatioiden välillä vallitsee lopulta käänteisen U-käyrän muotoinen suhde.

Edellä esitetyn käänteisein U-käyrä hypoteesin lisäksi tässä tutkimuksessa tarkastellaan myös kilpailun ja suorien t&k -avustusten yhteisvaikutusta samaisessa mallikehikossa. Teoreettiset tulokset viittaavat siihen, että kilpailun ja t&k –avustusten kannustinvaikutukset voivat olla toisiaan tukevia. Olennaista tässä yhteisvaikutuksessa on se, että suoran t&k –tuen innovointia kannustava vaikutus riippuu toimialan sisäisen kilpailun asteesta: Ensin, hyvin alhaisilla tai hyvin korkeilla kilpailun asteilla t&k –avustusten innovointia lisäävät vaikutukset voivat jäädä hyvin pieniksi. Toiseksi, toimialan sisäisen kilpailun ollessa kohtuullinen, suoran t&k –tuen innovointia lisäävä vaikutus voi olla merkittävä. (kts kuvio 1).

Mikäli edellä kuvatut hypoteesit pätevät reaalimaailmassa on tietenkin empiirinen kysymys. Käsillä olevassa tutkimuksessa näitä hypoteeseja testaan empiirisesti suomalaisella yritystason aineistolla. Yritystason aineisto sisältää tietoa yritysten taloudellisesta asemasta, patenteista, t&k –toiminnasta ja t&k –avustuksista. Empiirisessä tutkimuksessa yritysten innovatiivisuutta mitataan patenttien ja patenttisitaatioiden avulla. Toimialojen sisäistä kilpailullisuutta mitataan vuorostaan ns. Lerner indeksin avulla. Lerner indeksi operationalisoidaan empiirisessä tutkimuksessa laskemalla yritysten voittojen suhde tuotannon arvoon. Tämä kilpailullisuuden mittari voidaan sitten ulottaa toimialatasolle laskemalla yrityskohtaisten tunnuslukujen keskiarvo tai mediaani.

Empiiriset tulokset osoittavat teoreettisen hypoteesin mukaisesti, että kun kilpailullisuuden astetta arvioidaan Lerner indeksin avulla, kilpailun ja innovaatioiden välillä näyttää vallitsevan käänteisen U-käyrän muotoinen suhde (kts. kuvio 9).

Lisäksi tulokset osoittavat, että kilpailun ja t&k-tukien välillä esiintyy jonkinasteinen yhteisvaikutus. Käänteinen U-käyrä kilpailun ja innovaatioiden välillä jyrkkenee kun patenteilla mitattua innovatiivisuutta selitetään toimialan sisäisen kilpailun lisäksi myös yritysten saamilla t&k –tuilla. Tätä tulosta on kuitenkin syytä tulkita varauksella, sillä tulokset osoittavat toisaalta, että t&k -avustusten suorat vaikutukset ovat kaikilla patentteihin perustuvilla innovaatiomittareillamme negatiiviset. Tämä näyttäisi viittaavan siihen, että t&k –avustukset keskimäärin hidastavat toimialojen innovatiivisuutta (kts taulukko 12).

Päällimmäinen politiikkaimplikaatio, joka nousee esille tuloksista on se, että toimialojen sisäiset kilpailutilanteet tulisi ottaa huomioon myönnettäessä suoria t&k –avustuksia yrityksille. Tutkimuksen teoreettiset tulokset osoittavat, että t&k-avustukset tuottavat suurimman t&k –toiminnan lisäyksen kilpailun keskitasoilla. Selektiivinen t&k –politiikka, jossa tuottavuudeltaan keskitason yrityksiä tuettaisiin, saattaisi edistää innovaatiotoimintaa. Tuottavuudeltaan keskitason yritysten kannustaminen innovointiin voimistaisi parhaiten kilpailun innovatiivisuutta tukevaa vaikutusta. Matalimman tuottavuuden omaavia yrityksiä uhkaa konkurssi tai markkinoilta poistuminen, jolloin näiden tukeminen on epävarmaa ja jopa kannattamatonta. Selektiivisten t&k-tukien ongelmallisuus lienee siinä, että korkeimman tuottavuuden omaavat teknologiset johtajat, jotka usein myös ovat suurimmat veronmaksajat, eivät näin saisi vastinetta verorahoilleen ja siten tämä tukikeino tuskin saisi kannatusta.

Lievempi versio edellä mainitusta keinosta tasoittaa toimialan kilpailua on yhteistyösopimukset ja tutkimustyön verkottaminen. Pienten yritysten on monella teknologian alalla lähes mahdotonta tulla toimeen yksin, koska t&k –projektit ovat usein suuria ja pitkäkestoisia. Yhteistyösopimukset on tässä mielessä oivallinen keino edesauttaa kriittisen massan edellyttävien mittakaavojen saavuttamisessa. Esimerkiksi bioteknologian alalla vain harvat yritykset ovat riittävän suuria pystyäkseen yksin kehittämään taloudellisesti menestyksekkäitä tuotteita. Siten yhteistyötä on tärkeä edistää julkisin keinoin. Suomessa on kehitetty tukimuotoja jotka ovat omiaan lisäämään verkottumista ja yhteistyötä t&k –toiminnassa sekä kotimaassa että kansainvälisesti. Suurille yrityksille myönnetyt tuen ovat ehdollisia yhteistyölle pienempien yritysten kanssa. Tämä yhteistyön edistäminen saattaa olla tärkeässä asemassa tuottavuushajonnan pienentämisessä, jolla näyttäisi olevan negatiivinen vaikutus innovaatioihin. Samalla on kuitenkin huomattava, että yhteistyö voi joissakin tapauksissa myös rajoittaa kilpailua ja tätä kautta hidastaa innovaatioita.

1 Introduction

In modern societies, a large part of the long-run economic growth measured by per capita GDP, is explained by increases in the productivity of labour. Productivity of labour, in turn, can largely be explained by accumulation of physical capital and particularly, accumulation and spillovers of knowledge and technological progress. This has generated a growing literature that aims at understanding the complex processes leading firms to innovate and thus promote technological progress. At the same time, the recognized importance of innovations and the pace of technological change poses an important challenge for science, technology and innovation (STI) policy, since the markets may allocate too much, or too little, of its factors of production to Research and Development (R&D). The allocation of factors of production between, say, R&D and investment in physical capital may fail to be optimal due to externalities, or due to financial and informational frictions that do not allow for firms to make optimal decisions from the point of view of the whole economy.

Public policy can then influence the allocation of resources between different factors of production by directly changing relative factor prices, providing financial intermediation that enables firms to overcome financial frictions, or finding more indirect ways of overcoming informational frictions that exist in the markets. In countries with reasonably well developed innovation systems, all three intervention schemes are in place, yet they can take various forms and different degrees of emphasis.

In Finland, the national innovation system has gained essential public support during recent decades. In 1981 its GERD/GDP ratio (1.2 %) was clearly below the OECD average. But large increases in privately funded R&D, as well as increasing public investment in the national innovation system, has made Finland one of the highest ranking countries in the world with respect to R&D expenditure measure; its GERD/GDP was 3.42% in 2001. As for public interventions, a wide range of policies and organizations have been established with the specific aim of enhancing the performance of the Finnish innovation system. These agencies support most aspects of the innovation process, such as research and development, invention, venture capital finance, and internationalization.[2] The core of the national innovation system, or as Georghiou *et al.* (2003) say, the "implementation infrastructure", consists of the organizations operating under the auspices of the Ministry of Trade and Finance (MTI), that offers a wide range of innovation financing instruments and support services.

The motivation for public intervention is well founded and rarely questioned, but the particular form of intervention remains a subject of debate among endogenous growth theorists. In endogenous growth theories, technical advance is regarded as an economic variable, and it thus becomes a part of the optimal decision. It will be motivated by the quest for profits and substantially affected by the initial allocation of resources. As a result, the first natural question that arises is if perfectly competitive market continues to retain its efficiency, and if not, what would be an arrangement that would be superior. Alternatively, the question is whether we can continue to rely on individual self-interest to promote an efficient aggregate outcome. Since the thoughts of Schumpeter (1934), few economists believe that perfect competition efficiently allocates resources necessary to maintain technical advance.[3] Rather, it is likely that some degree of imperfection, combined perhaps with some degree of government financing of Research and Development is the best alternative. As a result, one may argue that a real challenge to successful public intervention, of whatever kind, resides in the complex interaction of economic incentives and market structure.

The importance of *ex ante* incentives and a market structure that induces firms

[2] For recent evaluations of the Finnish Innovation Support System, see Berghäll and Kiander (2003) and Georgiou *et al.* (2003).

[3] See Kamien and Schwartz (1975).

to conduct R&D activities was emphasized already by Schumpeter (1934) in his influential work on the theory of economic development. Schumpeter (1934) came to the conclusion that market power (or monopoly power) provides essential incentive for firms to innovate. According to Schumpeter, the incentives to perform R&D depend on the rent prospects of a successful innovator, while the incumbent monopoly has weak incentives to innovate, since it already enjoys monopoly rents. These ideas where further developed by Arrow (1962), who argued that an outside firm can gain more from an innovation than an incumbent by appropriating the profits of the incumbent. Arrow's argument was based on the view that knowledge has the properties of a public good in that it can be consumed by many simultaneously without impinging on the value to any individual user and that it is not possible to exclude others from making use of new knowledge.

This Arrow (replacement) effect, together with the ideas of Schumpeter (1934), led to the controversial paradigm according to which competition drives out innovative activity by reducing monopoly rents and is thus harmful to economic growth. Moreover, the problems related to excluding others from making use of knowledge created elsewhere suggests that returns on innovation as perceived by the individual innovator will diverge from those accruing to society as a whole.

Schumpeter's paradigm was later formalized in the New Growth Theory, which has developed since the mid-1980s. New Growth Theory considers long run growth to be endogenously determined by R&D and technological change. Indeed the New Growth Theory has had a strong impact on policymakers. For already several decades governments throughout the developed world have pursued policies to improve the innovation performance of domestic industries. Until recently, R&D policy has focused largely on public intervention in the form of subsidies to private R&D and developing the patent system, in order to remedy the non-excludability problem.

Schumpeter's original ideas and related more formal theories of economic growth[4] have correctly emphasized the interaction between market structure and ex ante incentives. However, these theories are still too rudimentary to fully describe strategic decision making in an environment where interaction between the firms is inherently dynamic and decisions are made under uncertainty (dynamic in the sense that the firms' pricing power can change over time and uncertain as regards *ex post* profits). Further, the idea of the importance of *ex post* monopoly rents has been contradicted by recent empirical work. The findings of Blundell *et al.* (1995) and Nickell (1996) suggest a positive correlation between product market competition and productivity growth within a firm or an industry.[5]

In line with the empirical findings of a positive relationship between productivity growth and product market competition, a more gradualist approach to technological progress has been presented in recent theoretical works by Aghion, Harris and Vickers (1997) and Aghion, Harris, Howitt and Vickers (2001). The leapfrogging approach is replaced by an assumed "step-by-step" technological progress. That is, a firm that is lagging behind the technological leader in the industry, must catch up with the leader before becoming a leader itself. In this framework, innovation incentives depend more on the difference between post-innovation and pre-innovation rents than on post-innovation rents *per se*. In this case, more intense product market competition may end up fostering innovations and growth as it may reduce a firm's pre-innovation rents by more than it reduces its post-innovation rents. In other words, competition may increase the incremental profits from innovation and thereby encourage R&D investment. These changes in assumptions enable an explicit analysis of the interplay between product market competition, innovations and

[4] See Romer (1990) and Aghion and Howitt (1992).

[5] Another criticism of the Schumpeterian paradigm is that the leapfrogging assumption (i.e. the monopolist market being overtaken by an entrant) fits poorly into the reality of many turbulent high-tech industries, where innovations contain tacit knowledge. The increasing amount of tacit knowledge attached to the technology makes imitation complicated and thus it is seldom possible for an entrant to sidestep the monopolist without first having to break even.

growth, by allowing the firms in an industry to race neck-and-neck.

The model of Aghion *et al.* (1997, 2001) generates the prediction of an existence of an inverted-U relationship between product market competition and innovation. This prediction has been tested against UK company data in a study by Aghion *et al.* (2002), where support was found for the theory of an inverted-U relationship between competition and innovation. It is worth noting, however, that already Kamien and Schwartz (1974) analyzed the existence of a degree of rivalry that would maximize the rate of technological development. They found that complete absence of rivalry may be most conducive to rapid introduction of innovations in some circumstances, while an intermediate degree of rivalry is more likely than monopoly to yield the most rapid development rate when innovator's expected quasi-rent is high.

In this paper, we make a rather modest but, we believe, useful theoretical extension to the model of Aghion *et al.* (1997, 2001). First, we study how tax financed direct public R&D subsidies affect the firms' dynamically optimal R&D decisions. Second, given the optimal R&D decisions of the firms, we study the interaction between the effectiveness of direct R&D subsidies and the market structure. It is shown that, at extremely low and extremely high degrees of competition, a direct R&D subsidy does not have the desired effect of boosting innovative activity. However, an elementary simulation exercise suggests that a direct R&D subsidy has a positive effect at moderate levels of competition.

Thus, the theory of Aghion *et al.* (1997, 2001) and the extension developed in this paper give rise to two predictions: (*i*) The relationship between product market competition and innovation has an inverted-U shape (*ii*) at moderate levels of competition firms receiving direct public R&D subsidy may innovate more than those not receiving any public aid.

Given the two rather straightforward theoretical predictions, we proceed to testing the two predictions with Finnish firm level data. In order to do this, we have compiled a unique data set of Finnish firms, covering patenting activity, R&D information, R&D subsidies and accounting data.

Our main results are that an inverted-U shape can be attained with each of constructed innovation measures and that there is evidence of a complementary relationship between competition and R&D subsidies. However, the results also suggest that, on the aggregate level, R&D subsidies tend to dampen the innovation rate of the economy.

The rest of the paper is organized as follows. Section 2 presents analytically the model of Aghion *et al.* (1997, 2001) and develops the extensions to the model. Section 3 discusses the empirical issues of which variables are best suited for measuring their theoretical counterparts developed in the previous section. Section 4 provides a description of the data, with emphasis on USPTO patent data, which in this study is combined for the first time with Finnish accounting data. Section 5 discusses the empirical methods used. Section 6 concludes and provides a short discussion of the main policy implications that derive from the results.

2 Theoretical issues of competition and innovation

The importance of the pace of technological change for the economic wellbeing of the society has given rise to a number of formal models that focus on economic incentives behind firms' innovative activities. These formal models are often referred to as endogenous growth models or models of technological progress. In this paper, we focus on a specific model of Aghion, Harris, Howitt and Vickers (2001), which gives a theoretical basis for an inverted-U relationship between degree of product market competition and rate of innovations. For convenience, we refer to this model as AHHV. The innovation process is assumed to be of a "step-by-step" character, where the follower in any industry must first catch up with the technological leader before being able to become a leader itself. In contrast to Schumpeterian growth models, the incumbent firm may also innovate in this model.

From this it follows, that innovation incentives depend more on the *difference* between post-innovation rents and pre-innovation rents than upon post-innovation rents *per se*. In particular, more intense product market competition (PMC) may stimulate firms' innovative activities because it may reduce the firms' pre-innovation rents by more than it reduces their post-innovation rents. In other words, competition may increase the incremental profits from innovating and thereby encourage R&D investment. This is in sharp contrast to the Schumpeterian prediction.[6]

2.1 Production technology

The model assumes that the economy is a continuum of intermediate goods producing industries indexed by $i \in [0, 1]$ and using labor as the only input. The final output of the economy, Y, is produced using input services from the intermediate

[6] The theoretical framework and the mathematical formalization presented in this section is that of Aghion *et al.* (1997, 2001) except where explicitly mentioned or ascribed to others.

industries, according to the following production function:

$$\ln Y_t = \int_0^1 \ln Q_i(t)\, di, \tag{2.1}$$

where $Q_i(t)$ denotes the output of industry i at time t, and $\ln Y_t$ denotes the log of the final output at time t.[7] It is further assumed that the final output is produced by a final goods sector using the aggregate of all the intermediate goods. Thus the model considers an economy with a fixed set of intermediate goods-producing sectors (each in the interval $[0, 1]$) and one final goods sector. Each intermediate goods producing industry is assumed to be *duopolistic* with respect to both production and research activities.[8] Thus, in each duopolistic industry, only one type of goods is produced. In other words, industry i produces two goods, A_i and B_i, each of the same type but with potential quality variations.

The assumption of duopolistic industries is important in the sense that it enables restriction of the analysis to the within-industry situation. This distinguishes the model from the Schumpeterian models with monopolistic competition, where the firms producing intermediate goods are seen as an entity, leading to formalizations of two or three-sector economies.[9] Moreover, duopolistic competition enables the analysis of the effects of changes in degree of competition on optimal production decisions of the firms within a particular industry.

As q_{Ai} and q_{Bi} respectively denote the output of the two firms in each industry

[7] The production function used by AHHV is of the functional form first introduced by Spence (1976) and later refined by Dixit and Stiglitz (1977), in which inputs are entered in an additively separable manner. The original form of the production function sums the discrete number of inputs, but the continuous nature of the inputs, and thus a shift to an integral over a continuum of inputs does not change the results (see Barro and Sala-i-Martin [1995]). In AHHV the range of varieties of intermediate goods is normalized to one.

[8] In the model, the intermediate goods-producing firms conduct the R&D themselves, with the objective of reducing production costs.

[9] See e.g. Aghion and Howitt (1992).

i, the industry output is generated according to:

$$Q_i = f\left(q_{Ai}, q_{Bi}\right), \tag{2.2}$$

where Q_i is an aggregate of the two goods produced by duopolistic industry i, defined by production technology $f(\cdot)$. Here $f(\cdot)$ is a symmetric subproduction function of the intermediate industry which is homogeneous of degree one in its two arguments and independent of i. In their model, AHHV focus on the particular case where the production technology has Constant Elasticity of Substitution (CES) and hence becomes:

$$f\left(q_{Ai,} q_{Bi}\right) \equiv \left(q_{Ai}^{\alpha} + q_{Bi}^{\alpha}\right)^{\frac{1}{\alpha}}, \alpha \in [0,1], \tag{2.3}$$

A higher $\alpha \in [0,1]$ reflects a higher degree of substitutability between the two production factors in industry i, q_{Ai}^{α} and q_{Bi}^{α}.[10]

The production function in (2.1) is logarithmically additive and separable for the quantity of goods Q_i. This implies that the marginal revenue of expenditure on intermediate inputs from any industry i is independent of the amount spent on intermediate inputs from any other industry, at any time t. As shown in Grossman and Helpman (1991), the logarithmic technology implies that the level of spending that maximizes output in (2.1) is attained when the final goods sector spends equal amounts on each intermediate goods-producing industry, at any time t. Thus, in equilibrium, the final goods sector spends a common amount on the output Q_i of each industry i. This common amount is normalized to unity using the expenditure as numeraire for the prices of the two goods in industries p_{Ai} and p_{Bi} at any time t. Thus the final goods sector chooses each q_{Ai} and q_{Bi} in order to maximize $f\left(q_{Ai}, q_{Bi}\right)$ subject to the budget constraint $p_{Ai}x_{Ai} + p_{Bi}x_{Bi} = 1$.[11] From this maximization

[10] A special case is when $\alpha = 1 \Rightarrow Q_i = q_{Ai} + q_{Bi}$. That is, when the two intermediate inputs produced in industry i are perfect substitutes.

[11] As will be discussed later, labor supply is assumed to be perfectly elastic. The wage rate $w(t)$ is considered to be exogenous (i.e. the only factor cost, as labor is the only input, will be

problem it follows that the demand functions facing the two firms in industry i are:

$$q_{Ai}\left(p_A, p_B, \alpha\right) = \frac{p_{Ai}^{\frac{1}{\alpha-1}}}{p_{Ai}^{\frac{\alpha}{\alpha-1}} + p_{Bi}^{\frac{\alpha}{\alpha-1}}} \quad \text{and} \quad q_{Bi}\left(p_B, p_A, \alpha\right) = \frac{p_{Bi}^{\frac{1}{\alpha-1}}}{p_{Ai}^{\frac{\alpha}{\alpha-1}} + p_{Bi}^{\frac{\alpha}{\alpha-1}}}. \tag{2.4}$$

The properties in (2.1) and (2.3) allow us to restrict the analysis to one industry and thus, the industry index i can be ignored.

2.2 Product-market competition

According to the above demand functions (2.4), the elasticity of demand $\left(\frac{\partial q}{\partial p}\frac{p}{q}\right)$, that each intermediate inputs-producing firm j faces is given by $\eta_j = \frac{(1-\alpha\lambda_j)}{(1-\alpha)}$ and where $\lambda_j = p_j q_j$, denotes the firms' revenue. Substituting (2.4) into the revenue equation gives the following symmetric revenue equations for the two firms producing goods A and B:

$$\lambda_j = \frac{p_j^{\frac{\alpha}{\alpha-1}}}{p_A^{\frac{\alpha}{\alpha-1}} + p_B^{\frac{\alpha}{\alpha-1}}}, \quad j = A, B. \tag{2.5}$$

Thus, under Bertrand competition, the equilibrium price of the inputs of each firm is:

$$p_j = \frac{\eta_j}{\eta_j - 1} c_j = \frac{1-\alpha\lambda_j}{\alpha\left(1-\lambda_j\right)} c_j, \; j = A, B, \tag{2.6}$$

and the equilibrium profit is:

$$\Pi_j = \frac{\lambda_j}{\eta_j} = \frac{\lambda_j\left(1-\alpha\right)}{1-\alpha\lambda_j}, \quad j = A, B. \tag{2.7}$$

Equations (2.5), (2.6) and (2.7) can be solved for unique equilibrium revenues, prices and profits. Given the degree of substitutability, α, the equilibrium profit of each

exogenous) and normalized to one. Thus the expenditure on output of industry i at time t is $P_i Q_i = 1$ for all i and t.

firm j is determined by its relative production cost. The relative production cost, z, is calculated by dividing the unit production cost of firm j by the unit production cost of the other firm $-j$, i.e. $z = \frac{c_j}{c_{-j}}$. This implies that an equiproportional reduction in both c_A and c_B would induce the firms to adjust the price in the same proportion without affecting the degree of competition and not hence firm's revenues and profits. Consequently, only a change in relative profit levels is of interest from the firm's point of view.

Formally, equations (2.5), (2.6) and (2.7) implicitly define a profit function $\phi(z, \alpha)$:

$$\Pi_A = \phi\left(\frac{c_A}{c_B}, \alpha\right) \quad \text{and} \quad \Pi_B = \phi\left(\frac{c_B}{c_A}, \alpha\right). \tag{2.8}$$

The substitutability parameter α in the profit function (2.7) corresponds to the standard measures of competition and can be used to parameterize the degree of competition within each industry. This can also be motived by the arguments of Boone (2000). Namely, he points out that any parameter positively affecting the profitability of having lower unit production costs or products of better quality than other firms is a suitable measure of product market competition. Examples of parameterizations of competition are the number of intermediate input varieties (and thus producers), a reduction in entry barriers, a switch from Cournot to Bertrand competition, and a reduction in import tariffs. All these parameterizations have a common feature: an increase in competition raises the profits of an efficient firm relative to the profits of a less efficient firm. In other words, competition reallocates profits from inefficient to more efficient firms. This is called the allocation effect. Another effect is that the absolute profit of the least efficient firms in the market is reduced by a higher degree of competition. These two effects together imply the effect that goes under the name *selection effect* of competition: more intense product market competition increases the relative market share of firms with lower unit production costs or better products. The reason why many studies examine relative profits is, according to Boone (2000), that the marginal cost differentials between firms in the market are mapped into profit differentials. This mapping becomes steeper as the competition becomes more intense, in the sense that a given cost differential is mapped into a larger profit differential.

More formally, α is a monotonically increasing transformation of the elasticity of substitution in demand $\left(\frac{1}{1-\alpha}\right)$ between the two rivals' outputs in any industry. Parameter α is also a monotonically increasing transformation of the elasticity of demand $\left(\frac{1-\alpha\lambda}{1-\alpha}\right)$ faced by the firm, given it's market share λ of the industry revenue.[12] The latter elasticity is in fact an inverse of the so-called Lerner index:

$$LI = \frac{1-\alpha}{1-\alpha\lambda}, \tag{2.9}$$

which is often used to characterize market structure in the literature of Industrial Organization. Consequently, by any of the measures, the degree of market power is measured inversely by the parameter α. In the extreme case where $\alpha = 0$, there is a minimal degree of competition, while in the opposite case where $\alpha = 1$, the two firms are engaged in Bertrand competition with undifferentiated products. The latter case results in perfect competition where both firms use the same production technology and hence have the same unit production cost.

A prominent feature of the Lerner index is that it can easily be operationalized empirically. Moreover, AHHV show that the Lerner index is a decreasing function of the substitutability parameter α, even after taking into account that the firm's Lerner index also depends on the firm's market share λ. In order to remove the effects of market share, AHHV show that a measure for α, derived by rewriting (2.9), could be used as an alternative measure of competition. In their empirical

[12] Also Boone (2000) argues that any parameter increase resulting in increased relative profitability of technologically more advanced firms is a suitable measure of product market competition.

analysis, AHHV find that both measures produce similar results. We shall discuss the empirical operationalization of the Lerner index in more detail in section 3.2.

2.3 Technology levels, R&D and innovation

Each firm uses labor as the only input according to a constant-returns production function. As the wage rate is taken as given, and the unit costs of production of the two firms in an industry, c_A and c_B, are independent of the quantities produced, a firm's unit cost depends only on the level of its technology. The unit cost of production can be expressed as $c_j = w\Lambda$, where w is the economy-wide wage rate and Λ is the firm's unit labor requirement. For convenience, the economy-wide wage rate can be normalized to one and thus the firm's unit cost can be written simply as $c_j = \Lambda$. Technological progress results in a decreasing unit labor requirement, Λ, and hence in a decrease in unit cost. Consequently, technological progress in the model is characterized as "labour saving technological progress", similarly to many standard models of economic growth.

The most essential novelty of the model is in the way technological progress takes place within each industry. Namely, it is assumed that technology advances through an innovation process where each new innovation improves productivity step-by-step. This assumption implies that it is impossible to leapfrog from being a follower (i.e. having higher production costs than the rival) in a duopoly to becoming a leader in the duopoly (i.e. having lower production costs than the rival) without first breaking even. Given this, a situation where the firms have similar production technologies and thus similar unit costs of production, must occur in the economy for the leader position to change. We refer to these cases as "neck-and-neck" situations in what follows. The step-by-step assumption implies a more gradualist approach to innovation as compared with the Schumpeterian tradition. One may interpret this as a situation where the companies producing intermediate goods must pursue

R&D activity themselves instead of subcontracting for it. This is in line with reality of many firms, especially of those in high-tech industries, where innovative activities are carried out e.g. in separate R&D departments.

More formally, productivity is assumed to improve by a factor $\gamma > 1$ each time a firm innovates and thus the unit labor requirement falls by γ with each new innovation. Consequently, the relative cost of a firm that is n steps ahead (or n steps behind if $n < 0$) of its rival is $z = \gamma^{-n}$.[13] Accordingly the firm's profit function is $\phi(\gamma^{-n}, \alpha)$, which varies with the size of its lead and the degree of competition, α. Importantly, it can be shown that a firm's profit increases with the firm's lead, n. Moreover, the positive effect of the increase in lead vanishes when the intermediate goods A and B become perfectly inelastic, i.e. as $\alpha \to 0$. In other words, as the product markets become more competitive, technological leadership becomes less profitable for the firm, in line with the traditional Schumpeterian paradigm.

2.3.1 R&D cost function

In order to pursue innovative activities, the firms hire R&D personnel. Each firm's R&D effort is thus measured in units of labor, which we now denote by x.[14] R&D activity (i.e. the innovation process) is however uncertain and thus the innovations do not increase linearly with an increase in R&D effort. It is instead assumed that the arrival of a new successful innovation follows a Poisson process, where a firm at the technological frontier (leader or neck-and-neck firm) moves one step ahead with

[13] It is assumed that the follower, who is n steps behind the leader, can catch up immediately whenever she innovates. Thus a single innovation is enough for the follower to catch up with the leader. Becoming a leader is still a step-by-step process, because it takes two innovations to go from being a follower to becoming a leader. The one-step case is an alternative case where each firm can move only one step ahead by innovating.

[14] Each industry is assumed to be duopolistic with respect to R&D as well as production. This is a strong duopolistic assumption, implying that innovations are only made by firms currently in the market. It further excludes the relaxing of the entry barriers and hence excludes increasing the number of firms in the industry as a means of increasing competition.

the Poisson hazard rate x.[15] This Poisson assumption means that the probability of a successful innovation depends only on the firm's own R&D effort, and not on its previous innovation history.

One can naturally think of a number of reasons why past research effort should make success more likely, such as accumulation of firm-specific knowledge and experience. However, there might also be reasons that would make succeeding innovation less likely, for instance, because simple innovations were made first or because of more subtle issues related to incentives and deteriorating learning capacity of R&D personnel. The Poisson assumption may thus be more plausible than it seems at a first glance. In any case, what is important is that the innovation process is inherently stochastic, and the units of labor x employed in the R&D sector characterize both the R&D effort and the probability (here called hazard rate) of a successful innovation.

The technological follower has the advantage of imitation, and can thus have a higher probability of innovating than the leader, at the same amount of R&D. By employing the same amount of R&D personnel as the leader, x, the follower innovates and hence catches up, at the hazard rate $(x + h)$. One way of interpreting the parameter $h \geq 0$ is as approximating the absence of legal and regulatory impediments associated with intellectual property right (IPR) regulations. The more stringent the IPR rights (lower h), the more difficult it is for followers to directly exploit rivals' technological discoveries. In this sense, the parameter h measures complementary R&D spillovers.

[15] A Poisson hazard rate means that some random event X is governed by a Poisson process. This is the probability of an event happening between t and $t + dt$ conditional to the event not having taken place by time t. Analytically, it means that the chance of event X occuring before t is a random variable, whose distribution is exponential with the parameter x, that is, the arrival rate $F(t) \equiv$Prob[event occurs before t] $= 1 - e^{-xt}$ Thus the probability of the event occuring sometime between t and $t + dt$ is approximately $\mu e^{-xt} dt$. In particular, the probability of an event occuring within dt from now (when $t = 0$) is approximately μdt. In this way μ becomes the probability per unit of time that the event will occur now, or equally the flow probability of an event. Cf. Aghion and Howitt (1998).

Finally, the cost function of R&D (in units of labor), $\psi(x)$, is assumed to be quadratic and thus an increasing and convex function of R&D effort:

$$\psi(x) = \frac{\beta x^2}{2}, \tag{2.10}$$

where β is the wage rate of workers employed in the R&D sector. The assumption that firms face rising marginal costs in R&D has important implications for the model in the sense that it allows both the incumbent firm and the follower to conduct R&D activity simultaneously.

2.3.2 Optimal R&D intensity

The optimization problem that firms face in the duopoly is to maximize the expected present value of the profit flow affected by an innovative advance by the firm.[16] The only thing relevant for the firm in setting its R&D investment strategy is the technological gap between firms (not the technology level itself) and whether the firm is a leader, neck-and-neck or follower. It is thus the relative profit, and not the level of profit, that determines firms' strategies. The firms take into consideration that the probabilities of innovation outcomes depend on their R&D effort, x. The same R&D effort gives different probabilities for success (i.e. for taking out a successful innovation) depending on the state of the firm. That is, whether the firm is a leader, follower, or in a neck and neck situation.

Let x_0, x_n and x_{-n} denote respectively the R&D efforts of a neck-and-neck firm, a leader in an industry with the technological gap $n \geq 1$ and a follower in the industry. R&D efforts represent the innovation probabilities, taking into account that the

[16] AHHV only consider pure strategic equilibria in perfect Markov strategies when formulating the strategies of how firms optimize their R&D effort in a dynamic duopolistic game. Thus the optimization problem follows a stationary Markov decision process. AHHV assume that Markov equilibrium in the industries always exist in the model and this assumption allows the use of Bellman's principle of optimality and hence solving Bellman equations via dynamic programming. The Bellman equations are used in this model to define an optimum in continuous time under uncertainty. As the optimum is defined in continuous time, the profit is a flow.

R&D process is a stochastic Poisson process. Further, V_0, V_n and V_{-n} denote the expected values of their respective profits. The equilibrium rate of interest is the time preference, r. The expected present value of the profits of a leader, V_n, can be derived from the Bellman equation where the R&D effort of the follower, x_{-n}, is taken as given by the leader. The wage rate β is also taken as given, assuming an infinitely elastic supply of labor. This gives rise to the following Bellman equations:

$$\begin{aligned} rV_n &= \pi_n + x_n \left(V_{n+1} - V_n\right) + \left(x_{-n} + h\right)\left(V_0 - V_n\right) - \frac{\beta \left(x_n\right)^2}{2} \\ rV_{-n} &= \pi_{-n} + x_n \left(V_{n+1} - V_n\right) + \left(x_{-n} + h\right)\left(V_0 - V_n\right) - \frac{\beta \left(x_{-n}\right)^2}{2} \\ rV_0 &= \pi_0 + x_0(V_1 - V_0) + \overbrace{x_0}^{\text{R\&D effort of a rival}} \left(V_{-1} - V_0\right) - \frac{\beta \left(x_0\right)^2}{2} \end{aligned} \tag{2.11}$$

The equations in (2.11) can be explained in words: the annuity value at date t of currently being a technological leader in an industry with gap n, rV_n, equals the current profit flow, π_n, minus the current R&D cost $\left(\frac{\beta x^2}{2}\right)$, plus the discounted expected capital *gain* from making an innovation and thereby moving one further step ahead of the follower, $x_n \left(V_{n+1} - V_n\right)$, plus the discounted expected capital *loss* from having the follower catch up. The annuity value of a follower, rV_{-n}, is explained similarly. In the Bellman equation for a neck-and-neck firm, the R&D efforts, x, of both firms are equal in symmetric Nash equilibrium, leaving both without a help factor, h, and hence implying that each firm takes into account only its own R&D cost in its investment decisions.

Each firm will choose its R&D effort to maximize its current annuity value. In particular, the leader's maximization problem is:

$$V_n = \max_x \left\{ \pi_n + x_n \left(V_{n+1} - V_n\right) + \left(x_{-n} + h\right)\left(V_0 - V_n\right) - \frac{\beta \left(x_n\right)^2}{2} \right\} \tag{2.12}$$

The maximization problem can be derived similarly for V_0 and V_{-n}. Thus each firm's R&D effort is strictly proportional to the incremental value that follows from innovating. Assuming the interior solution exists, the limiting value function of the leader is differentiable with respect to the leaders R&D effort, x_n. This leads to the following first order condition:[17]

$$V_n'(x) = \frac{\partial V_n}{\partial x_n} = (V_{n+1} - V_n) - \beta(x_n) = 0 \tag{2.13}$$

$$\iff x_n = \frac{(V_{n+1} - V_n)}{\beta}. \tag{2.14}$$

The first order conditions for the the neck-and-neck firm, V_0, and the follower, V_{-n}, are respectively:[18]

$$x_{-n} = \frac{(V_0 - V_{-n})}{\beta}, \tag{2.15}$$

$$x_0 = \frac{(V_1 - V_0)}{\beta}. \tag{2.16}$$

The obtained x_n, x_{-n} and x_0 are the flow innovation probabilities of, respectively, the leader, the follower, and the neck-and-neck firm. Equations (2.11)∼(2.16) then solve recursively for the sequence of $\{x_n, x_{-n+1}, V_n, V_{-n+1}\}_{n\geq 0}$.

2.4 One-step case

It has been argued that leaders have less incentive than followers to perform R&D. In her controversial article Reinganum (1983) develops a non-deterministic R&D game between two firms such that when an innovation is drastic (i.e. the innovator will force the other producers out of the market) the leader will invest less in R&D

[17] The corner solutions can be ignored here because the incremental value of R&D is never negative.

[18] As mentioned, it is assumed that the neck-and-neck firm takes the competitors R&D effort, x_0, as given while maximizing its own R&D effort. Therefore it can be ignored while differentiating wrt x_0 for the neck-and-neck firm's optimal R&D effort.

than the follower, as the two firms are otherwise alike.[19]

AHHV discuss a special case where the size of the innovation, γ, is very large and the leaders do not conduct R&D, which is in line with the assumptions of Reinganum (1983). In this case, the length of a lead cannot be greater than one innovation. AHHV show that when $\gamma \longrightarrow \infty$, the equilibrium level of R&D effort of the leading firm will approach zero. When γ is very large, even a one-step lead would raise the leader's profit almost to the maximal level $(\phi(\gamma^{-1}, \alpha) \simeq 1 \text{ for } \alpha \geq 0)$, and thus the incentive to innovate would decrease. This greatly simplifies the AHHV model and allows the results to be derived analytically. The one-step case developed in the remainder of this section is formulated by Aghion *et al.* (2002).[20]

In the one-step case, the maximum technological gap between leader and follower in an industry is $n = 1$. In this case, the firm's R&D effort is x_n, where $n \in (-1, 0, 1)$ and the expected present value of the profit is denoted V_0, V_1 and V_{-1} respectively for a neck-and-neck firm, a leader and follower in an industry. The wage rate is taken as given and normalized to unity ($\beta = w = 1$), assuming a perfectly elastic labour supply. Taking into account the fact that the technological leader does not invest in R&D in the one-step case, the above Bellman equations take the following form:

$$\left.\begin{aligned} rV_1 &= \pi_1 + x_{-1}(V_0 - V_1) \\ rV_0 &= \pi_0 + x_0(V_1 - V_0) + x_0(V_{-1} - V_0) - \tfrac{(x_0)^2}{2}. \\ rV_{-1} &= \pi_1 + x_{-1}(V_0 - V_{-1}) - \tfrac{(x_{-1})^2}{2} \end{aligned}\right\} \qquad (2.17)$$

Here it is worth recalling that the R&D efforts, x_0 and x_{-1}, for the neck-and-neck firm and the follower respectively entail uncertainty (that follows a Poisson process). The R&D process is stochastic and thus the R&D effort represents the probability of a firm innovating. The difference between the value functions $(V_1 - V_0)$ is the

[19] See Gilbert and Newbury (1982) for a deterministic case where the monopolist always innovates before the entrant.

[20] Although AHHV (2001) formulate the case where the size of innovations is large, in this study we refer to Aghion *et al.* (2002) when discussing the one-step case.

difference in profit flows between leader and neck-and-neck firm. The intuition behind the value functions for the firms in each state is the following: the annuity value for a leader, rV_1, equals the current flow of profit, π_1, plus the discounted expected capital loss from being caught by the follower, $x_{-1}(V_0 - V_1)$. The annuity value of the neck-and-neck firm, rV_0, equals the current flow of profit, π_0, plus the discounted expected capital gain from making an innovation and thereby moving one step ahead of the competitor, $x_0(V_1 - V_0)$, plus the discounted expected capital loss from becoming a follower when the other firm innovates first, $x_0(V_{-1} - V_0)$, minus the current R&D cost, $\frac{(x_0)^2}{2}$. The annuity value of being a follower rV_{-1}, is the current flow of profit, π_{-1}, plus the discounted expected capital gain from catching up with the leader and thus becoming a neck-and-neck firm, $x_{-1}(V_0 - V_{-1})$, minus the current R&D cost, $\frac{(x_{-1}^2)}{2}$. Using the fact that each firm chooses its R&D effort to maximize its current value, the following first order conditions are obtained:

$$\left.\begin{aligned} x_0 &= V_1 - V_0 \\ x_{-1} &= V_0 - V_{-1} \end{aligned}\right\} \tag{2.18}$$

2.4.1 Equilibrium R&D intensities

The equilibrium R&D intensities can be derived using the information of the first order conditions in (2.18) and equation (2.17). It follows that the R&D effort of a neck-and-neck firm, x_0, and that of a follower, x_{-1}, can be solved. Eliminating the Vs yields the following reduced form R&D effort equations:

$$\frac{(x_0)^2}{2} + rx_0 - (\pi_1 - \pi_0) = 0 \tag{2.19}$$

$$\frac{(x_{-1})^2}{2} + (r + x_0)\,x_{-1} - (\pi_0 - \pi_{-1}) - \frac{(x_0)^2}{2} = 0. \tag{2.20}$$

These quadratic equations (2.19) and (2.20) can be easily solved for x_0 and x_{-1} using the second degree quadratic equation solution and ignoring the negative solution. The obtained equations give the flow innovation probabilities (or hazard rates) of the neck-and-neck firm and follower, respectively:

$$x_0 = -r + \sqrt{r^2 + 2(\pi_1 - \pi_0)} \tag{2.21}$$

$$x_{-1} = -(r + x_0) + \sqrt{r^2 + (x_0)^2 + 2(\pi_1 - \pi_{-1})}. \tag{2.22}$$

When examining the effects of competition on the innovation probability in the one-step case, Aghion *et al.* (2002) assume that a reduction in the neck-and-neck profits, π_0, represents intensified product market competition.[21] Aghion *et al.* (2002) argue that the analysis and the results in the one-step case can be replicated parameterizing competition by the elasticity parameter, α.

Differentiating the expressions (2.21) - (2.22) by π_0 yields:

$$\frac{\partial x_0}{\partial \pi_0} = -\frac{1}{\sqrt{r^2 + 2(\pi_1 - \pi_0)}} < 0 \tag{2.23}$$

$$\frac{\partial x_{-1}}{\partial \pi_0} = \frac{\partial x_0}{\partial \pi_0}\left[-\frac{x_0}{\sqrt{r^2 + (x_0)^2 + 2(\pi_1 - \pi_{-1})}}\right] > 0. \tag{2.24}$$

Equations (2.23) and (2.24) imply that intensified product market competition, as characterized by a fall in the neck-and-neck profits, π_0, will lead to an increase in the R&D effort of the neck-and-neck firm, x_0. The follower will decrease its R&D effort, x_{-1}, as the PMC is intensified. This opposing behavior of the neck-and-neck firm and the follower, in regard to R&D efforts, resulting from intensified PMC, is explained by two different effects.

As for the decrease in R&D effort of a follower, x_{-1}, Aghion *et al.* (2002) argue that this is the basic *Schumpeterian effect* at work, resulting from the reduced prospective rent of the successful innovator, which manages to catch up with its

[21] For simplicity it is assumed that π_1 and π_1 are unaffected by a change in competitiveness. According to Aghion and Howitt (1998) the analysis remains essentially unmodified also for cases where π_1 is increased and π_{-1} reduced by an increase in competition.

rival. More intense competition induces a neck-and-neck firm to innovate, in order to escape from competition. Thus, these firms increase their innovative activity, so that x_0 increases. This is because, as the difference in profits between being a leader and being a neck-and-neck firm ($\pi_1 - \pi_0$) increases (π_0 falls and π_1 remains unchanged), the incremental value of getting ahead increases with intensified PMC. Aghion *et al.* (2002) refer to this effect as the *escape from competition effect*. The sum of these effects is that the higher the fraction of neck-and-neck sectors in the economy, the more positive the effect of intensified PMC on the average innovation rate.

2.4.2 Competition and innovations

The aggregate effect of intensified product market competition on the steady-state innovation rate is ambiguous, because of its different effects on industries in leveled (neck-and-neck) and unleveled (leader-follower) states. The overall effect on average productivity growth depends on the time a sector spends being neck-and-neck in the steady-state. This is formulated by letting μ_1 and μ_0 respectively denote the steady-state probability of being unleveled and leveled. During any unit time interval an unleveled sector can become leveled with a steady-state probability, $\mu_1 x_{-1}$. Furthermore, the probability of a leveled sector becoming unleveled is $2\mu_0 x_0$, which is the aggregate probability of one of the firms innovating when both firms try to escape competition. In the steady-state these two probabilities must be equal:

$$\mu_1 x_{-1} = 2\mu_0 x_0, \tag{2.25}$$

since the fraction of sectors in each state must remain unchanged. Combining (2.25) with the fact that the fractions of unleveled and leveled sectors sum up to one

($\mu_1 + \mu_0 = 1$) yields the steady-state distribution of the fractions μ_1 and μ_0:

$$\mu_0 = \frac{x_{-1}}{x_{-1} + 2x_0} \quad \text{and} \quad \mu_1 = \frac{2x_0}{x_{-1} + 2x_0}, \tag{2.26}$$

and further the average rate of innovations:

$$I = \mu_0 2x_0 + \mu_1 x_{-1} = \frac{4x_0 x_{-1}}{2x_0 + x_{-1}}. \tag{2.27}$$

Aghion *et al.* (2002) show by numerical simulations of the model, that the relation between product market competition and the innovation rate, I, follows an inverted-U shaped pattern.

Each industry follows a two-stage cycle in the one-step case with the frequency of completed cycles being the fraction of time spent in the unleveled state, μ_1, times the frequency of innovations in the unleveled state, x_{-1}. The output rises by factor $\ln\gamma$ with each completed cycle and hence the average growth rate of each industry is $\mu_1 x_{-1} \ln\gamma$. From equation (2.26) it follows that the average growth rate of final output in the one-step case is:

$$g = \mu_1 x_{-1} \ln\ \gamma = \frac{2x_0 x_{-1}}{x_{-1} + 2x_0} \ln\gamma. \tag{2.28}$$

2.4.3 Inverted-U relationship

To better understand the intuition behind the inverted-U shape, it is worthwhile taking a closer look at how product market competition affects the average rate of innovation in the AHHV model. This is easiest done by examining the effects of intensified competition on the firm's R&D effort and hence the overall R&D effort in the industry. On the aggregate level, competition is assumed to affect the innovation rate by determining the distribution of industries in leveled and unleveled states. In other words, competition has a *composition effect* on the industries in the economy.

When product market competition is close to zero, and hence the incremental profit of innovating is small for a neck-and-neck firm (π_0 is close to π_1), there is little incentive to innovate when the industry is leveled. Thus the overall innovation rate will be highest when a sector is unleveled and there is asymmetric competition, and the industry will be quick to leave the unleveled state (which it does as soon as the follower innovates).

Since the industry leaves the leveled state slowly (that will not happen until one of the neck-and-neck firms innovates), the industry will spend most of the time in the leveled state, where the escape from the competition effect dominates (x_0 is decreasing in π_0). In other words, if the degree of competition is initially low, an increase will result in a faster average innovation rate.

At high degrees of competition, π_0 is close to π_{-1}, so there is relatively little incentive for the follower to innovate in an unleveled state.[22] Thus the industry will leave the unleveled state relatively slowly. Meanwhile the large incremental profit, $\pi_1 - \pi_0$, gives firms in the leveled state relatively large incentives to innovate, and hence the industry will be relatively quick to leave the leveled state. Consequently, the industry will spend most of the time in the unleveled state, where the Schumpeterian effect is at work on the follower, and the leader does not innovate in the one-step case. In other words, when the degree of competition is initially very high, an increase in PMC results instead in a lower average innovation rate.

From the analysis of how intensified competition affects the average innovation rate, it follows that, when competition is initially low, intensified competition may raise the rate of innovation through the escape from the competition effect on neck-and-neck firms. When competition is already fierce, the Schumpeterian effect may decrease the innovation rate, by decreasing the followers' incentive to innovate. Thus

[22] The follower still has some incentive to innovate even in cases where $\pi_0 = \pi_{-1}$, because, although an innovation won't raise current profits, it will take the firm one step closer to the possibility of becoming a leader and attaining π_1.

the inverted-U shaped pattern between competition and innovation results from the interplay between the escape from competition and the Schumpeterian effects. The reason why one effect is stronger for low degrees of competition, whereas the other dominates for high degrees, is due to the composition effect on the steady state distribution of leveled and unleveled industries.

The composition effect can be seen more clearly from the steady state distribution of the fraction of industries in the leveled state and the unleveled state in equation (2.26). When there is no competition ($\pi_0 = \pi_1$), it is clear from equation (2.21) that $x_0 = 0$, and thus the industry is always leveled ($\mu_0 = 1$ in (2.26)). Under perfect competition ($\pi_0 = \pi_{-1}$), (2.21) and (2.22) imply that neck-and-neck R&D efforts will be larger than followers' R&D efforts, $x_0 > x_{-1}$. Thus the overall rate of innovation is at least twice as high in the leveled state as in the unleveled state. Hence the fraction of time μ_1 spent in the leveled state is less than $\frac{1}{3}$ under perfect competition.

At low levels of PMC, most sectors will be leveled, and the escape from competition effect dominates on average, whereas at high levels of PMC, most sectors will be unleveled, and the Schumpeterian effect on followers' R&D efforts dominates on average. This in turn implies that intensified PMC will have a positive effect on innovative activity at low initial levels of PMC and a negative effect at high initial levels of PMC.

2.5 Competition, taxes and R&D

An interesting issue is the effect of taxes on innovation, and how taxes could function as an incentive scheme by reducing the slack of the firms. In a case where firms pay taxes and receive tax financed R&D subsidies, the interplay between competition and tax financed subsidies seems to be complementary. The effect of competition on innovations is likely to be reinforced by an increase in tax financed subsidies, provided the distorting effect of taxes is sufficiently small. We will elaborate on these considerations in the following subsection by introducing a corporate ad valorem tax on profits and wage subsidies for R&D activity into the framework of the AHHV model. More specifically, the incentive effects of a wage subsidy for R&D activity will be analyzed as well as how a subsidy interacts with competition.

For expositional simplicity, the analysis will follow the one-step case, where the maximum sustainable gap is $n = 1$, and where there is no help factor for followers ($h = 0$).[23] As in the AHHV model, we take the wage rate as given, with the implicit assumption of an infinitely elastic supply of labor at wage $w = 1$. As already discussed, these assumptions are restrictive in many ways, but they are helpful in deriving some of the analytical equilibrium results of the model and understanding important incentive effects shaping dynamically optimal R&D decisions of firms.

More formally, let τ be an ad valorem tax levied on corporate profits, and let ρ denote a direct R&D subsidy which reduces the costs of innovating. The Bellman equations for equilibrium R&D investments can then be written as

$$\begin{aligned} rV_1 &= (1-\tau)\pi_1 + (x_{-1})(V_0 - V_1) \\ rV_0 &= (1-\tau)\pi_0 + x_0(V_1 - V_0) + x_0(V_{-1} - V_0) - \frac{(1-\rho)(x_0)^2}{2} \\ rV_{-1} &= (1-\tau)\pi_{-1} + (x_{-1})(V_0 - V_{-1}) - \frac{(1-\rho)(x_{-1})^2}{2}. \end{aligned} \tag{2.29}$$

In the above equations, $1 - \rho$ can be interpreted as the firm's own share of its R&D costs. By analogy to the basic one-step case, the first order conditions for the neck-and-neck firm and the follower are derived as

[23] See Aghion *et al.* (2001)

$$\frac{\partial r V_0}{\partial x_0} = (V_1 - V_0) - (1-\rho)\, x_0 = 0 \tag{2.30}$$

$$\frac{\partial r V_{-1}}{\partial x_{-1}} = (V_0 - V_{-1}) - (1-\rho)\, x_{-1} = 0. \tag{2.31}$$

Consequently, the innovation probabilities of the neck-and-neck firm and the follower are

$$x_0 = -r + \sqrt{\left(r^2 + 2\,(1-\rho)^{-1}\,(1-\tau)\,(\pi_1 - \pi_0)\right)} \tag{2.32}$$

$$x_{-1} = -(r + x_0) + \sqrt{\left((r+x_0)^2 + 2\,(1-\rho)^{-1}\,(1-\tau)\,(\pi_0 - \pi_{-1}) + x_0^2\right)} \tag{2.33}$$

Substituting (2.32) into (2.33) we derive an alternative expression for x_{-1}:

$$x_{-1} = -(r + x_0) + \sqrt{r^2 + x_0^2 + 2\,(1-\rho)^{-1}\,(1-\tau)\,(\pi_1 - \pi_{-1})}. \tag{2.34}$$

The first important observation from (2.32) is that

$$\frac{\partial x_0}{\partial x_{-1}} = 0. \tag{2.35}$$

In other words, when neck-and-neck firms choose their R&D effort x_0 optimally, they only take into account their own R&D investment, as the rivals effort equals x_0 in a symmetric Markov equilibrium. Important strategic interaction, however, arises from the fact that the innovative activity of the follower is affected by the responses of the neck-and-neck firm. In fact, it can be shown that in the symmetric equilibrium:

$$\frac{\partial x_{-1}}{\partial x_0} = -\frac{x_{-1} + r}{x_{-1} + r + x_0} < 0. \tag{2.36}$$

Given that derivative $\frac{\partial x_{-1}}{\partial x_0}$ is negative, there is a strategic substitutability between the innovative activity of the follower and that of the neck-and-neck firm:

any factor that *increases* the innovative activity of the neck-and-neck firm, will *decrease* the innovative activity of the follower. Moreover, looking at $\frac{\partial x_{-1}}{\partial x_0}$ from a partial equilibrium perspective, we can see that strategic substitutability is "strongest" when the innovative activity of the neck-and-neck firm x_0 is very small. In fact, it can easily be seen that

$$\frac{\partial x_{-1}}{\partial x_0} \rightarrow -1, \tag{2.37}$$

as $x_0 \rightarrow 0$. On the contrary, when $x_{-1} \rightarrow 0$, we have

$$\frac{\partial x_{-1}}{\partial x_0} \rightarrow -\frac{r}{r+x_0} > -1. \tag{2.38}$$

This leads us to the conjecture that the impact of an R&D subsidy must crucially depend upon the strength of strategic substitutability and the market structure. More formally, this can be seen by analyzing the direct effects of tax financed R&D subsidies.

The direct effect of a tax financed R&D subsidy on the probability of innovation by neck-and-neck firms and followers can be evaluated by looking at the partial derivatives $\frac{\partial x_0}{\partial(1-\rho)}$ and $\frac{\partial x_{-1}}{\partial(1-\rho)}$. From (2.32) it is clear that

$$\frac{\partial x_0}{\partial\left(1-\rho\right)} < 0, \tag{2.39}$$

for all realistic values of profit tax, τ, and profit difference $\left(\pi_1 - \pi_0\right)$. In other words, an increase in the R&D subsidy will increase the R&D effort of a neck-and-neck firm x_0. In the case of the follower, however, the effect is more complicated, precisely because of the strategic substitutability. By direct application of the chain rule, we however know that

$$\frac{dx_{-1}}{d\left(1-\rho\right)} = \underset{(-)}{\frac{\partial x_{-1}}{\partial x_0}} \underset{(-)}{\frac{dx_0}{d(1-\rho)}} + \underset{(-)}{\frac{\partial x_{-1}}{\partial(1-\rho)}}. \tag{2.40}$$

Given that the partial derivatives on the right hand side are of opposite sign, the final effect of a direct R&D subsidy remain ambiguous. After some tedious but straightforward algebra, it can however be shown that

$$\begin{aligned} \frac{dx_{-1}}{d(1-\rho)} &< 0 \\ &\Leftrightarrow \\ \frac{x_{-1}(\pi, x_0) + r}{x_0(\pi) + r} &< \frac{\pi_1 - \pi_{-1}}{\pi_1 - \pi_0}. \end{aligned} \tag{2.41}$$

Condition (2.41) needs to be interpreted at the model's equilibrium. It is solely an implicit condition, given that the left hand side still depends upon profits. However, we can already draw some interesting conclusions regarding how R&D subsidies and product market competition interact for different industries.

Firstly, at low degrees of product market competition (i.e. when π_0 is close to π_1), the incremental profit $(\pi_1 - \pi_0)$ approaches zero. There are hardly any incentives to innovate in the leveled state, and consequently $x_0 \to 0$. However, provided that the incremental profit of innovating for the follower is still large enough, a direct R&D subsidy will have a positive effect on the follower's innovating activity. This is due to the fact that the left hand side of the equation (2.41) approaches infinity as leader and neck-and-neck profits converge $(\pi_1 \to \pi_0)$. It is thus more likely that the inequality in (2.41) will hold.

On the contrary, when competition is quite intense, a follower's incremental profit from innovating $(\pi_0 - \pi_{-1})$ is low as $\pi_0 \to \pi_{-1}$. There is relatively little incentive for the follower to innovate in an unleveled state. Moreover, we know from above that the neck-and-neck R&D efforts will be larger than the follower's R&D efforts, i.e. $x_0 > x_{-1}$, when product market competition is fierce. Consequently, condition (2.41) is less likely to hold and thus a direct R&D subsidy leads to a deterioration of the follower's R&D activity.

The above analysis seems to suggest that R&D subsidy is likely to lead to a desired increase in the R&D activity in those industries in which product market competition is relatively muted. However, the overall effect of an R&D subsidy on the average rate of innovation at different degrees of product market competition depends on the steady state distribution of leveled and unleveled industries.

2.5.1 Average innovation rate with corporate tax and R&D subsidy

As already argued, the overall effect of an R&D subsidy on the average rate of innovation depends on the steady state distribution of leveled and unleveled industries in the economy and naturally on the degree of competition in general.

Starting with the case where there is no competition at all ($\pi_1 \rightarrow \pi_0$), we notice from (2.32) that neck-and-neck firms no longer have incentive to innovate at all, and hence $x_0 = 0$. In the steady state equilibrium, all the industries are eventually driven down to the neck-and-neck state, and thus all industries will eventually be leveled, $\mu_0 = 1$. Given that the average flow of innovations is $I = \mu_1 x_{-1} + 2\mu_0 x_0$, it is clear that in the steady-state the average innovation rate is also eventually driven down to zero. Consequently, at low degrees of competition, R&D subsidies turn out to be completely ineffective. Although the follower's innovative activities could, at low levels of PMC, be boosted by subsidies, their share in the economy eventually approaches zero, and hence they have no impact on the average innovation rate. Technological progress and economic growth both decline, regardless of how much the firms are subsidized.

At high degrees of competition, both follower and neck-and-neck firms innovate at positive rates:

$$x_{-1} = -(r + x_0) + \sqrt{r^2 + x_0^2} \tag{2.42}$$

$$x_0 = -r + \sqrt{\left(r^2 + 2\left(1-\rho\right)^{-1}\left(1-\tau\right)\left(\pi_1 - \pi_0\right)\right)}. \tag{2.43}$$

What is important to notice, however, is that the R&D subsidy affects the innovating activity of the follower only to the extent that it affects the neck-and-neck firm, x_0. From this follows, in case of perfect competition, that

$$\frac{dx_{-1}}{d(1-\rho)} = \underset{(-)}{\frac{\partial x_{-1}}{\partial x_0}} \underset{(-)}{\frac{dx_0}{d(1-\rho)}} > 0. \tag{2.44}$$

This implies that when competition is fierce an increase in a direct R&D subsidy leads to a deterioration of the innovative activity of the follower. This is due to the strategic substitutability effect, $\frac{\partial x_{-1}}{\partial x_0} < 0$. Finally, making use of the average rate of innovation in (2.27), it can be shown that

$$\frac{\partial I}{\partial x_0} < 0, \ \forall \ r > 0, \ x_0 > 0. \tag{2.45}$$

In other words, in the case of perfect competition, an increase of innovative activity of neck-and-neck firms leads to a decline of the average flow of innovations in the economy. This is due to the fact that a strategic substitutability effect dominates the positive effect of R&D subsidies on the neck-and-neck firms. Furthermore, this means that any public subsidy on the costs of innovating will reduce the total innovation flow of the economy, regardless of how innovations actually are financed.

Consequently, we have derived the two results which suggest that R&D subsidies either have very little effect on the average innovation rate of the economy, or that the effect is of the opposite sign from the expected. The two situations are however analyzed in the extreme cases of no competition and perfect competition, which represent rather unrealistic situations, existing in their purest only forms in textbooks. We thus turn our attention to the intermediate cases, which are essentially more useful for practical predictions of the theory, as well as for its empirical validation.

2.5.2 A simulation exercise

Analytical results of the intermediate cases are hard to derive and we thus rely here on simple numerical simulations, which enable us to examine the effects of a tax financed R&D subsidy on incentives to innovate in the world located between monopoly and full competition. Figure 1 depicts the average innovation rate at different degrees of competition as well as at different degrees of R&D subsidy. The vertical axis measures the average innovation rate and the horizontal axis the degree of competition. The degree of competition is measured by letting π_0 increase from 0 to π_1.[24] This gives an inverted-U shape relationship between average rate of innovations and competition, just as in the original AHHV article. However, this inverted-U shape relationship becomes steeper and reaches higher average rates of innovation as R&D subsidies are increased. This points to the fact that there might be complementarity between direct R&D subsidies and competition. Moreover, it seems that the highest additionality would be achieved at moderate levels of competition.

A numerical example, where $r = 0.04$, $\pi_{-1} = 0$, $\pi_1 = 5$, $\tau = 0$ and ρ takes the values 0, 0.1 and 0.5 (in other words, respectively, a zero, 10 percent and 50 percent subsidy), gives an inverted-U shape relationship between competition and innovations. This inverted-U shape relationship becomes steeper as the R&D subsidies are increased, while at high and low levels of competition, R&D subsidies do not affect the average innovation rate at all. This implies that direct R&D subsidies and competition are complementary by nature.

When positive taxes are introduced into the simulation, the relationship continues to hold, as the taxes only reduce the complementarity between R&D subsidies and product market competition.

[24] The values of the profits should be interpreted as the price cost margin, in percent terms.

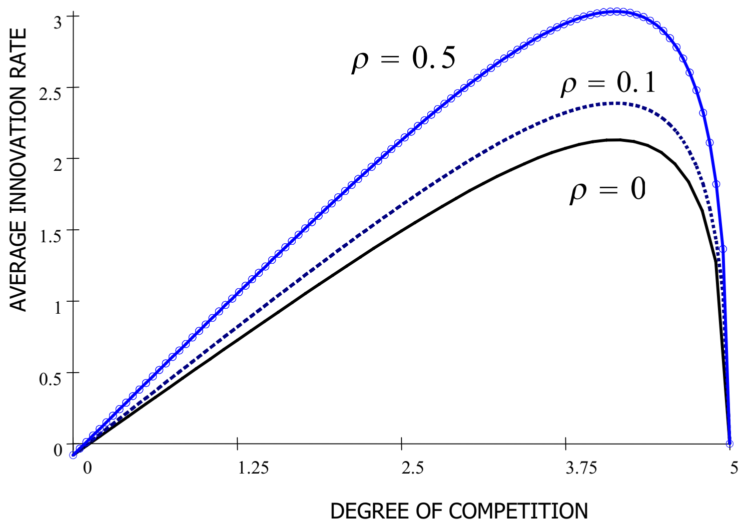

Figure 1: Innovations, competition and a direct research and development subsidy.

2.6 Summary of theoretical predictions

The theoretical part of this study can be summarized as follows. In the Schumpeterian growth model of Aghion *et al.* (2001) it is analytically shown that when firms innovate 'step-by-step' and innovation follows a Poisson process, competition may increase the incremental profit from innovating and hence increase the incentive to innovate. On the other hand, competition may reduce innovation incentives for followers by reducing the prospective gains from catching up with the leader. There are thus two effects at work affecting the innovation effort as a response to changes in the competitive climate within the industry. Firstly, the increased post-innovation rents relative to pre-innovation rents may due to intensified competition, lead neck-and-neck firms to increase their R&D efforts, in other words, escape from competition. Secondly, as intensified competition decreases neck-and-neck profits, it may decrease the follower's effort to catch up with the leader, which is in line with the Schumpeterian reasoning of post-innovation rents being the driving force of innovation.

On the aggregate level, the composition of leveled and unleveled industries in the economy determines the final effect of product market competition on the rate of innovation. The relationship between product market competition and innovation is shown to be of an inverted-U shape (this goes especially for the one-step case, where innovations are large and no imitation is considered). With an extension to the AHHV model, we come to the conclusion that a direct R&D subsidy financed by a corporate tax has little effect on innovation at extremely high and extremely low degrees of competition. However, simulations of the intermediate case show that the gains on direct R&D subsidies are achieved at moderate levels of competition, where the escape from competition effect dominates and the majority of industries are in the neck-and-neck state.

The theoretical part of this study gives rise to predictions that are worth explicit statement before proceeding to test them empirically:

1. The AHHV model generates the prediction of an inverted-U shaped relationship between product market competition and the average rate of innovations.

2. This inverted-U relationship can be strengthened by direct public R&D subsidies. The results of our extension to the AHHV model suggest that there exists a complementarity between product market competition and R&D subsidies. Thus, the more direct R&D subsidies firms receive, the steeper the positive effect of product market competition on innovation and the greater the number of innovations.

The first prediction is already tested in Aghion *et al.* (2002) using data on UK companies listed on the London Stock Exchange. They found evidence of an inverted-U shape relationship between competition and innovation in their data. We will use Finnish data, described in detail below, to test whether the same inverted-U shape relationship holds in the Finnish data as well. Moreover, we will test whether there exists a complementarity between R&D subsidies and competition, as stated above.

3 Empirical issues of competition and innovation

We now turn to the empirical analysis, based on data on Finnish manufacturing firms. First, we need to construct quantifiable measures for a firm's innovative output, the degree of product market competition, the size of the technology gap between firms within an industry, and the R&D subsidy. The choice and construction of these measures is not trivial and thus deserve some specific attention, since there are several different measures found for each in the literature. Therefore, this section is specifically devoted to a discussion of the measurement issues.

3.1 Measuring innovation intensity

The search for accurate and applicable indicators for innovation intensity has attracted much attention lately in the empirical IO literature. Commonly used firm level measures are R&D expenditures, patenting activity, innovation counts and total factor productivity. Although R&D intensity is a standard measure for innovative input as well as a proxy for innovative output the problem one often faces is that R&D data have been poorly reported until recent years. Another problem that arises when using R&D spending as a proxy for innovation intensity is related to the differential role of formal R&D.[25] Especially in small firms a substantial part of the R&D activity may be informal and hence unlikely to be reported. Thus, using R&D spending as a proxy for innovative output might entail a downward bias. For this reason, it is tempting to look for other measures of innovation, such as e.g. patenting activity.

Patent data have been used in the economic analysis of technological change since the pathbreaking analyses of Scherer (1965) and Schmookler (1966). The computerization of patent statistics in the 1970s gave easier access to patent data and

[25] For a discussion of the problems related to R&D as an indicator for innovations, see Griliches (1990).

further stimulated econometric analysis using such data. Moreover, as information on patent citations has become available in computerized form, the informational content of patent data has notably increased.

Following Aghion *et al.* (2002), we use patents as the main indicator of innovative activity.[26] More specifically, we use information on patents granted by the United States Patenting Office (USPTO) and originating in Finland. Since the USPTO is the place where innovations are patented internationally, all major innovations are patented in the U.S.. Thus, many low value patents are screened out by focusing on USPTO patents.

3.1.1 Micro-level patent data

The patent system can be seen as an institutional devise to remedy a problem of non-excludability of the innovation, in the sense that a patent is by definition a temporary legal monopoly granted to investors for the commercial use of an invention. In principle, in order to receive this right, the invention must satisfy the following conditions:(*i*) the invention must be nontrivial, in the sense that it must not be obvious to a skilled practitioner of the relevant technology, (*ii*) it must be useful in such a way that it has a commercial value, and (*iii*) the patent application must relate to and identify "prior art", the practice of which is necessarily excluded from the property right granted by the patent.

If a patent is granted, an extensive public document is created. This document contains detailed information about the invention, the inventor(s), the organization to which the inventor assigns the patent property right (usually an employer), and the technical antecedents of the invention. Thus, as Griliches (1990) points out, the

[26] Alternatively, there is a large number of innovation surveys available, though usually on the domestic level only. An exception is the Community Innovation Survey (CIS) , which collects countrywise information on significant innovations in Europe. Also, in Finland, the Sfinno group at the Technical Research Centre of Finland (VTT) has collected data on significant innovations of economic or organizational importance to the companies. See Palmberg *et al.* (1999) for a detailed description of the Sfinno database.

patent system serves two purposes in encouraging invention and technical progress. It does this by providing a temporary monopoly for the inventor and by creating knowledge spillovers by forcing early disclosure of the innovation.

The so-called prior art that the patent relates to is identified by references or citations. Prior art also includes previous patents and other previously published material that identify aspects of the relevant publicly known technology. Thus, along with the detailed description of the novelty of the innovation in the patent claim, citations play an important role in delimiting the property right that the patent application represents. The citations are not necessarily made before filing an application. A cited patent can also be identified via a search conducted by the inventor's patent attorney, or by the patent examiner who reviews the application for the patent office.

3.1.2 Patent citations

A patent application for a technological innovation explicitly identifies other patents as constituting the technological "state-of-the-art" on which the present patent builds. Thus patent citations may be seen as providing information on two major aspects of innovation. The first is the technological impact of individual patents. Indeed, given the underlying heterogeneity in what is measured by a patent[27], information on citations received and made in patents is important for increasing the applicability of patents as indicators of technological change. Using data on patent citations, one can get an idea of the influence that an innovation has had on successive innovations. The second aspect of innovation to which citation data contribute is the study of knowledge spillovers. Citations enable quantitative analysis of linkages between inventions, inventors and assignees over time and space. However, as Hall *et al.* (2000) point out, one must bear in mind that there is a substantial amount of

[27] The technical and economic significance of patents differ greatly. For a discussion, see Griliches (1990).

"noise" in patent citations data (due to the fact that citations may be made by different persons in several stages of a patent application process). Thus, one must be careful in drawing inferences about spillovers solely from the analysis of citations.[28] In particular, problems arise, according to Hall *et al.* (2003), when using citations as evidence of spillovers or knowledge flows from cited patents to citing inventors. This is due to the fact that many of the citations are added by the inventor's patent attorney or the patent examiner, and may hence refer to inventions completely unknown to the citing inventor. On the other hand, Hall *et al.* (2000) argue that, in using citations to a patent as an indicator of the patent's impact, or even economic value, the citations that are identified by parties other than the citing inventor may well be just as important as the ones made by the inventor of the patent in reflecting "the size of the technological footprint" of the cited patent. In a detailed survey of inventors, Jaffe *et al.* (2000) come to the conclusion that, qualitatively, one-half of citations appear to correspond to some kind of impact of the cited innovation on the citing inventor, and around one-quarter seem to correspond to a fairly rich knowledge flow, fairly significant impact, or both.

The impact of citations on the economic value of a patent is a rather unexplored area of research. Trajtenberg (1990) collected, in his seminal work on patent citations, data on patents related to a class of medical instruments (computerized tomography (CT) scanners), and related the flow of patents over time to the estimated social surplus created by improvements of CT scanners. When simple patent counts were used, no correlation was found with the estimated surplus. However, when citation-weighted patent counts were used, the correlation between welfare improvements and patenting were extremely high, on the order of 0.5 or more. This suggests that citations can be used as a measure of patent quality, as indicated by

[28] For an overview of interesting applications using patent-citations data, see Jaffe and Trajtenberg (2002).

the promotion of social welfare.[29]

3.1.3 Patent stocks and citation weighted patents

Given that patents receive different numbers of citations and these citations occur over time, it is necessary to construct a some kind of weighting scheme for the number of citations. A straightforward way, introduced by Trajtenberg (1990), is to weight each patent i by the actual number of citations that it subsequently receives, denoted by C_i. In this linear weighting scheme all patents and citations are assigned a value of one. Using this measure one can construct an index of weighted patent counts (WPC) for a given product class in a given year t:

$$WPC_t = \sum_{i=1}^{n_t} (1 + C_i), \tag{3.1}$$

where n_t is the number of patents issued during year t in a given product class.

In this weighting scheme, it is assumed that a citation is worth as much as a patent. However, in reality there may be increasing or decreasing returns to the informational content of citations, in which case the weighting scheme would be nonlinear. Trajtenberg (1990) also considers a more general specification of citation weighted patent counts. He finds that the marginal informational content of WPC_t increases with the number of citations, which strengthens the potential role of WPC_t as an indicator of the value of innovations. Other findings are that the variance in the value of patents appears to be larger and the distribution of those values more skewed than one would infer from a simple citation count.

Patents and citations have also been used by Hall *et al.* (2000) to calculate the "book" value of knowledge capital owned by a firm. Patents are considered a

[29] Also Lanjouw and Schankerman (1997, 1999) find in their studies that a patent quality measure based on multiple indicators, such as citations, number of claims and number of different countries in which the invention is patented, has significant power in predicting which patent rights will be renewed upon expiration and which will be litigated.

more accurate proxy for knowledge capital than R&D expenditure because patents better represent the success of an R&D programme. When using R&D expenditures as a proxy for knowledge stock, it is implicitly assumed that each dollar spent on research generates the same amount of knowledge capital. Thus, "dry holes", i.e. unsuccessful projects, are not separated from successful innovation-producing R&D, which causes robustness problems in the measure. Although some of the patents held by a firm might represent the same kind of dry holes[30], Hall *et al.* (2000) argue that the bias can be at least partially corrected for by constructing citation-weighted patent stocks.[31]

When calculating a patent based proxy for knowledge stocks, it makes more sense to use a stock measure rather than a flow measure for knowledge. A stock measure better captures the idea that benefits from a patent are likely to persist far into the future. We use the approach of Hall *et al.* (2003) and Bloom and Van Reenen (2000) in computing the citation-weighted patent stock, using the perpetual inventory method. More formally, we denote by $C(t,\tau)$ the number of citations in year τ to patents applied for in year t. Thus, the total number of citations to the patents applied for in year t and observed at the end of the period (1999) is

$$C(t) = \sum_{\tau=t}^{1999} C(t,\tau). \tag{3.2}$$

We calculate the citation stock using a standard declining balance formula; hence the total citation stock observed in year t is

$$(\text{Citation Stock})_t = (1-\delta) \times (\text{Citation Stock})_{t-1} + (\text{Citations})_t. \tag{3.3}$$

We assume that the knowledge depreciation rate, δ, is 30%, as in, e.g. Bloom and

[30] As mentioned above, the (ex post) value of patents is extremely skewed, with at least 1/4 of the patents being completely worthless. See Pakes and Schankerman (1984) and Pakes (1986).

[31] See Hall *et al.* (2003) for a good explanation of how to construct citation weighted knowledge stocks and related problems.

Van Reenen (2000).[32] We follow their approach in using only the first five years of citations (after an application) to obtain a “five year cite stock”.[33] This measure has the actual advantage, compared to measures observing longer periods, that no normalization is needed to deal with truncation bias. In order to avoid the problems of truncation bias caused by taking into account only citations made until the end of the observed period, we select our citation estimation period to run up to 1994 while our citing data runs up to 1999. Consequently, we have 5 years of observations on citations for every patent. Bloom and Van Reenen (2000) show that this measure correlates strongly with measures using a longer period of observation of citations and normalized citations per patent.

As an alternative measure for impact corrected patent counts, we calculate the normalized citation intensity for each patent. This measure attempts to improve the comparability between patents of different grant years. Comparability between patents of different grant years is difficult due to the truncation bias, i.e. that we only observe citations received up to the end of the period of observation. Another problem that biases comparisons between numbers of received citations per patent is citation inflation. In order to obtain a measure that is comparable across patents of different grant years, we use the estimates by Hall *et al.* (2001) of the shape of the citation-lag distribution in each technology field, i.e. the fraction of lifetime (defined as the 30 years after the grant date) citations that are received in each year after the patent is granted. This distribution is assumed to be stationary and independent of the overall citation intensity and enables the estimation of total citations for a patent in any technology field for which a part of the citation period is observed.

We also remove the effects due to the changing propensity to cite. This is done simply by dividing the observed sum of citations of a patent by the fraction of

[32] We also calculate the stock measure using the, perhaps more conventional, 15% depreciation rate; see Hall *et al.* (2003).

[33] See Appendix C for details on the construction of the citation weighted patent stock.

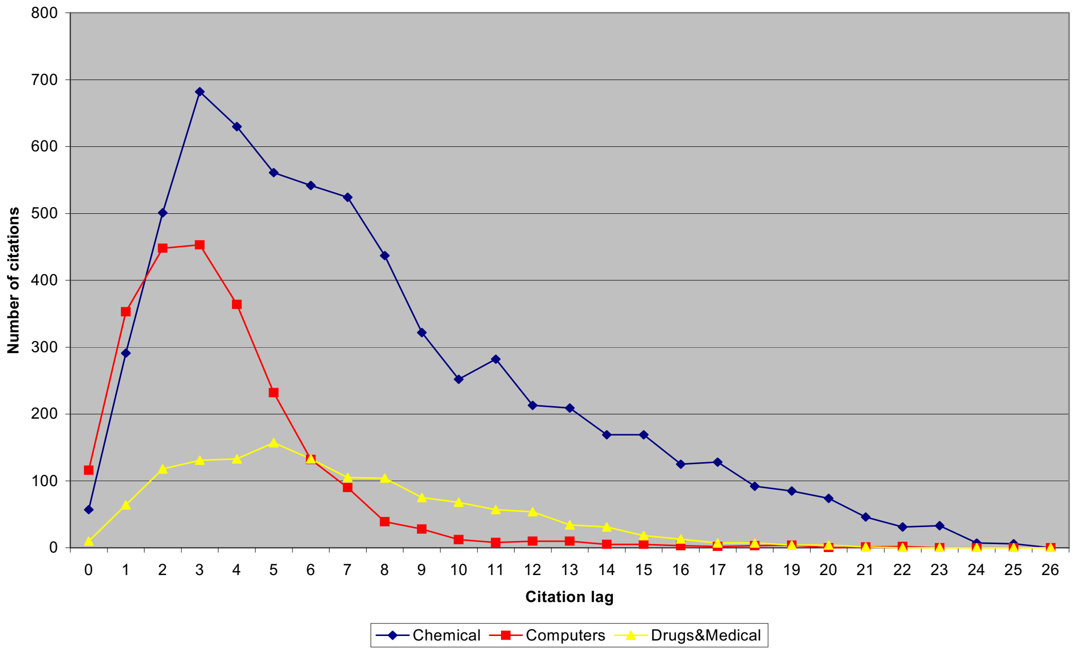

Figure 2: Citation Lag Distribution by Technological Field

the population that lies in the interval for which citations were observed and by the citing year deflator. As Hall *et al.* (2000) point out, at least three years of actual observations on citations should be available for each patent in order to be able to estimate the lifetime citations accurately. For patents, for which a shorter period is at hand, a problem arises due to the fact that few patents receive citations during their first years of patent life, leading to predictions of zero lifetime citations for innovations that might be frequently cited a few years after patenting. Thus estimates are likely to be noisy if only a short track of the patents "career" is observed. This phenomenon is illustrated in Figure 2, which shows a citation lag at 3 different industries in Finland.

3.2 Measuring the degree of market power and product market competition

In real world industries, one seldom finds all firms setting prices equal to the competitive price level. In fact, most firms are expected to have some degree of market power. In assessing the level of market power, the first question to arise is which theoretical measure of market power should be used. The second question, which follows from the first, is how to empirically operationalize the chosen measure.

Empirical studies typically use some measures of market concentration or profit margin as indicators of market power. Further, in some studies import penetration is used as a proxy for the degree of foreign competition. As Ahn (2002) argues, these measures are admittedly not accurate measures of competition. However, they are relatively easily calculated and hence the most widely used:

- Concentration: A concentration ratio is often calculated as the combined output share or employment share of the largest n firms in a market. One problem with this measure is that it does not reflect the competitive pressures coming from potential entrants originating in contestable markets. Another weakness of the concentration measures is the difficulty of defining actual market boundaries (both geographic and product boundaries), where competition occurs.

- Price-cost margin or mark-up: Measures of profitability are often used as measures of market power. In theory the price-cost margin is measured by the *Lerner index*, defined as the ratio of the firm's mark-up (that is, the difference between the price p_i and the marginal cost C_i') over price: $L_i = \frac{(p_i - C_i')}{p_i}$. The index reflects the degree of monopolistic mark-up pricing above marginal cost. Thus the index increases with the mark-up charged by the firm, which should be the most desirable feature of any index of market power. However, as Motta (2004) argues marginal cost is mainly a theoretical concept and is generally not observable even with the best knowledge of the technological conditions in which the firm operates. In real world applications, the Lerner index is commonly calculated as value of sales less payroll and material costs divided by value of sales. In this calculation, average variable cost is used as a proxy for marginal cost. Aside from the difficulties of measuring marginal costs, another difficulty in direct application of the Lerner index is that monopolistic firms are characterized by productive inefficiency. Thus, a firm's market power is not always revealed by applying the Lerner index, as it has relatively high costs (and hence relatively low margins), whereas such high costs might be the result of its monopoly power.

- Import penetration: The ratio of imports to domestic production is often used as a measure of foreign competition. In measuring the degree of product market competition in a highly integrated international market, it might be necessary to consider concentration in world markets rather than focusing on domestic markets.

The intuition behind using a concentration ratio or a markup ratio to measure competition is clear. In a market where the individual suppliers are infinitesimally small relative to market size, suppliers have no power to set prices above marginal cost and hence the concentration ratio and price-cost margin will be zero in the ideal case of perfect competition. On the other hand, in a monopolistic or oligopolistic market, one or a few players are expected to use their market power and earn profits by charging prices above marginal cost. In this sense, one could say that the concentration ratio and the mark-up ratio are closely correlated with the degree of market power.

The measure of product market competition which is best suited for our empirical analysis and which also avoids many of the problems of market power-based measures of competition is the Lerner index. We calculate this measure as

$$li = \frac{\text{operating profit}}{\text{value of gross output}} \tag{3.4}$$

Operating profits are calculated by deducting compensation to employees and capital costs from the firm's value added.[34] The numerator in this operationalization is thus more similar to price minus average cost than to price minus marginal cost. By dividing the operating profits by the value of gross output we then obtain a firm specific Lerner index.

We then construct our industry level measure of the Lerner index. This is done by classifying firms into industries by the two-digit SIC code in which the firms are registered and then calculating a weighted average across all firms in the industry[35]:

$$c_{ij}^{w} = 1 - \left(\frac{1}{\sum\limits_{i \in j} L_{it}} \sum_{i \in j} li_{it} \cdot L_{it} \right). \tag{3.5}$$

where i is the firm index, j the industry index, and t the time index. L_{it} is the number of total hours worked in the firm i in year t and is used to measure the size of the firm. Note that we use 1 minus the Lerner, which gives us that a value of 1 indicates perfect competition (price equals marginal cost) while values below 1 indicate some degree of market power.

Following Aghion *et al.* (2002), we construct an alternative measure for competition by removing the effect of market share on a firm's profit margin:

$$A_{it} = \frac{1 - li_{it}}{1 - ms_{it} \cdot li_{it}}. \tag{3.6}$$

[34] As a measure of capital cost we use the implicit price index of the investments, calculated from national accounts. Capital stock is measured using the perpetual inventory method and deflated to 1995 prices.

[35] Note that we use 1 minus the Lerner, which gives us that a value of 1 indicates perfect competition (price equals marginal cost) while values below 1 indicate some degree of market power.

Market share is measured as the firm's share of output produced by firms in the same two-digit industry. As above, the weighted[36] industry level average is calculated as

$$\alpha_{jt}^{w}=\frac{1}{\sum\limits_{i\in j}L_{it}}\sum_{i\in j}A_{it}\cdot L_{it}. \tag{3.7}$$

Figure 3 shows the 1-Lerner Index and market share adjusted index (α) for some two-digit level industries in Finland in 1985-2001. As a general observation, one can see that in almost all 2-digit industries, the industry level Lerner index suggests that competition has increased in 1985-2000. Moreover, the figure shows that after removing the effect of market share on firm's profit margin, a general view on the level and development of competition at different industries remains largely the same.

3.3 Productivity as a technology measure

Productivity indicators are often used as measures of technological change and technological differences across plants at a given point of time (Maliranta, 2003). This is legitimately done, assuming that each unit maximizes its profits and hence minimizes its costs, leaving no resources unexploited. This calls for addressing two issues. First, how well do productivity measures, such as standard total factor productivity (TFP), reflect technological change and, second, can the evenness of the technological distribution within an industry be used as a measure of competitive pressure within the industry. The second question depends largely on how differences across plants within an industry are measured, since there are many ways to capture the distribution of technological levels. Let us briefly take up the first question before returning to the second one.

[36]Note that here we use the superscript w to indicate that a measure is weighted by the number of employees. For simplicity, we drop the superscripts in reporting the empirical results and use only c_{jt} and α_{jt}.

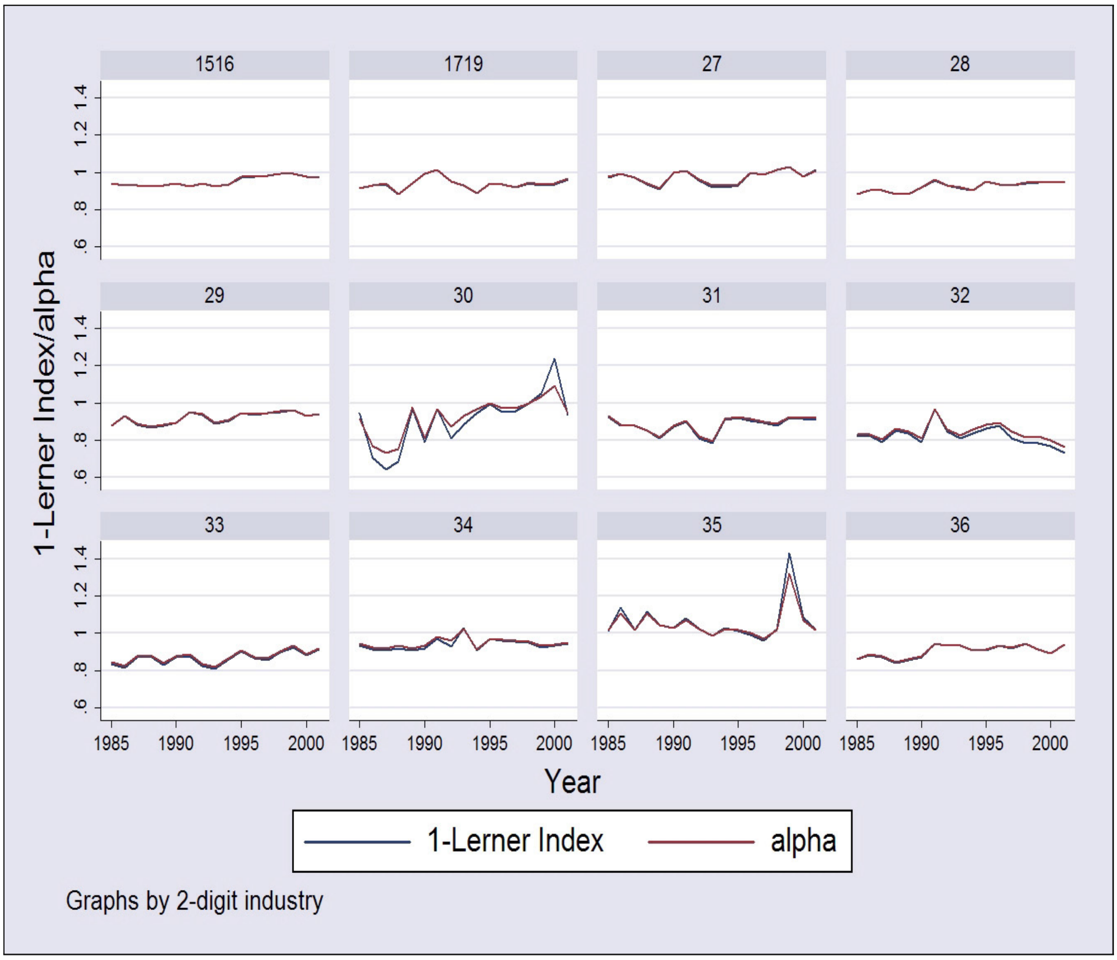

Figure 3: Degree of competition as measured by 1- Lerner index and market share adjusted index in 12 Finnish industries (here indexed by their two-digit SIC code, see Table 2 for the corresponding names.).

In the presence of imperfectly competitive product markets the standard TFP measures tend to be biased. For this reason these measures serve at best as rough measures of technological change. Furthermore, as Leiberstein (1966) argues, the differences in X-inefficiency might also cause bias in the TFP measures. This means that units similar in all relevant aspects have different productivity due to differences in X-inefficiency. It is difficult to draw a sharp distinction between a relatively low technological level and X-inefficiency. This holds especially in cases where technology is given a broad interpretation, e.g. when managerial skills are included in the concept.

The technological similarities within an industry are closely related to competition. If the firms are technologically close to each other (i.e. the industry is neck-and-neck), the whole industry is expected to innovate more on the aggregate level, as discussed in section 2.4.3. Measuring the technology gap, i.e. the distribution of technology levels between firms, is often done by calculating the proportional distance a firm is from the industry's technological frontier and calculating the average distance across all firms in the industry.[37]

The first problem one faces when constructing this measure is the X-inefficiency, as mentioned above. X-inefficiency causes harm also when defining technological levels in the sense that some firms, even though technologically advanced, contain "fat" (see Borenstein and Farrell, 1999), i.e., inefficiency that is not inevitable (e.g. poor management that causes the firm to perform on a lower productivity level than other firms using the same technology). Such inefficiency can usually be reduced by internal adjustments instead of technological progress.

The second problem is that the most productive firm in the industry is usually represented by an outlier. In this case, a firm with an exceptionally large technological advantage over the second most productive firm in the industry might give a false picture of the actual technology gap. More accurate and robust measures for technology gap can be found by defining the technology frontier as the mean of a set of the most productive companies in the industry and calculating the technological distance of the firms from this mean or by calculating industry level standard deviation measures. The standard deviation measures, however, might also give a false picture when productivity distribution is heavily skewed.

Consequently, in order to approximate technology gaps within each industry and avoid at least partially the above mentioned problems, we calculate the distance between the productivity of level of the third quarter and that of the first quarter

[37] See e.g. Aghion *et al.* (2002).

in the industry. In other words, we calculate the distance between the productivity level of the companies at the 75th percentile in the productivity distribution and the productivity level of the companies at the 25th percentile.

3.3.1 Measuring public funding

In general, all public funding that removes market imperfections and creates additionality in research should be considered as R&D subsidies.[38] However, since our theoretical measure of an R&D subsidy is most closely related to a wage subsidy, we chose to consider only direct R&D subsidies. We thus use data on the financing decisions of subsidies granted to product development by the National Technology Agency of Finland (Tekes). More specifically, we measure direct R&D funding as Tekes direct subsidies for product development.

Tekes provides funding and know-how for R&D projects at companies registered in Finland, Finnish research institutes and universities, and promotes national and international networking. In 2003 Tekes received 28.1% of the total government expenditures on R&D, i.e. EUR 407.2 million, which was roughly 8 % of total R&D in Finland that year (total R&D in Finland in 2003 was EUR 4.8 billion).[39] The main instruments of Tekes are industrial R&D grants and loans to firms (roughly 60% of the funding is directed to the industry) as well as grants awarded to public organizations for applied technical research. Of Tekes' total budget, roughly 80% is spent on direct subsidies (i.e. not repayable grants) for product development and research projects and 20% is directed to loans for applied technological research and product development (i.e. repayable loans priced at below-market interest rates). Direct R&D subsidies form the cornerstone of Tekes' funding (roughly 40% of the total budget) along with the other type of direct subsidy, grants for research projects.

[38] See Hyytinen and Toivanen (2002) for a discussion of measures of government funding of R&D.

[39] For a detailed report on the allocation of public R&D expenditures in Finland for 2003, see the report on the Government R&D funding in the state budget for 2004, compiled by Statistics Finland.

However, grants for research projects are mainly directed at universities and research institutes and would thus not contribute much to our analysis even if considered.

Since the founding of Tekes in 1982, its role in the national innovation system has increased steadily and direct subsidies have become the main form of financing. An increasing part of the funding is directed at SMEs[40] which got roughly 60% of industry funding in 2001. Also joint instruments for seed and start-up funding have been developed in cooperation with the Finnish National Fund for Research and Development (Sitra), and agencies that support the commercialization of innovations (such as Finpro, a service organization aimed at internationalization of Finnish firms) now play a larger role in the new technology programmes of Tekes.[41] Tekes can provide SMEs with R&D grants of up to 35% of total project finance and R&D loans of up 70% of the predicted costs of a project. These figures are lower for large companies, and finance is granted only on condition of some degree of networking or other cooperation.

[40] The conclusions of an independent evaluation of Tekes by Zegweld and Guillaume (1995) suggested that the SMEs should be more actively included in the sphere of influence.

[41] For an analysis of cooperation between organizations contributing to the Finnish innovation system, see Gergiou *et al.* (2003).

4 The data

We construct our data set using data on the financing decisions of Tekes, the company register at the Business Structures Unit (BSU) of Statistics Finland, the R&D panel data of the BSU, a patent data set constructed by combining data drawn from the National Board of Patents and Registration of Finland (NBPR) and the so-called NBER patent citations file[42], documented in more detail below, and the BSU's longitudinal plant level data on Finnish firms. As the base population, we use the register of financing decisions of Tekes. The "grant" data comprise 8 493 observations between 1985 and 2002 (one observation being the amount received per firm per year) of 4 084 different firms. Since we restrict the analysis to manufacturing industries, we are only able to match a subset of the entire grant data to our industry level measures. Concentrating on firms which have received grants for R&D is expected to screen out the firms conducting unsuccessful R&D, since it is assumed that evaluators of grant applications of the technology agency make assessments of the feasibility of the R&D projects. Another advantage of using the grant data as the base population is that we reduce the problem of excess zeros of the dependent variable, the U.S.patents, since the firms applying for R&D subsidies are expected to conduct more R&D than the average firm. We match the grant data with the company register comprising data on all registered firms for each year between 1988 and 2001.

We are able to match 6 763 observations to the company register, from which we obtain the industry classification of the companies. As mentioned above, we classify firms by their two-digit SIC code and acknowledge the problems related to business demographic issues such as mergers, acquisitions and exits. These problems are partly avoided due to the fact that our base population is the grant register of

[42] The matching of NBPR and NBER patent data files enables the analysis of citations to USPTO patents originating in Finland. In this sense, our data set consists of valuable information on patents not previously applied to Finnish data.

Tekes, which has attempted to follow up the financing history of each firm and hence has kept the original SIC code in most cases of mergers and acquisitions. We match with our data the patenting information from the NBER patent citations data file containing information on all U.S. patents originating in Finland between 1963-1999. We find that 464 firms took out 2 534 U.S.patents during the period 1985-1999. We also match information on R&D expenditures from an R&D panel based on an extensive R&D survey of Finnish companies between 1987-2001.[43]

Our competition measures and technology gap measures are calculated using a plant-level panel data set constructed especially for research purposes.[44] It is based on the annual Industrial Statistics surveys that cover essentially all Finnish manufacturing plants employing at least 5 persons, up to year 1994, and from 1995 on plants owned by firms that employ no less than 20 persons. We match this information to a subset of our data set comprising only the companies in the manufacturing industries. We exclude the observations with more than 50 patents per year and exclude from our data outliers with respect to the competition measure. Finally, after excluding the industries without any U.S. patents during the period of observation our data comprises 3 247 observations of 1 517 manufacturing companies.

4.1 Descriptive statistics

Tables 1 and 2 presents the descriptive statistics for our sample of 3 247 observations.

Firstly, it is easy to see that our patent count distribution is highly skewed, with the majority of the firms taking out no patents in any given year.[45] The mean of the industry level Lerner index is 0.077, implying that the firm's average price-cost margin is roughly 8%. The figure is surprisingly similar to that found in

[43] The R&D figures are collected by Statistics Finland in a survey which firms are obliged to answer. Until 1994 this survey was done every other year.

[44] We use the entire sample of the plant-level data set in constructing the industry level competition and technology gap measures.

[45] See Table 1 for a distribution of firms by total patents.

	N	Mean	Std	Median	Min	Max
U.S.Patents	3247	0.39	2.67	0	0	50
EPO Patents	3247	0.80	8.10	0	0	214
Domestic Patents	3247	2.03	12.95	0	0	317
Lerner index	3247	0.077	0.05	0.071	-0.08	0.27
Technology gap	3247	0.71	0.24	0.66	0.18	1.61
R and D expenditure (MEUR)	1872	3.23	16.0	0.347	0	572.8
Own R and D expenditure (MEUR)[1]	2015	2.83	12.2	0.313	0	398.9
R and D subsidies (EUR 1000)	3247	206.1	489.4	67.3	-134.5	8535.4
Subsidy/Inhouse R and D	1740	0.54	1.34	0.235	-0.49	38.2
Employment	3247	439	1249	55	0	16228
Observations per firm	3247	3.8	3.09	3	1	15
Sales (MEUR)	3247	104.4	489.5	6.5	0	8220.0
R and D/Sales	2011	0.278	2.7	0.026	0	86.1

[1]R and D data for a subset of 2015 observations
Employment is the number of employees

Table 1: Descriptive statistics

Aghion *et al.* (2002). Our measure of the technology gap also has a large variation ranging from industries in which leaders and followers have similar technologies, and hence similar levels of total factor productivity (TFP), to industries where the most productive quarter is 160% more productive than the least productive one. Also it can be seen that in Finland, Information and telecommunications sector have produced the largest amount of patents. The second largest industry producing patents is Mechanical engineering, but there seems to be also relatively large number of patents produced in Chemicals industry.

The average firm sales per year of roughly 104 million EUR against the median of 6.5 million indicates that the data are severely skewed with respect to firm size. Also the employment figures give an indication of a highly skewed distribution of size of firms in our sample, with roughly 439 workers in the average firm while the median firm has 55 workers. The average in-house R&D investment for a firm is EUR 2.8 million, although there is wide variation within the sample, also in terms of this figure; the median yearly investment on R&D is roughly a tenth of the mean and the maximum observation is EUR 572 million. The average R&D

Industry	N	Average firm level Lerner index	Average number of annual U.S.Patents	Total sum of U.S. Patents
1516 Food manufacture, beverages and tobacco*	242	0.028	2.3	30
1719 Textile and leather industry**	133	0.059	0.9	11
20 Wood products	213	0.034	0.5	6
21 Paper and pulp industry	83	0.056	0.7	9
23 Mineral oil processing	13	0.06	2.9	38
24 Chemicals	206	0.102	16.8	219
25 Rubber and plastic products	156	0.062	0.7	9
26 Non metallic mineral products	173	0.077	0.9	12
27 Metal manufacturing	105	0.034	2.7	35
28 Manufacture of metal goods	346	0.065	3.5	45
29 Mechanical engineering	688	0.067	20.5	267
31 Electrical and electronic engineering	191	0.111	3	39
32 Information and telecommunication	225	0.184	29.8	388
33 Instrument engineering	350	0.128	11.2	145
34 Motor vehicles	56	0.047	0.2	2
35 Manufacture of other vehicles	67	-0.015	1.2	15
Total	3247	0.068	6.1	1270

*The tobacco industry (16) is combined with food and beverages manufacture (15).
**The textiles (17) and leather industry (18) are combined.

Table 2: Distribution of observations with patents and R and D intensity data by industry

subsidy (i.e. direct subsidy by Tekes to industry R&D) is EUR 206 000 and quite naturally, following from the distribution of R&D expenditures, this figure is also skewed with the median yearly subsidy being EUR 67 300.[46] The median of the relative R&D subsidy is roughly 23% of a firm's in-house R&D investments. The unusually high mean of relative R&D subsidies is perhaps explained by the fact that some firms have been unable to commit themselves to spending allocated R&D shares reported in grant applications.[47] The weighted average of relative R&D subsidies by industry per year is 0.17 and the corresponding median is 0.11.[48] The median share of R&D expenditures per sales is 2.6%. This figure seems rather small taking into consideration that the firms in our data (i.e. all the manufacturing firms receiving direct R&D subsidies by Tekes between 1985-2001) are assumed to conduct more R&D than the average firm.

Tables 3 and 4 give more detailed figures on R&D spending and subsidies in Fin-

[46] The minimum R&D subsidy in the sample is a negative figure due to the fact that firms are obliged to refound the grant in case of neglecting the contract terms.

[47] As mentioned above, Tekes funding contribution should not exceed 50% of the budget.

[48] We further see that in 506 observations the ratio of Subsidy/ Inhouse R&D expenditures was above 0.5, i.e. over 50% of the in-house R&D is financed by R&D expenditures.

	Total subsidies and loans	Direct industry R and D subsidies	Direct research funding	Loans
1985	52	21	13	19
1986	63	22	16	25
1987	69	25	21	23
1988	89	27	28	34
1989	100	39	31	30
1990	120	41	38	42
1991	145	58	44	43
1992	171	65	55	51
1993	238	114	75	49
1994	236	110	78	48
1995	259	132	86	41
1996	232	109	89	35
1997	331	137	132	63
1998	361	146	140	74
1999	400	168	153	79
2000	373	154	140	79
2001	387	160	146	81

Table 3: Tekes funding in the state budget, M EUR

land. From these we see that as public aid to R&D has increased heavily since 1985, so has also business R&D investment. It is naturally hard to detect the causality between private and public increases in R&D expenditures. One can however see that the rate of increase of R&D subsidies is lagging slightly behind that of R&D expenditures, increasing the relative importance of business R&D. From Table 4 we can see that the companies in our sample represent a large share of the yearly domestic industry R&D activity, varying between 18% to 61% of all Finnish business R&D expenditure.

	Observations in whole sample	Observations for which R and D data	Finnish private R and D[1]	Total R and D in sample[2]	Percent of Finnish R and D	Inhouse R and D in sample	Direct subsidies by Tekes	Percent of sample inhouse R and D
1986	73							
1987	-	-	673.1	-	-	-	-	-
1988	62		-					
1989	66	50	924.9	328.4	35.5	320.2	13.1	4.0
1990	70		-					
1991	102	78	975.1	422.7	43.3	393.2	29.7	7.5
1992	124	57	-	336.9		336.9	21.4	6.3
1993	220	141	1048.5	575.9	54.9	459.5	46.9	10.2
1994	242	102	1249.8	410.1		410.1	44.7	10.8
1995	264	192	1373.4	597.2	43.5	453.0	54.3	12.0
1996	270	94	1656.7	312.0	18.8	269.2	24.8	9.2
1997	381	287	1916.7	1149.1	61.2	898.9	57.4	6.3
1998	362	239	2252.8	521.6	23.2	450.1	54.1	12.0
1999	386	307	2643.9	540.5	20.4	466.6	56.8	12.1
2000	360	269	3135.9	695.2	22.1	654.0	66.4	10.1
2001	265	200	3284.0	638.3	19.4	604.2	50.6	8.4

[1]Source: OECD Main Science and Technology indicators. All monetary figures are in EUR million.
[2]R and D data available for 2016 observations.

Table 4: Descriptive statistics of Finnish Research and Development

Patents	1 or more	5 or more	10 or more	30 or more	100 or more
Firms	967	135	72	27	11

Table 5: Distribution of firms by total patents 1968-1996

4.1.1 USPTO Patents data set

As mentioned above, we use the NBER patent citations data file developed by the NBER group (Hall, Jaffe, Trajtenberg etc.) of innovation and productivity researchers.[49] The original data comprise detailed information on almost 3 million U.S. patents granted between January 1963 and December 1999, all the citations made to these patents between 1975 and 1999 (over 16 million) and a variety of original measures constructed using citation data, such as backward and forward citation lags. The main technological categories of patents are Computers and Communications, Drugs and Medical, Electrical and Electronics, Chemical, Mechanical, and Others. The complete data base is available on the NBER web site.

We restrict our attention to patents granted by Finnish companies. The data base contains 6 429 patents originating in Finland, of which 5 435 are assigned to (967 different) companies. The rest of the patents are assigned to either individuals, the government, or non-governmental institutions. As Table 5 shows, most companies very rarely take out patents at the USPTO, while only one percent of the companies have taken out more than 100 patents during the period of observation.

The patenting activity has steadily increased since the beginning of the 1970s, as can be seen from Figure 4, where the total number of patents are graphed by year of application. In Figure 5 the same statistics are graphed by technological field. As expected the patenting activity has increased most rapidly in the field of computer and communication technology, but there has also been steady increases in the other fields, especially in mechanical engineering and in chemical industry.

[49] For a description of the NBER Patent-Citations data file, see Hall *et al.* (2001).

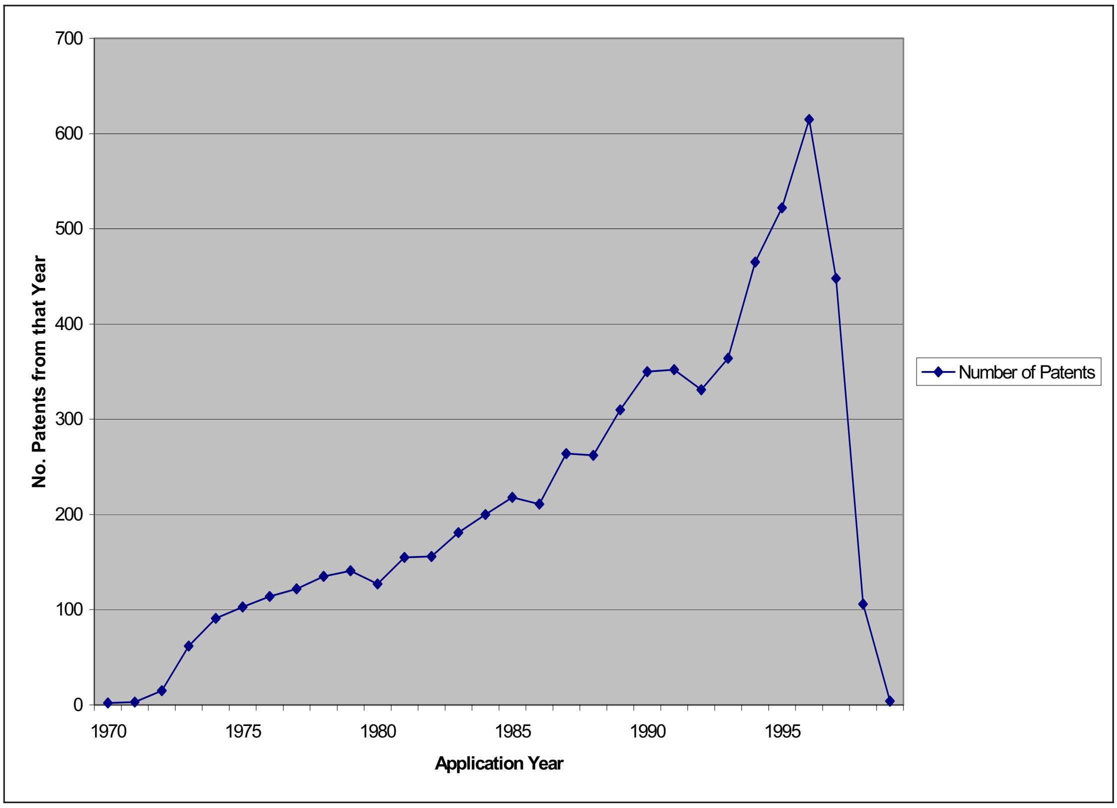

Figure 4: Total number of patents by year of application

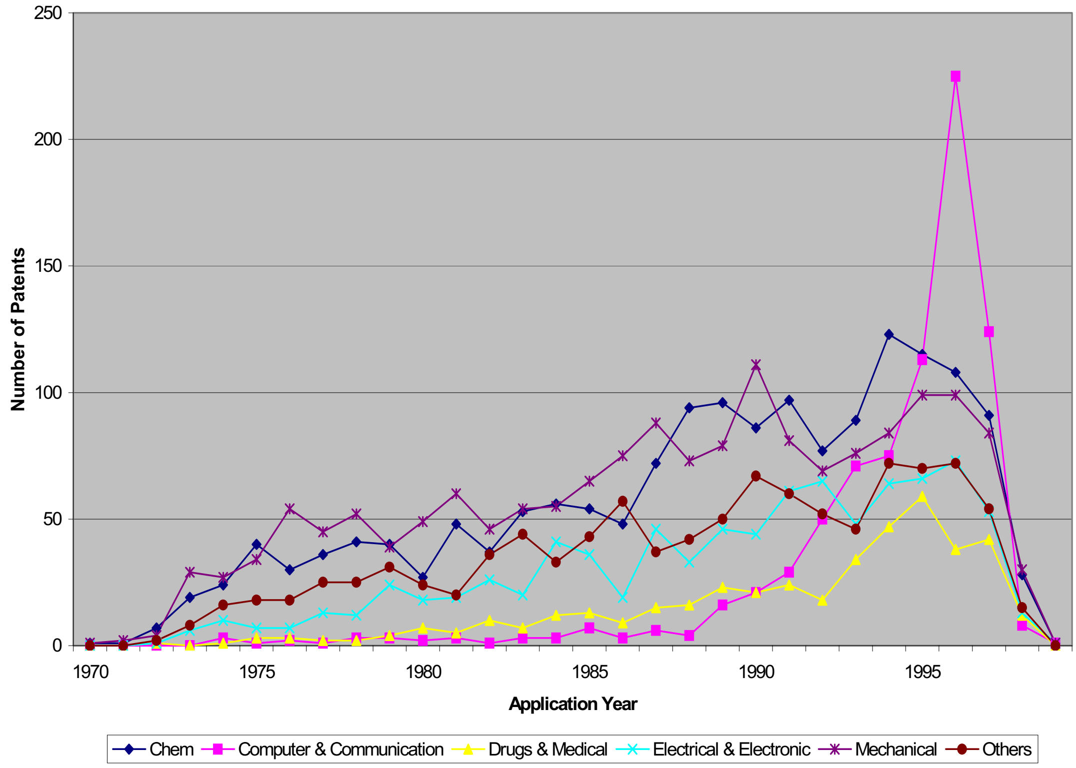

Figure 5: Number of patents by year of application in different industries

Notice that the rapid decline in the number of applications in the latter part of the period is due to the truncation problem. Because statistics are collected only on patents granted, the nearly two year average application-grant lag causes a downward bias toward the end of the period.

We also use the data on citations made by any of the 3 million patents in the main data set to the 6 429 patents in our sample. The total number of citations received by the Finnish patents in our sample is 20 058, while the total number of citations made by the patents in our data is 40 505. As discussed above, it is assumed that those patents that are frequently cited are likely to be more productive and thus more valuable to the firm. In Figure 6 we plot a histogram of the lag between a patent being taken out and the subsequent citations to it. It is worth noticing that even more than 20 year old patents receive citations, implying that some innovations maintain their technological value long after patent application.

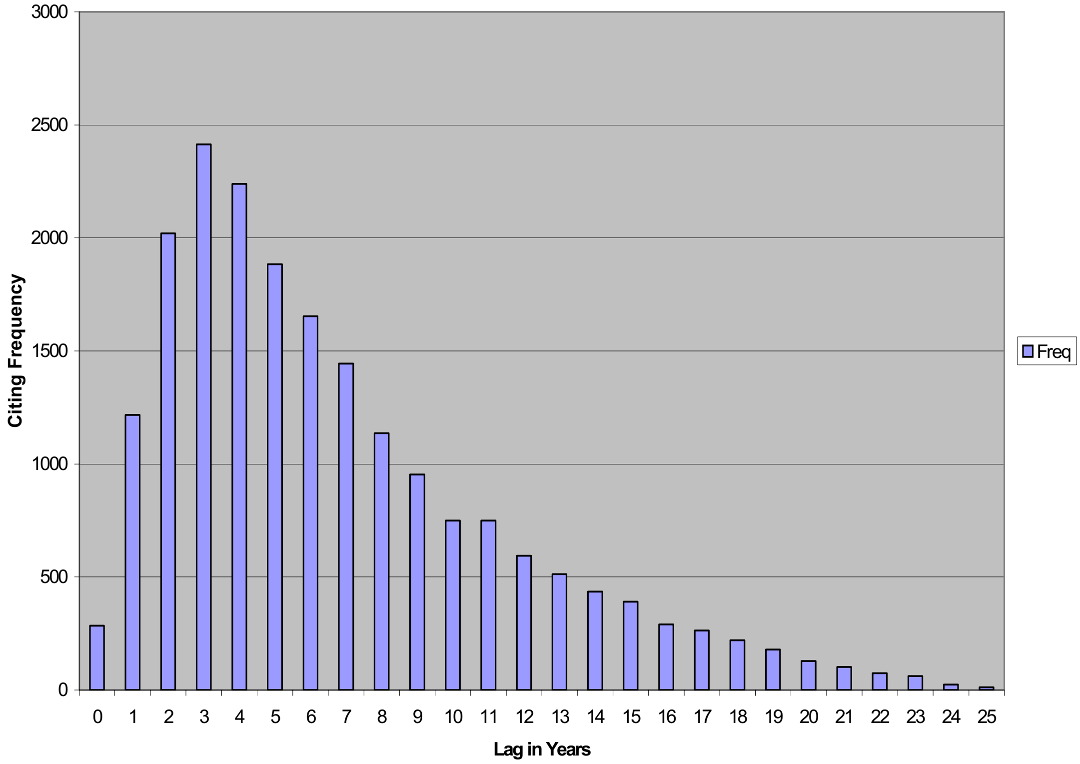

Figure 6: Lag from patenting to citation

From the distribution of the backward lag of citation in Figure 7 we see that it is skewed to the left, since most of the citations refer to recent patents in the same technological field.[50] In Figure 8 we plot a histogram of cites per patent received. From the histogram it is clear that many patents never receive any citations and quite few are successful in stimulating further research along the same technological trajectory.

Finally, in order to make use of the data on patents originating in Finland in the NBER data file we need to match them to a patent data base (containing only data on patent numbers, grant years, and company SIC codes) at Statistics

[50] The mean backward citation lag is 9.3 years and the median is 7 years. The oldest backward citation lag in our data is 41 years, made to a patent applied for in 1950.

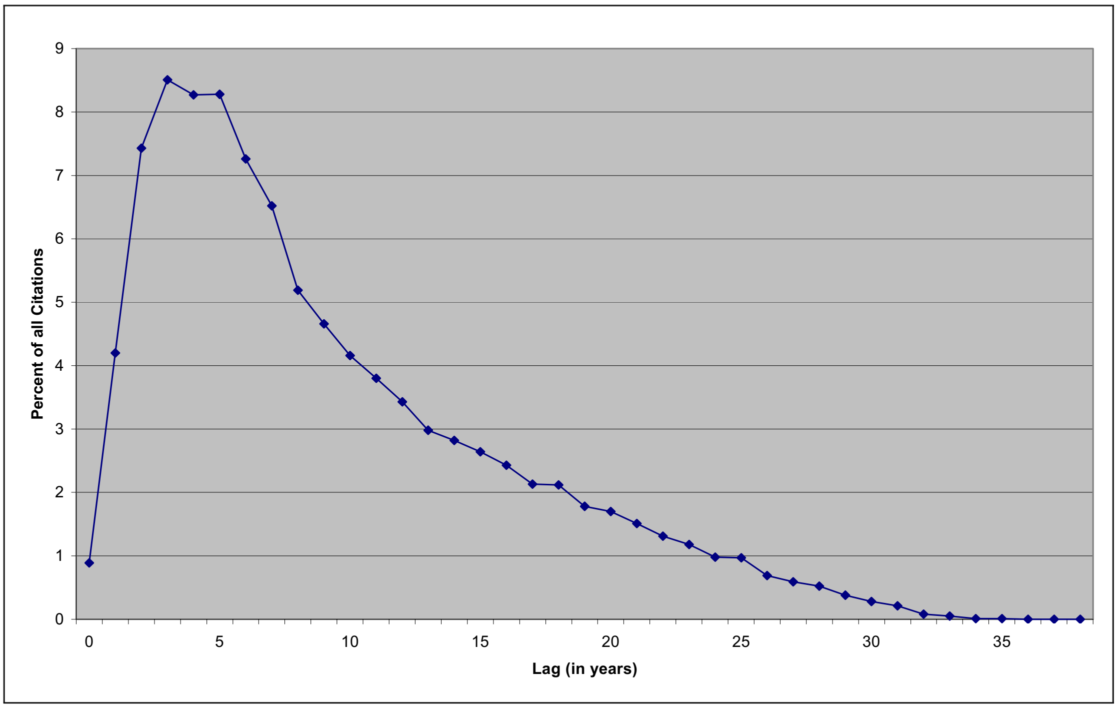

Figure 7: Distribution of backward citation lags

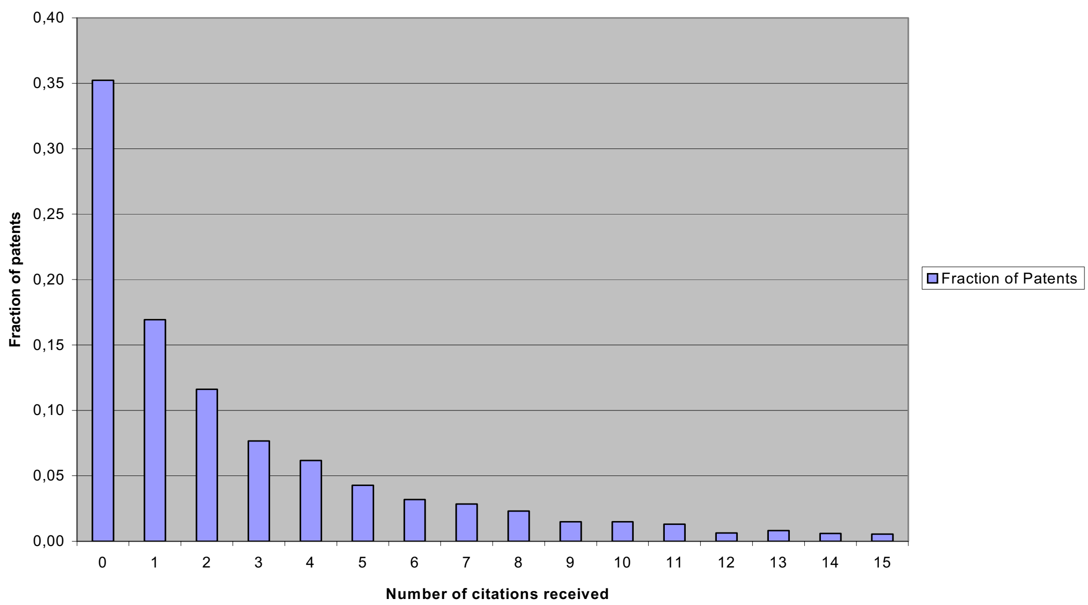

Figure 8: Histogram of a number of citations received per patent

Finland, comprising all patents taken out by Finnish companies between 1985-2001. This information was originally received from the National Board of Patents and Registration of Finland (NBPR) and compiled at Statistics Finland into a functional data set that enables matching. We find that for the period of observation these two data sets are matched completely except for two patents in the NBPR data that were not found in the NBER data file.

5 Econometric methods

Following our theoretical model, our primary interest is to next find out whether there exists a nonlinear relationship between product market competition and the innovation rate, in particular, whether it is of an inverted-U shape. We further want to test our prediction of the interaction between competition and R&D subsidies. We begin with the functional relationship which relates innovations, I_{ijt}, to the measure of product market competition, c_{jt}, and control variables, x'_{ijt} :

$$I_{ijt} = f\left(c_{jt}, x'_{ijt}\right), \tag{5.1}$$

where i indexes firms, j industries and t time. As discussed above, we measure an increase in product market competition as an increase in product substitutability, α, which in turn is reflected in a decrease in the Lerner index. Hence a reduction in the Lerner index is associated with a higher value of α and thus more intense competition. Furthermore, our dependent variable, I_{ijt}, is a count of patents which has a skewed distribution and contains many zeros. The natural estimator for this type of data is a Poisson model. We will also make use of other methods, such as Kernel estimation and spline estimation in order to adopt more flexible functional forms.

5.1 Poisson regression

Our analysis follows that of Aghion *et al.* (2002) in that we use a log-linear regression model and a basic quadratic specification. We use patent counts as a proxy for innovative effort and are thus referred to count data models. We suppose that the patent process, i.e. our discrete random variable p, is Poisson distributed with hazard rate $n = e^{g(c)}$, where c is the measure of competition. In this case, the resulting count of patents, p, will in any time interval have the density

$$\Pr[p = y \mid c] = \frac{e^{g(c)y} e^{-e^{g(c)}}}{y!}, \qquad y = 0, 1, 2, ..., \tag{5.2}$$

i.e. p, given c, is Poisson distributed with the density in (5.2). In the log-linear version of the model the expected number of patents can be written as

$$E[p \mid c] = e^{g(c)}. \tag{5.3}$$

In this case, the Poisson Maximum Likelihood Estimator provides a consistent estimator for the expected number of patents. However, we acknowledge the fact that our patent counts data are excessively dispersed, as is usually the problem with patent data sets. This leads to an incorrectly estimated variance covariance matrix. Estimated standard errors can however be corrected by using heteroscedasticity-corrected standard errors, as suggested by Blundell *et al.* (1999).

In the estimation, we use firm level data on patent counts, since we are interested in the performance of the individual firm, and industry level data on competition, since we want to measure the overall competitive pressure within the industry. The firms $i = 1, ..., N_t$ in our data are thus grouped into J mutually exclusive industries with $i \in I_j$ and $j = 1, ..., J$. We observe firms for $t = 1, ..., T_i$ periods. Following from the specification of the conditional mean (5.3), we write

$$E[p_{it} \mid c_{jt}] = e^{g(c_{jt})}. \tag{5.4}$$

It is likely that the differences in patenting activity between technology fields are due to institutional features of the industries unrelated to product market competition. This will cause spurious correlation unless controlled for the industry fixed effects. We also include time effects to remove common macroeconomic shocks.

Thus, when industry within effects and time effects are included, average patent behavior is related to industry competition according to

$$E\left[p_{it} \mid c_{jt}, x_{jt}\right] = e^{\left\{g\left(c_{jt}\right)+x_{it}'B\right\}}, \tag{5.5}$$

where the x_{it} represent a complete set of time and industry dummy variables.

We also include the industry level technology gap measure in the quadratic specification in order to capture the degree of neck-and-neckness of the industries. As mentioned above, the innovation incentives, and hence the reactions to changes in competitive climate, depend on the degree of neck-and-neckness in the industries (i.e. how close the rivals are in cost/technology space). When including our technology gap measure, NN_{jt}, in the specification we get

$$E\left[p_{it} \mid c_{jt}, NN_{jt}, x_{jt}\right] = e^{\left\{g\left(c_{jt}\right)+\gamma NN_{jt}+x_{it}'B\right\}}. \tag{5.6}$$

Since we are interested in allowing our data to determine the shape of the relationship between innovation and product market competition, we adopt a flexible specification for $g(c)$ and use nonparametric methods[51]. However, following Aghion *et al.* (2002), we also estimate the model where $g(c)$ is approximated with a quadratic specification.

Finally, in order to test for complementarity between product market competition and R&D subsidies, we allow the inverted-U relationship to become steeper as the R&D subsidies are increased. To analyze this interaction between competition and R&D subsidies we include an interaction term in the quadratic specification. We thus acquire a quadratic specification of the form where competition c_{jt} is multiplied by the relative R&D subsidies (direct industry R&D subsidies per inhouse R&D

[51] See Appendix B for a closer description of the non-parametric methods used in this study.

expenditures), ρ:

$$E\left[p_{it} \mid c_{jt}, \rho_{it}, x_{jt}\right] = e^{\alpha+\beta_1 c_{jt}+\beta_2 \left(c_{jt}\right)^2+\beta_3 c_{jt}\rho_{it}+\beta_4 \left(c_{jt}\right)^2 \rho_{it}+\beta_5 \rho_{it}+x'_{it}B}. \tag{5.7}$$

The theoretical predictions of an inverted-U shape imply that the sign of the coefficient β_1 in the quadratic specification (5.7) should be significantly positive and that the constants α and β_2 should be significantly negative, in order to turn the curve into an inverted-U shape. Predictions of the interaction terms are more ambiguous, based on our theory. However, our theory of the interaction between competition and R&D subsidies suggests that β_5 is significantly positive.

6 Results

6.1 The inverted-U relationship

Regressions using the exponential quadratic specification and without other control variables are presented in Table 6 and Figure 9.

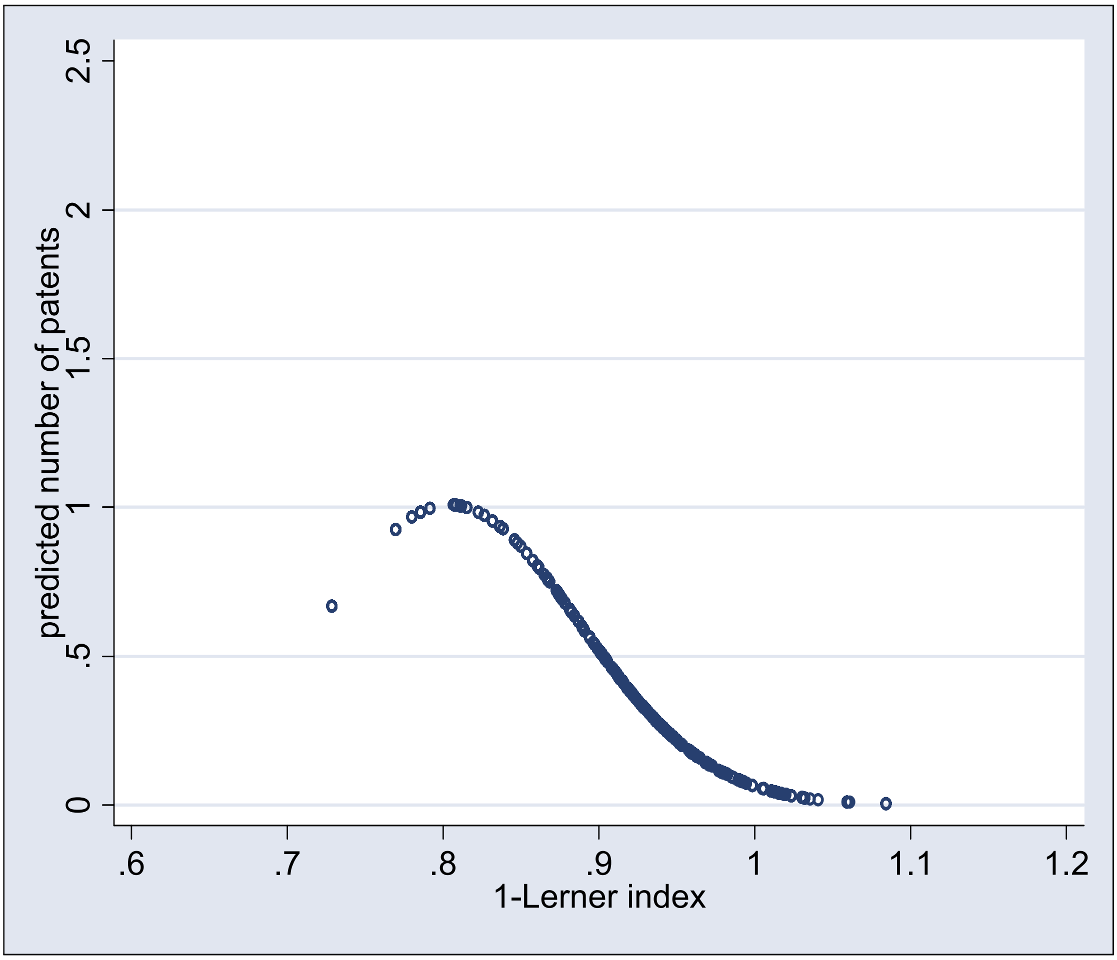

Figure 9: Basic quadratic specification using simple patent counts

We can see from the figure and the estimated coefficients that the exponential quadratic specification shows a clear inverted-U relationship. This relationship is retained, although not as pronounced, when industry and time effects are included. Using market share adjusted competition measure as constructed in equation (3.7), the results remain qualitatively the same (see Table 7.)

Dependent variable:			
Simple patent counts			
Observations	3174	3174	3174
Constant	-46.80**	-87.47**	-5.92
s.e.	(6.03)	(7.41)	(9.26)
c_{jt}	116.39**	194.31**	16.79
s.e.	(13.84)	(16.98)	(20.83)
c_{jt}^2	-72.35**	-109.51**	-11.89
s.e.	(7.9)	(9.67)	(11.72)
Industry effects	-	yes	yes
Time effects	-	-	yes
Implication for an inverted-U relationship	yes	yes	no
** = significant at 1% level			
* = significant at 5% level			
We use the same notation for significance levels of coefficients in all tables			

Table 6: Regression with basic exponential quadratic specification

We alternatively use, as dependent variable, the citation weighted patent counts constructed using the formula in (3.1). We can see from the first column in Table 8 that the inverted-U relationship also holds for this measure. Including the industry fixed effects in column 2 makes the relationship more pronounced while the relationship does not hold when time effects are also included.

When using the estimated lifetime citations as dependent variable in the exponential quadratic specification our results are ambiguous, as reported in Table 9. Without time and industry effects, the coefficients produce a normal U-shaped relationship between competition and innovation, with the innovation rate being the highest at extremely high and extremely low levels of competition.

When time and industry effects are included, we get a weak inverted-U relationship. Estimations using the other impact corrected measure for innovation, i.e. the 5-year cite stock calculated as in (3.3), are presented in Table 10. We see that the inverted-U relationship is not robust to this impact corrected innovation measure. We can see from the highly significant coefficients that a clear U-shaped relationship

Dependent variable:			
Simple patent counts			
Observations	3174	3174	3174
Constant	-43.92**	-101.45**	-14.32
s.e.	(7.76)	(9.91)	(11.32)
α_{jt}	108.96**	223.63**	34.76
s.e.	(17.51)	(22.39)	(25.24)
α_{jt}^2	-67.6**	-124.86**	-21.50
s.e.	(9.87)	(12.57)	(14.06)
Industry effects	-	yes	yes
Time effects	-	-	yes
Implication for an			
inverted-U relationship	yes	yes	

Table 7: Basic quadratic specification using alpha as explanatory variable

Dependent variable:			
Simple citation weighted patent counts			
Observations	3174	3174	3174
Constant	-53.52**	-103.33**	13.03*
s.e.	(3.35)	(3.91)	(5.55)
c_{jt}	139.99**	237.21**	-15.36
s.e.	(7.81)	(9.11)	(12.52)
c_{jt}^2	-88.88**	-135.43**	3.08
s.e.	(4.52)	(5.26)	(7.08)
Industry effects	-	yes	yes
Time effects	-	-	yes
Implication for an			
inverted-U relationship	yes	yes	no

Table 8: Regression with basic exponential quadratic specification

is attained between competition and innovations.

The quadratic specification of an inverted-U shape might be incorrect, leading to ambiguous results, as discussed above. Nonparametric methods however allow more flexible specification. We therefore make use of the smoothing methods discussed more in detail in appendix B, in order to capture the relationship between product market competition and innovations. Using the 5-year cite stock as dependent vari-

Dependent variable:		
Estimated lifetime citations		
Observations	1420	1420
Constant	55.68**	-1.83
s.e.	(3.32)	(4.39)
c_{jt}	-118.13**	18.46
s.e.	(7.55)	(9.92)
c_{jt}^2	63.44**	-16.61**
s.e.	(4.27)	(5.61)
Industry effects	yes	yes
Time effects	-	yes
Implication for an inverted-U relationship	no	yes

Table 9: Basic quadratic specification using estimated total of lifetime citations as dependent variable

able and both a quadratic spline regression[52] and kernel estimation[53], we find that the relationship between citation weighted patent counts and our measure of competition takes a quite different form than predicted by the theory. Namely, from Figure 10 we can see that estimating a Poisson model with a quadratic spline, we attain a two peaked fit.

The peak at lower levels of competition is arguably a phenomenon that one cannot describe using the simple causal relationship between competition and innovation. The levels of competition are in this case essentially too low for a change to have any effect on the incentives to innovate. Turning to the second local maximum, we can see that it is roughly at Lerner values of 0.05, with the fit rapidly decreasing moving toward zero profit levels. It is striking that this local maximum coincides almost without exception with the local maximum of the regression splines in Aghion *et al.* (2002). We are tempted to explain this second peak with the theory behind the inverted-U shape. Thus, for exceptional profit margins, the escape from competition effect does poorly in describing changes in innovation efforts. How-

[52] We use 8 evenly spaced knot points between 0.75 and 1.10.
[53] We use a Gaussian kernel with a bandwidth of 0.025.

Dependent variable:			
5-year cite stock			
Observations	886	886	886
Constant	46.79**	43.13**	20.11**
s.e.	(2.05)	(3.10)	(4.33)
c_{jt}	-87.90**	-92.63**	-35.26**
s.e.	(4.69)	(6.98)	(9.81)
c_{jt}^2	42.79**	51.17**	15.24**
s.e.	(2.68)	(3.92)	(5.58)
Industry effects	-	yes	yes
Time effects	-	-	yes
Implication for an inverted-U relationship	no	no	no

Table 10: Basic quadratic specification using 5-year cite stock as dependent variable

ever, moving closer to perfect competition, we attain an inverted-U relationship between competition and innovations, which is better motivated by the escape from competition and the Schumpeterian effects on innovation. We attain a similar two peaked relationship using Gaussian kernel estimation with bandwidth 0.025, as seen in Figure 11.

Finally, we also look at how the dispersion in within-industry technology levels affects the rate of innovation. This was done by including our technology gap measure in the quadratic specification. After controlling for technology gap, our results on the inverted-U relationship become ambiguous. However, we find that in three out of four cases (i.e. when altering between our measures of proxy for innovation), we get a negative sign for the technology gap measure, i.e. γ in (5.6). The negative sign suggests that the smaller the technology gap, the higher the expected number of patents, and hence the curve (whatever the shape) is shifted up. This is a rather interesting result on its own, as it seems to point to the fact that industries with very dispersed technology levels innovate less on average.

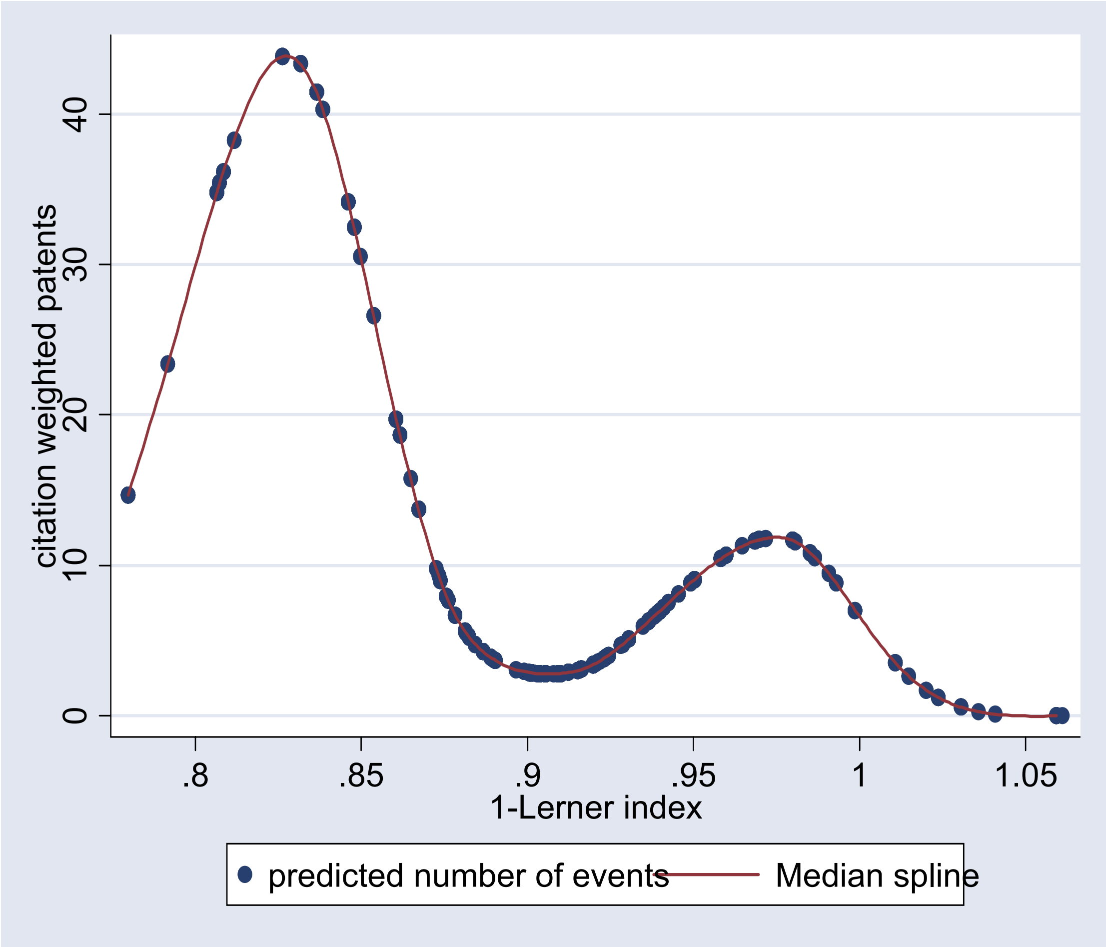

Figure 10: Non-parametric estimation with splines and using the 5 year cite stock as dependent variable

6.2 The complementarity between product market competition and R&D subsidies

The estimation results above were derived without specifically controlling for R&D subsidies received by firms. In this section, we discuss the results of estimations where we study the complementarity between competition and R&D subsidies. This is done by including interaction terms in the conditional mean function, as in (5.7) .Table 12 summarises the results. In columns 6 and 7, we present the coefficients of estimations using the estimated lifetime citations discussed in section 3.1.3 as the dependent variable. Columns 8 and 9 in turn show the results of using the

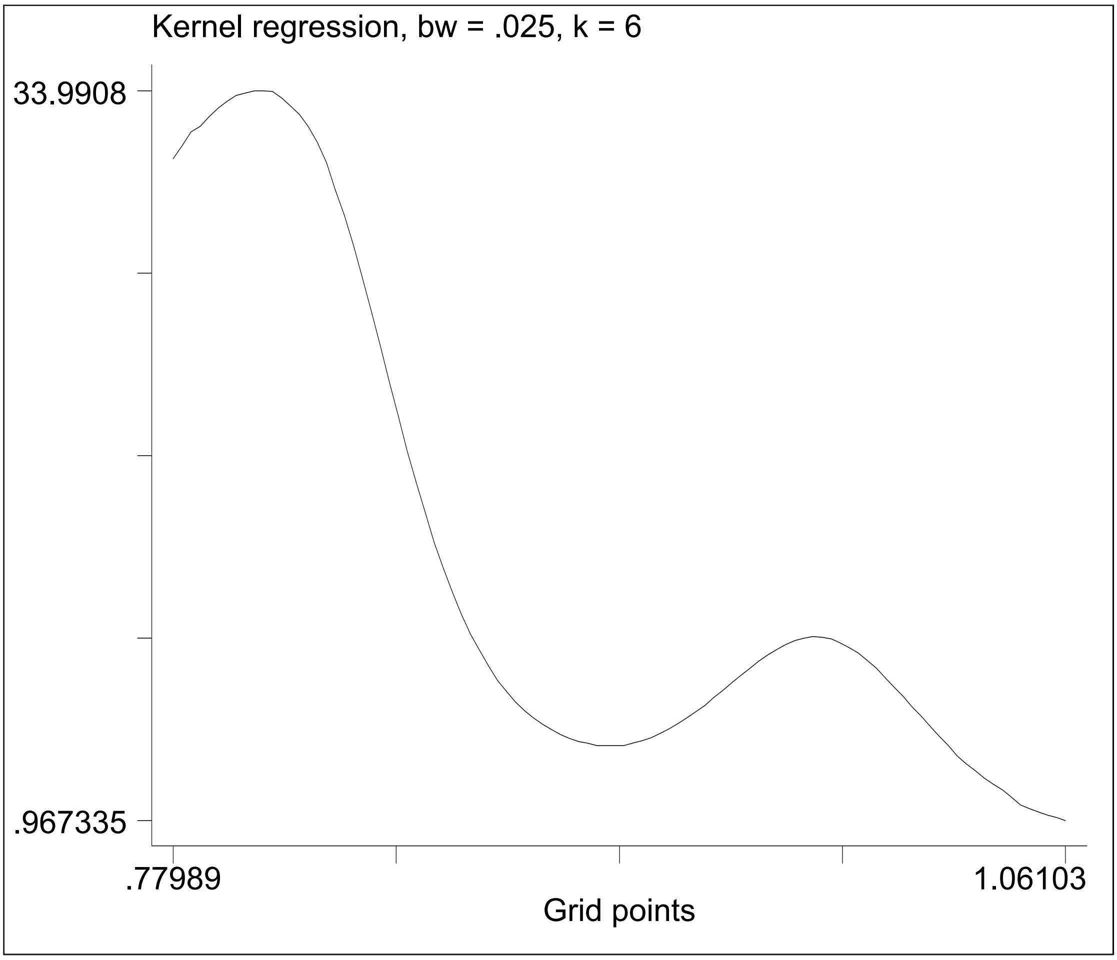

Figure 11: Non-parametric kernel estimation using bandwidth 0.025 and Gaussian weights

5-year cite stock as the dependent variable.

Interestingly, we can see that the inverted-U relationship between competition and innovations is consistent regardless of the innovation measure, once relevant interaction terms between the measure of competition and R&D subsidies are included in the quadratic specification of the model. However, the sign and significance of the coefficients of interaction terms vary considerably. Using simple patent counts and simple citation weights gives positive coefficients for the first order interaction term and negative coefficients for the relative R&D subsidy.

Dependent variable:				
	SPC	WPC	Lifetime cit.	5-year CS
Observations	3174	3174	1420	886
Constant	-5.60	20.90**	7.32	46.75**
s.e.	(9.33)	(5.74)	(4.49)	(4.59)
c_{jt}	16.29	-30.07**	1.71	-86.71**
s.e.	(20.92)	(12.83)	(10.07)	(10.33)
c_{jt}^2	-11.67	10.29	-8.51	41.24**
s.e.	(11.75)	(7.22)	(5.67)	(5.85)
NN_{jt}	-0.05	-0.64**	-0.79**	-1.73**
s.e.	(0.18)	(0.12)	(0.09)	(0.08)
Industry effects	yes	yes	yes	yes
Time effects	yes	yes	yes	yes
Implication for an inverted-U relationship	-	no	-	no

Table 11: Quadratic specification controlling for neck-and-neckness

	Dependent var: Simple patent counts		Dependent var: Citation weighted patent counts		Dependent var: Estimated total lifetime citations		Dependent var: 5-year cite stock	
Observations	1740	1740	1740	1740	660	660	395	395
Constant	-17.13	-22.89	-40.05**	-45.57**	-2.78	-71.75**	-2.56	-43.64**
s.e.	(8.29)	(14.12)	(3.96)	(8.28)	(3.52)	(6.61)	(2.97)	(6.21)
c_{jt}	52.86**	55.12	114.93**	114.86**	32.02**	175.47**	31.26**	110.18**
s.e.	(18.93)	(31.58)	(9.13)	(18.48)	(8.02)	(14.76)	(6.79)	(13.94)
c_{jt}^2	-36.83**	-32.97	-76.13**	-69.42**	-28.17**	-104.50**	-26.73**	-67.62**
s.e.	(10.79)	(17.65)	(5.26)	(10.33)	(4.55)	(8.25)	(3.87)	(7.84)
$c_{jt} \times$ (R andD subsidies)	592.42**	362.39	155.03**	24.24	-147.88**	-152.55**	-224.88**	-278.11**
s.e.	(166.24)	(212.27)	(50.91)	(64.20)	(45.03)	(52.77)	(35.83)	(38.10)
$c_{jt}^2 \times$ (R and D subsidies)	-314.37**	-185.0	-56.37*	10.79	106.47**	108.43**	142.60**	168.48**
s.e.	(92.73)	(117.74)	(27.34)	(34.20)	(24.13)	(28.04)	(19.46)	(20.62)
Relative R and D subsidies[1)]	–283.43**	-181.37	-99.81**	–36.22	-38.91	42.74	79.27**	107.89**
s.e.	(74.47)	(95.50)	(23.67)	(30.01)	(20.92)	(24.71)	(16.41)	(17.48)
Industry effects	-	yes	-	yes	-	yes	-	yes
Time effects	-	yes	-	yes	-	yes	-	yes
Pseudo R^2	0.1997	0.4748	0.2254	0.6170	0.2808	0.5356	0.2723	0.5192
Implication for an inverted-U relationship	yes	yes	yes	yes	yes	yes	yes	yes
[1)] Relative R and D subsidies calculated as direct industry R and D subsidies received from Tekes								
over inhouse R and D expenditure								

Table 12: Interaction between R and D subsidies and competition

This implies that the inverted-U relationship between competition and innovation becomes steeper when the interaction between product market competition and direct R&D subsidies is considered. However, the coefficient of relative R&D subsidies is negative, indicating that R&D subsidies tend on average to reduce the probability of innovating. The final effect depends on the degree of competition. Given that at high and low levels of competition the rate of innovation is already initially low, it is likely that the final effect of a direct R&D subsidy will have a negative effect on innovation. However, given that an R&D subsidy has a complementary role, at intermediate levels of competition the R&D subsidy is more likely to have a desired positive effect on the average innovation rate of the economy, as suggested in the theoretical model. When time and industry effects are included, the interaction terms and the relative R&D subsidy are no longer significant at the 95% significance level. When using the impact corrected measures for innovation, we attain contradicting results. The sign of the first order interaction term is negative, pointing to a reducing effect for the interaction term. This could be interpreted as a sort of substitutability between competition and public aid to innovations.[54]

[54] In some theoretical studies, the substitutability between competition and credit constraints with respect to innovations is discussed. See e.g. Aghion, Dewatripoint and Rey (1999).

7 Conclusions

This paper contributes to the series of recent studies exploring the non-monotonous relationship between innovation incentives and market structure. The aim of this study has been to identify how the degree of product market competition affects innovative activity within industries and, on the aggregate level, of the economy. The recent growth literature has paid increasing attention to the dynamic efficiency gains of competition. These efficiency gains are broadly defined in terms of productivity-enhancing innovations. In particular, when a gradualist framework to technological progress is adopted, as is done by Aghion *et al.* (1997, 2001), it can be analytically shown that intensified product market competition between firms with equal technologies will increase each firm's incentives to acquire a lead over its rival. In this framework, product market competition has a central role in fostering innovation, in the sense that intensified PMC may reduce pre-innovation rents by more than it reduces post-innovation rents. In other words, competition may increase the incremental profits from innovating. On the other hand, competition may also reduce the followers' prospective gains from catching up with the leader. In a model by Aghion *et al.* (1997, 2001), where the innovation process is assumed to be of a step-by-step character, they derive an inverted-U relationship between competition and innovation. This theoretical result deserves attention in the policy discussion of public intervention in R&D activity, since it implies that the regulatory policy is closely related to traditional R&D policy. However, the result should first be confirmed by empirical studies, as is the case in Aghion *et al.* (2002). Their results suggest that the prediction of an inverted-U relationship is found to accord well with observed behavior.

In this paper, we confront the prediction made by Aghion *et al.* (1997, 2001) with data on Finnish firms and extend the theoretical model of Aghion *et al.* (1997, 2001) by introducing R&D subsidies. In a simulation exercise we derive the result that the interplay of the incentive effects of intensified product market competition and an R&D subsidy might be complementary in the sense that the R&D subsidy only steepens the inverted-U shape at the aggregate level.

This suggests that, at extremely low and extremely high degrees of competition, R&D subsidies may not have the desired effect of boosting innovative activity. An important factor behind these results lies in the strategic substitutability effect, which was shown to depend upon the degree of competition within an industry.

Turning our attention to our empirical results, we found relatively strong evidence in favour of the inverted-U shape hypothesis in the Finnish data. Moreover, we also find some evidence of complementarity between competition and R&D subsidies. Namely, our results suggest that the inverted-U relationship tends to be steeper when R&D subsidies are also considered. The latter result can be interpreted to be in line with our theoretical result that additionality of R&D subsidies depends upon the degree of competition. However, this result should be interpreted with some caution, given that the direct effect of an R&D subsidy on our different measures of innovation was found to be negative, indicating that the R&D subsidies tend on average to reduce the probability of innovating.

A further finding is that industries with more dispersed technology levels tend to innovate less compared with industries with more equal levels of technology between the firms. This result is also in line with the model of Aghion *et al.* (1997, 2001), which suggests that competition has a stronger impact on innovation for industries that are closer in technology space.

If confirmed by subsequent research, the results in our study indicate that the level of competition within industries clearly has an impact on innovation incentives. Implications that can be drawn from the results are that the within-industry product market competition should be taken into consideration when designing public interventions to R&D activity. In particular, R&D subsidies may not be justifiable at all degrees of competition. Or at least, when deciding upon the distribution of R&D subsidies, public authorities should opt for a selective R&D policy which takes into account the within-industry market structure.

On the one hand, our theoretical results suggest that the highest additionality would be achieved in industries with moderate levels of competition. On the other hand, selective R&D subsidy schemes for middle-range productivity firms is a form of public intervention that might foster innovations. In order to increase the competitiveness of the industry, followers (i.e. companies lagging behind the leaders) should be encouraged to challenge the leader and so raise the level of competition. This form of subsidy should be directed at the middle-range productivity firms, while the least productive firms are exposed to the selection effect. In other words, the risk of subsidizing the least productive companies is very high, as they might be forced to exit the market soon. Thus it can be argued that it is irresponsible to tax payers to subsidize the least efficient firms in the market, as the return on investment is fairly insecure. The selective R&D subsidy scheme can be criticized on the grounds that it does not offer a *juste retour* to the leaders in the industry, who arguably still pay the largest corporate taxes. Thus it will be difficult to legitimize such a policy.

A moderate version of the former public intervention is to encourage R&D joint ventures between large and small companies. As R&D costs for developing successful innovations are high and the time frames of the innovations are short, it has become almost impossible for small entrants to compete with leaders in many industries. Joint ventures is one solution for small firms to overcome the thresholds of critical mass in many industries. For example, in the biotech industry, there are only a few companies in the world that can cover the critical mass for developing a successful concept. It is thus extremely important to lead companies together into research consortia by publicly subsidized joint venture schemes. This goes especially for small countries, where the absolute mass of research is limited. In Finland, Tekes has developed instruments especially designed to promote national and international networking. The grants awarded to large companies are conditional to at least some degree of networking or other type of cooperation with e.g. subcontractors. This may importantly facilitate knowledge spillovers between the firms.

Finally, this study has opened up several interesting paths for further research and extensions. First, the robustness of the results could be improved by controlling for endogeneity of our competition measure. This can be done by considering policy instruments that would provide exogenous variation in the degree of industry-wide competition. A second interesting modification would be to take a somewhat different approach to measuring innovation, by using survey data instead of patent data. Also the possibility of combining patent data with existing innovation surveys should be explored. Then survey data on the impact of the innovation could be used to evaluate the value of the innovation for the company.

A third possible methodological extension would be to introduce into the analysis alternative empirical applications of measuring competition, such as estimates of relative profit differences (RPD), a competition measure introduced in a theoretical paper by Boone (2004). The data needed to estimate RPD are the same as those needed for constructing the Lerner index. Thus our plant level data set allows us to estimate RPD. Another alternative measure for competition suggested by Vives (2004) is the extent that each firm internalizes the profits of other firms. If firms are strongly interconnected with each other through cross-shareholdings, the competitive pressure in the industry is assumed to be low.

Regarding extensions, it would be interesting to include in the analysis incentive mechanisms related to financial constraints and the capital structure of the firm. Recent studies have shown that higher debt pressure might have a similar disciplining effect as competition, in the sense, that it induces firms to innovate more in order to escape debt pressure.[55] Also the additionality of R&D subsidies for credit constrained firms has been studied empirically by Toivanen and Niininen (2000), who find that the highest sensitivity to R&D subsidies occurs at moderate levels of credit constraints. There is reason to believe that the financial climate and the additionality of R&D subsidies is closely related to the incentive effects of competition. These interactions should be carefully explored in subsequent studies.

[55] See Aghion *et al.* (1999).

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Appendices

A Weighting scheme

We follow Hall *et al.* (2000) in weighting the patents using the information on citations that a patent has received from subsequent patents.[56] In order to avoid problems related to truncation bias, we calculate a "5 year cite stock", first introduced by Bloom and Van Reenen (2000). Let $C_{i,x}(t,s)$ be the number of citations in year s to patent x of company i applied for in year t $(s \geqslant t)$ at the USPTO. The total number of citations received in year s by patents applied for in year t by company i is thus equal to

$$C_i(t,s) = \sum_{x=1}^{N_i(t)} C_{i,x}(t,s),$$

where $N_i(t)$ is the number of patents by company i applied for in year t. From this follows that the total number of citations to patents applied for at time t becomes

$$C_i(t) = \sum_{s=t}^{t+T} C(t,s),$$

where T is the maximum time span in which the patent gets cited (in our case $T = 5$). We thus give every patent five years to receive citations. Since our data runs up to 1999, we select our citation-weighting period to run up to 1994 in order to have 5 years of observations on citations for every patent. Thus no truncation bias correction is needed for this patent measure.

We set the depreciation rate for the "private value" of the patent at 30% and denote the depreciation rate as δ. We only consider citations that occur during the 5-year period of observation and depreciate the citations as of the date when

[56] See also Stavrevska and Tan (2003) for an exceptionally clear description of the citation weighting method of Hall *et al.* (2003).

they occur. Using the standard declining balance formula, our 5-year citation stock measure is defined by the following equation:

$$\begin{aligned}
CS\left(t\right) &= \left(1-\delta\right)CS(t-1)+C\left(t,t\right) \\
&= \left(1-\delta\right)CS\left(t-1,t\right)+C(t,t) \\
&\quad +\left(1-\delta\right)CS\left(t-2,t-1\right)+C\left(t-1,t\right)+ \\
&\quad +\left(1-\delta\right)CS\left(t-2,t-1\right)+\left(1-\delta\right)^{2}CS\left(t-3,t-2\right)+C(t-2,t) \\
&\quad +\left(1-\delta\right)CS(t-3,t-1)+\left(1-\delta\right)^{2}CS\left(t-3,t-2\right) \\
&\quad +\left(1-\delta\right)^{3}CS\left(t-4,t-3\right)+C(t-3,t) \\
&\quad +\left(1-\delta\right)CS(t-4,t-1)+\left(1-\delta\right)^{2}CS(t-4,t-2) \\
&\quad +\left(1-\delta\right)^{3}CS\left(t-4,t-3\right) \\
&\quad +\left(1-\delta\right)^{4}CS\left(t-5,t-4\right)+C(t-4,t) \\
&\quad +\left(1-\delta\right)CS(t-5,t-1)+\left(1-\delta\right)^{2}CS(t-5,t-2) \\
&\quad +\left(1-\delta\right)^{3}CS(t-5,t-4) \\
&\quad +\left(1-\delta\right)^{4}CS\left(t-6,t-5\right)+C(t-5,t) \\
&\quad +.....
\end{aligned}$$

The 5-year cite stock is defined by the following equation:

$$
\begin{aligned}
CS(5) &= (1-\delta)CS(t-1) + C(t) \\
&= C(0) \\
&\quad +(1-\delta)CS(0) + C(1) \\
&\quad +(1-\delta)CS(1) + (1-\delta)^2 CS(0) + C(2) \\
&\quad +(1-\delta)CS(2) + (1-\delta)^2 CS(1) + (1-\delta)^3 CS(0) + C(3) \\
&\quad +(1-\delta)CS(3) + (1-\delta)^2 CS(2) + (1-\delta)^3 CS(1) + (1-\delta)^4 CS(0) \\
&\quad +C(4) + (1-\delta)CS(4) + (1-\delta)^2 CS(3) + (1-\delta)^3 CS(2) \\
&\quad +(1-\delta)^4 CS(1) + (1-\delta)^5 CS(0) + C(5)
\end{aligned}
$$

B Semi-parametric methods

As our conjecture is that the relationship between product market competition and innovation follows a nonlinear relationship, we wish to estimate the relationship without imposing too much structure. Thus a useful nonparametric method for investigating this relationship is a smoother. The advantage of a smoother is that it does not assume too rigid a form for the dependence of Y on $X_1, ..., X_p$.

B.1 Kernel estimator

We follow Aghion *et al.* (2002) in using a kernel smoother to estimate the relationship between product market competition and innovation in semi-parametric fashion. A kernel smoother uses an explicitly defined set of local weights, defined by the kernel, to produce the estimate at each target value.[57] Usually a kernel smoother uses weights (e.g. Gaussian) that decrease smoothly as one moves away from the target point. The weight given to the jth point in producing the estimate

[57] See Eubank, R. (1988) and Yatchew (1998), for a more detailed description of kernel smoothers.

at a specific point on the x-axis, here p_0, is defined by

$$S_{0j} = \frac{e_0}{\lambda} d\left(\left|\frac{p_0 - p_j}{\lambda}\right|\right)$$

where $d(t)$ is an even function decreasing in $|t|$. While the shape of the weights is determined by d, the parameter λ controls the magnitude of the weights and is normally referred to as the bandwidth. A large value of λ results in greater weights on observations that are far from p_0.[58] The constant e_0 is usually chosen so that the weights sum to unity. As mentioned, the standard Gaussian density can be used for d. The Gaussian kernel smoother thus uses the Gaussian density function to assign weights to neighboring points. Another popular kernel is the Epachnikov kernel. More important than the choice of kernel, according to Yatchew (1998), is the choice of the right bandwidth over which observations are averaged.

We use the Nadaraya-Watson estimator, defined as

$$s(x_0) = \frac{\sum_{i=1}^{n} d\left(\frac{p_0 - p_j}{\lambda}\right) y_i}{\sum_{i=1}^{n} d\left(\frac{p_0 - p_j}{\lambda}\right)}. \tag{B.1}$$

B.2 Spline estimator

Although the exponential quadratic specification of a Poisson model provides a reasonable approximation of the relationship, it is symmetric in its character. This does not necessarily need to be the case, since we have highly overdispersed patent data (i.e. excess amount of observations with zero patents) and a skewed distribution of the Lerner index. The upward slope of the inverted-U shape is expected to be steeper than the downward slope and hence the quadratic specification is expected to be systematically biased; the decrease in patenting activity appears to be slower than it actually is. We use a regression spline, which is a less rigid form of parametric fitting,

[58] Chosing a too large value of λ will result in oversmoothing and selecting a too-small value will cause the estimator to track the data too closely, decreasing the generality of the results. For selecting the smoothing parameter a cross-validation method is proposed (Yatchew, 1998).

Spline	Basis Terms	Parameters	Properties
Linear	$\sum_{i=1}^{N}(x-K_i), 1, x$	N+2	level equal at knots
Quadratic	$\sum_{i=1}^{N}(x-K_i)^2, 1, x, x^2$	N+3	level,1^{st} derivative equal at knots
Cubic	$\sum_{i=1}^{N}(x-K_i)^2, 1, x, x^2, x^3$	N+4	level,1^{st},2^{nd} deriv. equal at knots
Quartic	$\sum_{i=1}^{N}(x-K_i)^2, 1, x, x^2, x^3, x^4$	N+5	level,1^{st},2^{nd},3^{rd} deriv. = at knots
Note: Knots are labelled $K_1, K_2, ..., K_N$			

Table 13: Main properties of splines

to avoid this systematic bias. The regression spline gives a *piecewise* polynomial fit. As Eubank (1988) argues, a regression spline provides a good compromise between the somewhat too global nature of the exponential mean specification and the local nature of the kernel estimator. The regions that define the pieces estimated are separated by a sequence of evenly spaced *knots* (e.g. breakpoints) on the horizontal axis. The piecewise polynomials are forced to join smoothly at these knots. The advantage of the spline is that the parameters vary within the observation interval. This allows for a more flexible estimation and a hence a more precise fit of the data. The cost of the flexibility is that the spline-curve is forced through the knots. We use quadratic and cubic splines in our analysis. The main properties of the splines are outlined in table (13). Using higher order splines ensures the derivatives are equal across knots up to a higher order, at the cost of including an extra parameter.

The quadratic spline can be used in a Poisson model. The patent count process is then written as

$$p_{it} = \exp(f(c_{jt}) + x'_{it}\beta) \tag{B.2}$$

where $f(c_{jt})$ is the spline function of competition and $x'_{it}\beta$ the dummy set of time and industry dummies.

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