NHH
INSTITUTT FOR FORETAKSØKONOMI
DEPARTMENT OF FINANCE AND MANAGEMENT SCIENCE

FOR 15 2011
ISSN: 1500-4066
September 2011

Discussion paper

R&D investment responses to R&D subsidies: A theoretical analysis and a microeconometric study

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R&D investment responses to R&D subsidies: A theoretical analysis and a microeconometric study*

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September 6th 2011

Abstract: Subsidies to the Norwegian high-tech industries have traditionally been given as “matching grants”, i.e. the subsidies are targeted, and the firms have to contribute a 50 % own risk capital to the subsidized projects. Our results suggest that grants do not crowd out privately financed R&D, but that subsidized firms do not increase their privately financed R&D either. Hence, the own risk capital seems to be taken from ordinary R&D budgets. We also investigate possible long-run effects of R&D subsidies, and show that conventional R&D investment models predict negative dynamic effects of subsidies. Our data, however, do not support this claim. On the contrary, there are indications of a positive dynamic effects, i.e. temporary R&D subsidies seem to stimulate firms to increase their R&D investments even after the grants have expired. We propose learning-by-doing in R&D activities as a possible explanation for this, and present a theoretical analysis showing that such effects may alter the predictions of the conventional models. A structural, econometric model of R&D investments incorporating such learning effects is estimated with reasonable results.

Forthcoming in a special issue of World Review of Science, Technology and Sustainable Development: “Evaluating the Effect of Public Policies on Corporate R&D and Innovation”

JEL classification: O38, O32, L53, H25, H32
Keywords: Technology policy, R&D subsidies, matching grants, short run additionality, long run additionality, Norwegian IT-industry

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* A previous version of this paper was circulated as Klette and Møen (1998). Tor Jakob Klette sadly passed away in August 2003. He was an irreplaceable mentor, colleague and friend. We have received useful comments from three anonymous referees, participants at the TSER meeting in Madrid in 1997, the TSER meetings in Urbino in 1998 and the NBER Summer Institute in 1998. The project is financed by the Research Council of Norway.

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1 Introduction

The public good nature of innovation and R&D investments has attracted economists' attention for decades. R&D activities generate products that are at least partially non-excludable and non-rivalrous. This was forcefully pointed out by Arrow (1962) and is a key ingredient in the seminal Romer (1990) model. According to economic theory, there are many different options available to deal with market failure due to externalities such as tax credits, subsidies, extending property rights and public production. All these policy instruments have been actively used to promote innovation and R&D activities by most OECD governments, but both the level and the optimal mix of instruments remain an open question. A large literature estimating effects of R&D subsidies has therefore emerged. While there is a fairly broad consensus that R&D tax credit is an effective tool for stimulating additional research, there is no strong consensus regarding the effectiveness of direct R&D grants.[1]

Our study focuses on R&D subsidies targeted at specific projects, and in particular on their impact on privately funded R&D investments. We contribute to the existing literature both by bringing new evidence on the effectiveness of matching grants R&D subsidies and by analyzing dynamic effects of R&D subsidies.

Using panel data for Norwegian high-tech firms from 1982-1995, we first examine the investment in R&D for firms receiving direct R&D grants from different public sources.[2] Our main question is whether public R&D subsidies result in a net increase or decrease in R&D expenditure, and we find that R&D subsidies in the industries we study have been successfully targeted at firms that have expanded their R&D investments. There is little tendency to "crowding out". On the other hand, there does not seem to be any significant degree of "additionality" associated with the subsidies either, even though the government requires that firms contribute 50 % own risk capital to subsidized projects. This own risk capital seems to be taken from ordinary R&D budgets.[3]

Next, we pursue the issue of dynamic or longer-run effects of R&D subsidies on R&D investments. Our empirical investigation suggests that such effects are positive,

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[1] The literature on the response of R&D investments to tax credits has been surveyed by Griffith, Sandler and Van Reenen (1995), Hall and Van Reenen (2000) and Ientile and Mairesse (2009). The literature on direct R&D grants is surveyed by David, Hall and Toole (2000) who conclude that "the findings overall are ambivalent". Garcia-Quevedo (2004) does a formal meta-analysis of the literature and concludes similarly that "the econometric evidence ... is ambiguous". Cosconati and Sembenelli (2010) provide a useful survey of the most recent literature.

[2] In 2002, the Research Council of Norway introduced an R&D tax credit scheme in addition to direct R&D grants. The data used in the present study do not extend into this period. The relationship between the R&D tax credit and other innovation policy instruments is analyzed in Hægeland and Møen (2007).

[3] Using similar data for the years 2001-2007, Henningsen, Hægeland and Møen (2011) find stronger additionality associated with grants from the Research Council of Norway. This suggests that the effectiveness of this policy tool has improved over time. This contrast the finding in Cincera, Czarnitzki and Thorwarth (2009) who report that the efficiency of public spending on R&D activities in stimulating additional R&D in the business sector in Norway has declined over time. However, Cincera et al. use a very different methodology, DEA, on macro data from a panel of OECD countries. They also differ by using all public R&D spendings as input in the analysis.

while conventional models of R&D-investments predict negative dynamic effects. We present a theoretical analysis of this question, where we argue that learning-by-doing effects in R&D may explain our empirical results. Such learning effects will generate positive feedback loops where temporary R&D subsidies increase the profitability of future R&D investments. We present estimates for a structural econometric model of R&D investment incorporating learning effects in line with the theoretical model.

Mowery's (1995) survey of the practice of technology policy points out that most OECD countries have grants and subsidy schemes for R&D where government funds are aimed at complementing and stimulating private R&D investments targeted at innovations with civilian industrial applications. The evidence regarding effectiveness is, however, mixed.

Scott (1984) concludes that federally funded R&D in private firms tends to stimulate the firms' own R&D expenditure, while Lichtenberg (1984) find no such tendency when he control for problems with selection bias embedded in Scott's estimate of the effect of federally funded R&D.[4] Keck (1993) also argue that recipients of public R&D grants do not increase their overall R&D activities, suggesting that public funds substitute for private financing in the German firms he studies. More recent studies of German technology policy reverse this finding, see e.g. Czarnitzki and Licht (2006) who find a large degree of additionality in public R&D grants using data from both Western and Eastern Germany. Using comparable data from Germany, Belgium, Luxembourg, Spain and South Africa, Czarnitzki and Lopes Bento (2010) conclude that on average, firms would have invested significantly less in R&D if they had not received subsidies. Moreover, they find that all these five countries except South Africa would benefit from an extension of their subsidy policies. Lach (2002), analyze a matching grants subsidy program in Israel, and finds positive additionality. The strength of the estimated effect fades with firm size, however. Busom (2000), using Spanish data finds full crowding out in about 30 % of the firms in her sample, while González, Jaumandreu and Pazó (2005), using a structural approach, report no crowding out of private funds in their sample of Spanish firms.[5] Based on US data from the Small Business Innovation Research program (SBIR), Wallsten (2000) finds evidence that the grants crowd out firm-financed R&D spending dollar for dollar. Wallsten claims to control for endogeneity, but his results contrast with those of Lerner (1999). Using a different identification strategy, Lerner finds a positive effects of SBIR awards, although the positive effect is confined to firms in areas with substantial venture capital activity. Studying the US pre-commercial Advanced Technology Program (ATP), Feldman and Kelley (2003) conclude that ATP appears to provide a certification function that increases the amount of funds that

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[4] Most of the federal funds studied by Scott (1984) and Lichtenberg (1984, 1987) are military contracts while later US programs like SBIR and ATP have a broader scope.

[5] The applications of structural methods to R&D subsidies have been limited, but another attempt is presented by Takalo, Tanayama and Toivanen (2010), who study targeted R&D subsidies awarded by the Finnish Funding Agency for Technology and Innovation (Tekes). They find that expected effects of the subsidies are very heterogeneous, but estimate that the social rate of return is 30-50 %.

firms are able to raise subsequently. Hall and Maffioli (2008) survey evaluations of government Technology Development Funds (TDF) in Argentina, Chile and Panama. They interpret the evidence to suggest that TDF-support does not crowd out private investments in R&D, but rather have a positive effect on R&D intensity.

It is not too surprising that the effects differ across these various studies, since public R&D schemes differ considerably in their aims. Moreover, there are several econometric difficulties related to selection and measurement involved in such evaluation studies, as stressed by Klette, Møen and Griliches (2000), Jaffe (2002) and Cerulli (2010) among others.

The rest of this article is organized as follows: Section 2 discuss the matching grant property of the Norwegian R&D subsidy scheme, and section 3 discuss the data. Section 4 presents a first look at the additionality data, and section 5 presents the main empirical results on short run additionality. Section 6 prepares the ground for an empirical analysis of long term effects of R&D subsidies by discussing dynamic effects and presenting a new theory model. Section 7 develops the theory model in section 6 into an emprical framework and presents structural estimates. Section 8 concludes and discuss remaining loose ends.

2 Matching grants R&D subsidy programs

In Norway there is a long tradition for an activist government policy towards the high technology industries, dating back to the aftermath of World War II (Wicken, 1994). Electronics in particular, was considered to be of strategic importance not only in a military perspective, but in a general economic perspective. In the 1980s this focus broadened to include general information technology. Key politicians and scientist firmly believed that private firms underinvested in R&D and new technology, and the most important policy instrument of these programs was therefore R&D support.

A common feature of Norwegian R&D grant programs has been the requirement that companies receiving subsidies must co-finance the supported projects. Matching grants have been the most common criteria, but sometimes the own risk has been more than 50 % and sometimes less. Despite the formality about own risk capital, it is obviously possible that subsidies in reality crowd out private investments, or at least that some of the private investments spent on subsidized projects would be invested in R&D even without subsidies.

To aid the discussion, and to prepare a model of matching grants R&D-subsidies, let

$$R = R^{G} + R^{PG} + R^{PP} \tag{1}$$

where R is total R&D investments, R^{G} is the R&D-subsidy received from the government, R^{PG} is the part of the subsidized R&D projects which a firm has to finance itself, i.e. the own risk capital, and R^{PP} is the R&D investments which the firm undertakes in non-subsidized projects. Let total R&D investments financed by the firm be $R^P = R^{PP} + R^{PG}$. Matching grants imply that $R^{PG} = R^G$.

The full effect of a subsidy on the firms' R&D investments is given by

$$\begin{aligned} \frac{dR}{dR^G} &= \frac{\partial R^{PP}}{\partial R^G} + \frac{\partial R^{PP}}{\partial R^{PG}} \cdot \frac{\partial R^{PG}}{\partial R^G} + \frac{\partial R^{PG}}{\partial R^G} + \frac{\partial R^{PG}}{\partial R^{PP}} \cdot \frac{\partial R^{PP}}{\partial R^G} + 1 \\ &= \left(2 + \frac{\partial R^{PP}}{\partial R^{PG}}\right) \end{aligned} \qquad (2)$$

since by the definition of a matching grant regime $\frac{\partial R^{PG}}{\partial R^G} = 1$ and $\frac{\partial R^{PP}}{\partial R^G} = 0$ can be assumed without loss of generality[6].

Two properties of the regime are critical to the firms' investment decision.[7] First, is the question of how well informed the governmental agency who allocates the grant is. Asymmetric information between private firms and the governmental agency will affect to what extent it is possible for firms to finance the own risk capital using ordinary R&D budgets. Second, is the question of whether the firm, if subsidized, faces a binding constraint on the size of the subsidized project, i.e. whether subsidized firms receive subsidies at the margin. Møen and Rybalka (2011) find that the probability of receiving a grant is decreasing in the amount of money applied for per year, all else equal. This may suggest that it is rational for the firms to constrain themselves, but given that we do not know how much R&D firms would do if given a 50 % subsidy with certainty, it is not possible to know whether firms in general are subsidized at the margin.

Figure 1 illustrates in a simplistic way the firms' demand for R&D. The dashed rectangle with base *abc* represents a subsidized R&D-project. $\overline{w}$ is the unit cost of R&D in the market, e.g. the hourly wage of a researcher, and R^* is the level of R&D that the firm will choose if it does not receive a subsidy. If the governmental agency is perfectly informed about R^*, it will only subsidize R&D projects to the right of this level. This is the case we define as full additionality, implying $\frac{\partial R^{PP}}{\partial R^{PG}} = 0 \Leftrightarrow \frac{dR}{dR^G} = 2$. The government then induces firms to increase their total R&D by two dollars when giving them a subsidy of one dollar because of the own risk capital requirement.

Consider now a situation where the governmental agency is not perfectly informed about the firms' R^*, the optimal level of R&D investments without subsidies. The firms then want to move as much as possible of their subsidized projects to the left of R^* in order to increase the private returns to the projects. If the firms succeed in moving the

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[6] As $R_t^{PG} = R_t^G$, considering $\frac{\partial R_t^{PP}}{\partial R_t^G} = 0$ simply means that the total effect of the subsidies is measured by the term $\frac{\partial R_t^{PP}}{\partial R_t^{PG}}$.

[7] Application costs are a third important property. We refrain from a formal treatment of application costs, because very little is known about the size of these costs. The perception that application costs in the matching grants program were large, however, motivated the introduction of an R&D tax credit scheme in Norway in 2002. This scheme has a very simple application process, and it has attracted applications from a lot of small firms with little R&D experience that had not previously applied for direct grants, see Cappelen et al (2010). This suggests that small firms with little knowledge capital self-selected out of the programs analyzed in this paper. Takalo et al. (2010), however, estimate application costs to be low on average in a sample of Finnish R&D grant recipients.

projects entirely to the left of R^*, there is full crowding out and $\frac{\partial R^{PP}}{\partial R^{PG}} = -2 \Leftrightarrow \frac{dR}{dR^G} = 0$. Subsidies are then pure transfers, and the government does not achieve anything. If, on the other hand, there is some, but not full, crowding out, $\frac{\partial R^{PP}}{\partial R^{PG}} \in \langle -2, -1 \rangle \Leftrightarrow \frac{dR}{dR^G} \in \langle 0, 1 \rangle$. One dollar spent on R&D subsidies will increase total R&D investments, but by less than a dollar since the firms reduce their privately financed R&D after receiving the subsidies. If there is neither crowding out, nor additionality, $\frac{\partial R^{PP}}{\partial R^{PG}} = -1 \Leftrightarrow \frac{dR}{dR^G} = 1$. In this case a governmental R&D subsidy does not influence the firms' privately financed R&D, and the subsidies will therefore increase total R&D investments dollar by dollar. With some, but not full, additionality, $\frac{\partial R^{PP}}{\partial R^{PG}} \in \langle -1, 0 \rangle \Leftrightarrow \frac{dR}{dR^G} \in \langle 1, 2 \rangle$. One dollar spent on R&D subsidies then increases the firms' privately financed R&D, but not with as much as a dollar. Total R&D investments will therefore increase by less than two dollars.

In order to discuss whether the firms are free to decide the size of the subsidized projects, i.e. whether they are subsidized at the margin, we need to distinguish between the unit cost of R&D in the market, and the firms' marginal cost of R&D. Let therefore w' denote the firms' marginal cost. If there is full additionality, and firms are allowed to decide the size of the subsidized projects, their marginal cost is $w' = \frac{1}{2}\overline{w}$, and they will expand their R&D investments until $R = R^{**}$ in Figure 1. If there is less than full additionality (but no crowding out), and the firms are allowed to decide the size of the subsidized projects, their marginal cost of R&D is

$$w' = \overline{w}\left(\frac{dR^P}{dR}\right) = \overline{w}\left(\frac{\frac{dR^P}{dR^G}}{1 + \frac{dR^P}{dR^G}}\right) = \overline{w}\frac{\alpha}{1+\alpha} \tag{3}$$

where we have renamed $\frac{dR^P}{dR^G} = \alpha$, and $\alpha \in [0, 1]$. With full additionality $\alpha = 1$. Note that as $\alpha \to 0$, (neither additionality, nor crowding out) the marginal cost of R&D according to the formula above approaches zero. The intuition behind this is that firms can expand their R&D activities at a very low cost if they are allowed to decide the size of subsidized projects where most of the own risk part is privately profitable, i.e. to the left of R^*. However, the governmental agency is bound to become suspicious if firms apply for subsidized projects which are large relative to their total R&D activities. This indicates that it is unlikely that firms are subsidized at the margin unless there is a significant degree of additionality associated with the subsidies. If the firms are constrained with respect to the size of the subsidized projects, their marginal cost of R&D is $w' = \overline{w}$.

Finally, let us consider a case with full or some crowding out. The size of the subsidized project will then be limited by the optimal private R&D to be crowded out (R^* in Figure 1), and the marginal cost of R&D will be $\overline{w}$. Hence, firms will in this case not be subsidized at the margin, even though their R&D investments will be larger than R^*.

3 Data

The core of the high-tech industries is the manufacture of office machinery and communication equipment, ISIC 3825 and 3832.[8] This is the kind of production most intensely promoted by the government, but subsidies have been awarded to a wider set of high-tech projects than those performed within these two sub-industries. To obtain a sample of reasonable size, and to avoid classification problems associated with companies having production and research activities covering a broader class of products than ISIC 3825 and 3832, we have used production and R&D aggregated to the three-digit line of business level. For the purpose of empirical analysis in this paper, we have therefore defined high-tech as the manufacture of machinery, electrical equipment and technical instruments, i.e. ISIC 382, 383 and 385. These industries have many R&D performing firms and are technologically related.

3.1 Data sources

The analysis uses merged data from R&D surveys and time series files of the manufacturing statistics. The manufacturing statistics of Statistics Norway is an annual census of all plants in the Norwegian manufacturing industries. From this source we use information on sales and cash flow. See Halvorsen et al. (1991) for documentation of the data base. R&D surveys are available for the years 1982-85, 1987, 1989, 1991, 1993 and 1995. Since 1991 the data have been collected by Statistics Norway. Before 1991, the data were collected by the Royal Norwegian Council for Scientific and Industrial Research (NTNF).[9] See Skorge et al. (1996) for definitions and industry level figures. We have aggregated R&D expenditures to the three digit (ISIC) line of business level before merging these variables to the manufacturing statistics. This means that our observations are not firms, but business units. A business unit is defined as all production activities within a firm having the same three digit ISIC classification. Single plant firms consist of one business unit, whereas multiplant firms may consist of several business units. Approximately 75 % of all manufacturing firms are single plant firms.

3.2 Sample construction

The R&D surveys have close to full coverage of firms with more than 20 employees in the industries studied, i.e. ISIC 382, 383 and 385. There are altogether 1658 time-year observations of business units at the three-digit line of business level in these industries included in the surveys. 1278 of these are successfully merged to the manufacturing

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[8] ISIC refers to the Norwegian Standard Industrial Classification of 1983 that builds on United Nations' International Standard Industrial Classification of all Economic Activities.

[9] Using these types of surveys, one may worry whether firms answer strategically or carelessly, but firms are commanded by law to answer, and the questionnaires are "audited" in order to detect mistakes. Hence, the data quality is perceived to be good and the data has been used in several microeconometric studies, starting with Klette (1996).

statistics. 714 observations had a time average of more than 20 employees, positive R&D investments and were included in at least two surveys. This sample was moderately trimmed leaving 697 observations for our empirical investigations. Outliers were defined as firms having value added per man-hour below the one percent percentile, above the 99 percent percentile or having an R&D intensity above the 99 percent percentile.

[TABLE 1 ABOUT HERE]

Table 1 gives some sample statistics. The panel consists of 192 business units with an average of 3.6 observations per business unit. All the included units are R&D performers, and 43 % of the observations have a positive subsidy variable. The average R&D intensity is 0.07. The average subsidy share, i.e., the share of subsidies in total R&D, is 0.23 for the units that receive subsidies. Hence, the degree of subsidization is substantial.

3.3 Variable construction

Sales are measured as the value of gross production corrected for taxes and subsidies. Cash Flow before R&D is measured as sales subtracted labor expenses, material expenses and rentals. To this measure are added R&D expenses financed by own means as given in the R&D surveys. Nominal variables in the manufacturing statistics are deflated using industry level deflators from the Norwegian national accounts. The R&D variables include both intramural and extramural R&D expenditures. The R&D expenditures, consisting mainly of labor costs, are deflated using an index based on the movement of average wage in ISIC 382, 383 and 385.

For the years 1982-1987, planned R&D is reported in man-years. When estimating the Euler equation in section 7.3, this variable is converted to Norwegian kroner using the firm-specific ratio between R&D man-years and R&D investments in the year of the survey, and inflated with the growth in the R&D price index during the following year.[10]

4 Crowding out or additionality: A first look

4.1 Questionnaire studies

To what extent subsidies actually stimulate R&D has been an important issue when technology programs have been evaluated. Table 2 summarizes questionnaire studies

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[10] Another weakness with the data for planned R&D is that they in 1995 include R&D-related capital investments. To adjust for this, the variable is reduced by the 1995 share of R&D-related capital investments in the sum of R&D and R&D-related capital investments. There is also an end-of-sample problem related to the instruments used in the Euler equation. Sales for 1996 are not included in the data set, and the 1995-observations therefore lack our proxy for expected sales. To circumvent this, we have constructed the proxy using sales in 1995, if possible, multiplied by the firm-specific growth rate from 1994 to 1995. We use a similar procedure for firms that exit the panel before 1995, and to construct the instrumental variable, lagged sales, where this is missing.

undertaken on this account in Norway. Looking at the pooled results at the rightmost column, about 18 % of the supported projects would have been undertaken in full without subsidies, while the subsidy was not completely crowded out in 82 % of the projects. Furthermore, according to the evaluation reports, 34 % of the projects had full additionality. Hence, these questionnaire studies suggest that R&D subsidies as implemented by the public agencies in Norway exert a positive influence on the R&D investments in private firms. It also seems that the degree of crowding out has been decreasing over time. This trend could indicate a learning process in the public agencies implementing the subsidy schemes, but it could as well indicate that firms have become less honest when they respond to the questionnaires. One would in any case suspect that these verbal reports are biased towards not admitting crowding out, as this would reduce the likelihood of similar programs being launched in the future. A more analytic approach is therefore desirable.

[TABLE 2 ABOUT HERE]

4.2 The effect of changes in the level of subsidies on deviation from planned R&D

One way to shed light on the effect of subsidies, is to examine the correlation between changes in the level of subsidies and the deviation from planned R&D. Such an analysis is possible because the firms in the R&D surveys have been asked about their R&D investment plans both one and two years ahead.[11] If a firms succeed in getting (additional) subsidies in year t, and subsidies stimulate R&D expenditures, we will expect that the firm invest more in R&D in year t than what they had planned before they got to know about the increase in subsidies.[12]

[TABLE 3 ABOUT HERE]

The R&D surveys were conducted annually from 1982 to 1985. For these years it is possible to calculate the correlation between the change in R&D subsidy and the deviation between planned and performed R&D within a one-year horizon, i.e. $Corr\left[\left(Subsidy_t - Subsidy_{t-1}\right), \left(R\&D_t - E_{t-1}R\&D_t\right)\right]$. From the first row in Table 3 we see that the one-year horizon correlation coefficient based on the available years is essentially zero. This lack of correlation most likely indicates that firms know the level of subsidies they will receive one year in advance and hence that they have already included the response to the expected subsidies in their investment plans[13]

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[11] From 1982 until 1989 the R&D investment plans were given in terms of man-years while from 1989 until 1995 they were given in nominal terms.

[12] Implicitly this formulation assumes that firms expect a stable subsidy level. This is obviously a rough approximation.

[13] The firms apply about a year in advance, and the data for year t are collected early in year $t+1$, i.e. year $t+1$ has started when the firms give their expectations for that year. Many of the applications for grants have probably been answered at that time.

The two-year horizon results are given in Table 3, rows two and three, based on R&D measures in man-years and nominal terms respectively. The coefficients strongly indicate that the correlation between an increase or decrease in subsidies and a deviation from planned R&D, is positive and significant. Our interpretation of this is that an increase in subsidies induces the companies to undertake more research than they otherwise would have done[14]. Note, however, that this does not give us any information about the strength of the effect. All that can be concluded is that there is not complete crowding out. To determine whether there is some degree of crowding out, some or full additionality, or maybe even more than full additionality, we need to frame the question within a regression analysis.

5 Short run regression analysis

In this section we regress the firms' R&D investments in year t on R&D subsidies received in year t, controlling for other factors determining R&D investments. Our aim is to estimate the causal effect of the subsidies, but establishing the counterfactual, i.e. what would have happened in absence of subsidies, is challenging. The recipients of subsidies are always a selected sample, and this makes it difficult to construct a valid control group. The more recent additionality literature discuss this problem within a "treatment framework", see e.g. Lach (2002) or Cerulli (2010).[15] Let us assume that the R&D investments of a firm i in period t, is given by

$$R_{it} = \beta_i D_i + \lambda_t + \alpha_i + u_{it} \tag{4}$$

where D_i is a dummy variable which is one if the firm has received R&D subsidies and zero otherwise. We ignore time subscript on D_i for simplicity, and, for now, also abstract from other observable regressors. λ_t represents unobservable time shocks common across firms, α_i represents permanent unobserved differences in firm investments related e.g. to managerial ability or the quality of the research team, while u_{it} represents unobserved temporary fluctuations in investments around the firm specific means, due to effects specific for individual R&D-projects. Equation (4) incorporates heterogenous responses to the R&D support (*ex post*) as indicated by the subscript i on the β-coefficient, and the distribution of these coefficients may differ systematically between the supported and the non-supported firms. Indeed, the agency allocating the R&D support might try to allocate their funds on the basis of anticipated differences in the β_i's.

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[14] An alternative interpretation is that those who came across a good research project after they gave the survey information both changed their plans and received subsidies. We do, however, believe that the time span involved is somewhat too short for this to be a plausible explanation. Within less than two years the firms would have to come up with the idea, file a detailed application for R&D support, have the application accepted and start the R&D project.

[15] This exposition borrows from Klette, Møen and Griliches (2000).

We will treat α_i as a firm specific parameter and allow it to be correlated with D_i. Then the estimated impact parameter is not biased if the supported firms are non-randomly selected, as long as the selection is based on firm characteristics that are largely invariant over time. Assuming that data are available before and after the supported firms have received their support, say at times t_0 and t_1, we may use the estimator

$$\begin{aligned} \widehat{\beta}_{\text{did}} &= \left(\overline{R}_{t_1}^{s} - \overline{R}_{t_0}^{s}\right) - \left(\overline{R}_{t_1}^{n} - \overline{R}_{t_0}^{n}\right) \\ &= \Delta\overline{R}^{s} - \Delta\overline{R}^{n}, \end{aligned}$$

where $\Delta\overline{R}^{s}$ and $\Delta\overline{R}^{n}$ are the average changes in R&D investments from before to after the allocation of an R&D subsidy, and the superscripts s and n refer to the subsidized and the non-subsidized firms, respectively. In the econometric literature, this estimator is referred to as the 'difference-in-differences' estimator (DID). Assuming that D_i and u_{it} are uncorrelated, we have that

$$\text{plim } \widehat{\beta}_{\text{did}} = E\left(\beta_i | D_i \ = 1\right) \equiv \beta^S$$

which is the parameter of interest, representing the average impact of the R&D-subsidies on the subsidized firms.[16]

The DID estimator derived above is closely related to the standard fixed effects ('within') estimator. Since we have observations for more than two years, and subsidy is a continuous variable, using the fixed effects estimator is preferable in practice.[17]

With respect to control variables, we draw on Swenson (1992) who summarizes the theoretical R&D investment literature into three main hypotheses about what affects the level of R&D investments in private firms. First, expected sales might be important if the development costs of new products or processes are fixed. Second, technological opportunity may vary across industries and time. This will in turn affect the returns to R&D and hence the incentive to invest. Third, the degree of appropriability is important. If it is difficult to protect innovations from leaking out to competitors, less profit may be made, and the incentive to innovate is reduced accordingly. In empirical studies, expected sales are often proxied by current sales. We have also included the square of sales to account for possible non-linearities in size. With respect to technological opportunities and the degree of appropriability, these effects should to

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[16] Notice, that this parameter (the mean impact of the treatment on the treated) may not be informative of what would happen if the R&D support scheme was extended to previously non-subsidized firms, when there are systematic differences in the responses to R&D subsidies between the subsidized and the non-subsidized firms.

[17] This is particularly so if the ideosyncratic errors, u_{it}, are not serially correlated. Note, however, that both the DiD (first difference) estimator and the fixed effects (within) estimator assumes strict exogeneity. This assumption is violated if current technology shocks have a feedback effect on future subsidies. In that case a dynamic panel data estimator is required. The similarity between our estimates in Table 4, column 1 (FE) and column 2 (FD), suggests that this kind of feedback is not a serious problem in our sample.

a large degree be absorbed by the time dummies (λ_t) and the firm – or rather business unit – fixed effect (α_i) discussed above. According to this, our regression equation is

$$R_{it} = \beta_0 + \beta_1 S_{it} + \beta_2 S_{it}^2 + \beta_3 CF_{it} + \beta_4 R_{it}^G + \lambda_t + \alpha_i + u_{it}. \tag{5}$$

R_{it}^G is public subsidies as before, and the coefficient on subsidies, $\beta_4 = \frac{\partial R_{it}}{\partial R_{it}^G}$, is the parameter of primary interest. S_{it} is sales and CF_{it}, is cash flow before R&D investments. We have included the firms' cash flow as a proxy for liquidity constraints influencing the level of investments, since R&D subsidies are partly motivated by the belief that R&D investments might be discriminated against in the capital markets. As pointed out by e.g. Bond et al. (2004), this cash flow variable may also be a proxy for investment opportunities beyond what is picked up by current sales. In our context, this is not a severe problem, since it is not our aim to establish whether or not liquidity constraints are present.[18] All observations are weighted by the square root of inverse sales to correct for heteroscedasticity.

We acknowledge that the specification above may not solve all potential selection problems. In particular, there may be correlation between the temporary shocks (u_{it}) and subsidy awards (R_{it}^G). As pointed out by Kauko (1996) and Jaffe (2002), firms may apply for subsidies when they discover particularly promising R&D projects. In that case they may invest more in R&D than usual even in absence of subsidies, and we will overestimate the impact of R&D-subsidies on company financed R&D investments. However, the bias may also go in the opposite direction. In Klette and Møen (1998), using the same data set as we do in this paper, we find that subsidized firms perform poor in terms of productivity and growth. We speculate that this is caused by the government subsidizing some large firms that were facing particularly severe problems when the IT industry was restructured towards the end of the 1980s. Subsidies may then be correlated with unobservable firm characteristics that affect R&D investments negatively, in which case we underestimate the impact of the subsidies. Finding instrumental variables to solve this kind of endogeneity problems is very challenging. In an analysis investigating additionality in more recent Norwegian R&D subsidy programs, Henningsen, Hægeland and Møen (2011) use proposal evaluation data to control for the intention to do R&D, as suggested by Jaffe (2002). This analysis shows that the bulk of variation in proposal grades is across firms rather than within firms. They therefore conclude that firm fixed effects go a long way towards solving the selection problem, but they also find evidence suggesting that there are measurement errors in the subsidy variable causing a negative bias.

Theory does not say anything about functional form, and various specifications

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[18] As pointed out by an anonymous referee, the effectiveness of matching grants may be lower than that of alternative types of subsidies in face of liquidity constraints. Matching grants requires (in principle) firms to have cash to finance 50 % of the project, and should therefore only be assigned to firms that are not fully or severely rationed. However, these firms will have better chances to carry out the investment even without public money.

have been tried in the literature. A matching grants subsidy regime implies a linear relationship between R&D investments and subsidies. This is the functional form used by e.g. Wallsten (2000) and Lach (2002). However, many other studies, e.g. Bound et al. (1984), suggest a loglinear relationship between R&D investments and sales. We prefer a linear relationship since the effect of subsidies is what we are primarily interested in. Our empirical results are reported in Tables 4 to 7. Column (1) always reports a linear functional form, estimated with fixed effects. We consider this to be our main regression. To test the robustness of this specification, column (2) reports a linear functional form estimated with the variables transformed to first differences between years t and $t-2$ and column (3) reports a loglog functional form estimated with fixed effects. The general impression from the tables is that the three different specifications agree on the main effects. We will base our discussion on the results in column (1) unless otherwise is stated.

5.1 Main results

From Table 4 we see that the additionality parameter, β_4 is 1.03 and highly significant. This suggests that there is no crowding out, but nor does there seem to be any degree of additionality. Estimating the regression without business unit fixed effects increases the coefficient by about 20 %. This shows that there is positive selection into the subsidy programs as expected. Firms that receive subsidies tend to have unobserved characteristics that are correlated with high levels of R&D investments. Note, however, that the fixed effects estimator is more vulnerable to measurement errors than ordinary least squares, hence 1.03 might be a somewhat conservative estimate (Griliches and Hausman, 1986).

The results of the questionnaire studies indicated that the effect of subsidies may have changed over time. In a set of regressions not reported, we have investigated this by including a dummy for observations from the 1990s in interaction with the subsidy variable. The results do not indicate that the effect of R&D subsidies has changed. We have also run regressions where the sample is extended to include all manufacturing industries[19], but the coefficient is still stable, β_4 then being 0.98.

[TABLE 4 ABOUT HERE]

With respect to the other variables, we see that sales squared has a significantly positive coefficient, implying that both small and large firms are more R&D intensive than medium size firms. This finding is supported by the empirical study of Bound et al. (1984), but runs contrary to previous work on the relationship between size and R&D cited in their article.[20] Finally, cash flow has a positive and significant effect on

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[19] This sample has 2141 observations, and is constructed in the same manner as the sample based on high-tech industries alone. The results are not reported.

[20] In the sample comprising all manufacturing industries, we find a significantly negative coefficient on sales squared, indicating that this relationship may vary across industries.

R&D investments, suggesting that liquidity constraints may be relevant to the R&D investment decision. In order to investigate this a bit further, we have constructed a dummy for whether the firm that a business unit belongs to owns several business units so that the cash flow of each individual business unit may not be a binding constraint on investments.[21] Including this dummy both separately and in interaction with cash flow, we find that business units which are part of a larger group have a lower cash flow sensitivity and larger R&D investments as compared to stand alone business units. This is consistent with the idea that cash flow proxies liquidity constraints for stand alone firms. However, these results should be considered explorative as there are relatively few such "multi-business-unit-firms" in the sample. Adding these extra controls have only a negligible effect on the additionality estimate.

5.2 Differences between small and large firms

In Table 5 we report regressions studying whether there are differences between small and large firms. We do this by including a dummy variable for small and large business units in interaction with the subsidy and cash flow variables. We have defined small business units as units with average employment below the 25th percent percentile, i.e. below 58 workers. Large units are defined accordingly as those larger than the 75th percent percentile, i.e. having an average employment above 263 workers, cf. Table 1.

[TABLE 5 ABOUT HERE]

In an interview study of Norwegian manufacturing firms, Hervik and Waagø (1997) find support for the hypothesis that large firms, having a portfolio of projects, will seek to obtain public support for those projects they have already decided to undertake, whereas small firms, being less diversified and possibly more liquidity constrained, will find subsidies with a matching grant claim to be a stimulus making increased R&D investments possible. It is difficult to find support for this hypothesis in our data. The only business units having some degree of additionality, approximately 25 %, associated with R&D subsidies, are the large ones. For small units there is neither crowding out, nor additionality, whereas for medium size units the point estimate indicates about 50 % crowding out. This finding might be rationalized if we extend the hypothesis of Hervik and Waagø by taking account of monitoring costs. It is probably difficult for the governmental agencies to assess whether R&D projects for which small and medium size firms apply, will be undertaken without support. The hypothesis of Hervik and Waagø then explains why we find crowding out for medium size firms, but not for small firms. Large firms, however, are likely to be monitored more closely by the government, as they receive large grants and are well known "regular customers". If these firms apply for projects which are obviously profitable without subsidies, the governmental

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[21] We are grateful to an anonymous referee for making this suggestion.

agencies might see through it, and they can even lose credibility with respect to future applications. This may explain why we do not find crowding out for these firms.

When it comes to cash flow, we see a similar, although somewhat less pronounced, pattern, as both small and large business units have a larger coefficient than medium size units. These results are hard to explain and cast some doubt on the cash flow variable being able to account for liquidity constraints.[22]

5.3 Differences between the effect of subsidies from various public sources

The R&D surveys have detailed information on R&D investments by source of finance, and this makes it possible to investigate whether the effect of R&D subsidies varies across different public sources. The main governmental agencies awarding R&D subsidies have traditionally been research councils, industry funds and ministries. Pure subsidies have mostly been awarded through research councils. Grants from industry funds are often subsidized loans, but still with an own risk capital claim. Grants from ministries consist of various R&D contracts, many of which are defense related. We believe that the demand for own risk capital tends to be weaker in these projects.

[TABLE 6 ABOUT HERE]

Table 6 reports the results of regressions with subsidies from the three main sources included as separate variables. We see that there are no clear cut differences between the effects of the various subsidies, but all regressions agree that subsidies from industry funds have a coefficient which is somewhat lower than the others. If the sample is extended to include all manufacturing industries, the regression results suggest that subsidies from research councils have a somewhat more positive effect than subsidies from the other two sources (not reported).

5.4 Dynamic effects

So far we have implicitly assumed that there are no dynamic effects associated with receiving R&D subsidies. As we will explain below, different models of accumulation of knowledge have different predictions with respect to the dynamic effects of R&D subsidies. A very simple first approach is to include lagged R&D subsidies in the regressions above. The results are reported in Table 7. We see that R&D subsidies lagged two years have a significantly positive effect in the fixed effects regression based on a linear functional form. In column (2), using first differences, there is also a positive coefficient, but it is not statistically significant, while in column (3), the loglog specification,

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[22] As pointed out by an anonymous referee, some of the cash flow effect we try to estimate with this specification may be absorbed by the firm fixed effects. How much of the relevant effect that is absorbed may vary between small, medium and large firms since they are likely to have different levels of cash flow on average.

there is a non-significant negative coefficient. When extending the sample to include all manufacturing industries, the coefficients in columns (1) and (2) increase both in magnitude and significance while the coefficient in column (3) becomes essentially zero (not reported).[23] This suggests that R&D subsidies are likely to have a positive dynamic effect, and we would like to point out explicitly the lack of evidence for a negative effect.

[TABLE 7 ABOUT HERE]

Dynamic effects of subsidies are obviously important for public policies, as they may influence the social return to subsidies. Positive dynamic effects indicate that the government permanently changes the firms' profit opportunities in favor of more R&D intensive products by awarding temporary subsidies which induce the firms to increase their R&D investment. A positive dynamic effect, then, will increase the social return to R&D subsidies if the level of commercial R&D is below its social optimum at the outset.

6 Dynamic effects of R&D subsidies: A theoretical analysis

We will now explore the dynamic effects of R&D subsidies more thoroughly. We start out by discussing the predictions of conventional models of R&D investments. Next we present an alternative structural model which we find better suited to explain the data. This alternative model captures the idea that firms which have invested heavily in R&D in the past, and hence have a large knowledge capital, will produce new knowledge more efficiently than less experienced firms. In the last part of the paper we attempt to estimate this structural model, before summing up our main findings.

6.1 The conventional R&D investment model

The most widely used specification for the accumulation of knowledge capital, K, is to treat R&D the same way as physical capital i.e.

$$K_t = K_{t-1}(1-\delta) + R_t. \tag{6}$$

where δ is the rate of depreciation, cf. Griliches (1979, 2000). As is well known, with this specification, knowledge capital is adjusted so that

$$\pi'(K_t) = w_t'(r+\delta) - \Delta\overline{w}_{t+1} \tag{7}$$

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[23] The coefficient in column (1) is then 0.58 and significant at the 1 % level. Testing for differences between large and small firms, we find that the positive dynamic effect is strongest for small firms. This positive small firm effect can also be detected with a loglog specification. Further evidence for the existence of this effect is given in Figure 2, explained in section 6.1.

where $\pi'(K_t)$ is the nominal marginal profit of knowledge capital, w'_t is the marginal cost of R&D, r is the discount rate and $\Delta\overline{w}_{t+1}$ is the change in the market price of R&D.[24]

If firms are subsidized at the margin, the effect on optimal R&D investments of a 50 % subsidy can be quite dramatic, at least if the profit function is not too concave in K. In particular, consider the case where an R&D subsidy in the form of a matching grant disappears. A 50 % (permanent) increase in *marginal* R&D costs when the subsidy disappears, should induce a significant reduction in the optimal amount of knowledge capital. Hence, it would be optimal to deinvest or at least not to continue investing in knowledge capital when the R&D subsidy disappears for reasonable specifications of the profit function and the depreciation rate. In the Cobb-Douglas case, the reduction in the optimal capital stock is 50 % for a given level of output, if the R&D price increases by 50 %.

From equations (6) and (7) we can deduce some simple comparative statics results. First, by totally differentiating (7) and adopting the standard assumption of a decreasing marginal product of knowledge capital, we have

$$\frac{dR_t}{dw'_t} = \frac{r+\delta}{\pi''} < 0 \tag{8}$$

Furthermore, along an optimal investment path we have that

$$\begin{aligned} \frac{dR_{t+1}}{dw'_t} &= \frac{dR_{t+1}}{dK_t} \cdot \frac{dK_t}{dR_t} \cdot \frac{dR_t}{dw'_t} \\ &= -(1-\delta) \cdot 1 \cdot \frac{r+\delta}{\pi''} > 0. \end{aligned} \tag{9}$$

Here $\frac{dR_{t+1}}{dK_t}$ is calculated by totally differentiating equation (6) and setting dK_{t+1} equal to zero. Equation (8) and (9) show that an increase in the marginal cost of R&D this period will reduce R&D investments in this period and increase R&D investments next period, all else equal. Hence, a temporary change in the marginal price will cause intertemporal substitution of the R&D investments.

If firms are subsidized, but not able to decide the size of their subsidized project, i.e. if they are not subsidized at the margin, their total R&D investments may be considered exogenous.[25] Keeping the assumption of a decreasing marginal product of knowledge capital, and a constant market price of R&D, and then totally differentiating equation (7) in period $t+1$, when writing K_{t+1} as a function of K_{t-1}, R_t, and R_{t+1}

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[24] The exact expression also includes the term $\delta\Delta\overline{w}_{t+1}$ which will be close to zero.

[25] If R&D subsidies are completely crowded out, R&D will be endogenous even if the subsidized firms are not subsidized at the margin, but our results in section 5 suggest that this is not the case.

with R_t as a function of w'_t, we find that

$$\frac{dR_{t+1}}{dR_t} = -(1-\delta) < 0 \tag{10}$$

Hence, whether or not firms are subsidized at the margin, R&D investments in period $t+1$ will be reduced relative to period t in firms which lose their subsidies. This runs contrary to the results reported in Table 7 where the effect of lagged subsidies was positive or at least not negative. Taken at face value, the result in Table 7 implies that an increase in past subsidies, all else equal, increases future R&D.

[FIGURE 2 ABOUT HERE]

Further support for our claim that the predictions of the conventional model do not fit the data can be found in Figure 2. The leftmost box-and-whisker plot shows the distribution of growth rates in R&D investments from year $t-2$ to year $t+2$ for business units which were not subsidized in those years, but which received subsidies in the middle year, t. This may be compared with the rightmost plot of firms not subsidized at all.[26] Growth is measured in percent of the average level of investments in year $t-2$ and year $t+2$. This limits the growth interval to ±200 %. A firm that starts investing in R&D will have a positive 200 % growth, while a firm that stops investing in R&D will have a negative 200 % growth. First note that there are no firms which stop investing in R&D when their R&D grant expires, and a large number of firms increase their R&D investments relative to the pre-subsidy level. Average growth for the subsidized firms is 11 %, whereas average growth for the non-subsidized firms in the rightmost distribution is -10 %. From the figure we also see that median growth is higher for firms which have received subsidies.

We conclude from the empirical results that the standard, perpetual inventory model for knowledge accumulation, equation (6), is too simple to serve as a basis for a realistic model of R&D investment behavior. We will now consider various modifications of this model, before we turn to a more drastic respecification.

6.2 Modifications of the conventional model: Rescue attempts

An obvious first step in making the perpetual inventory model more realistic is to add a non-negativity constraint to R&D investments such that $R \geq 0$, i.e. one cannot

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[26] The "box" in the Box-and-Whisker plots extends from the 25th percentile (x_{25}) to the 75th percentile (x_{75}), i.e. the interquartile range (IQ). The lines emerging from the box are the "whiskers", and extends to the upper and lower adjacent values. The upper adjacent value is defined as the largest data point less than or equal to $x_{75} + (1.5 * IQ)$. The lower adjacent value is defined symmetrically. Observed data points more extreme than the adjacent values, are individually plotted. Unfortunately, the number of business units that have a pattern of subsidies which allows them to be included in Figure 2 is very small, 13 in the leftmost distribution and 69 in the rightmost distribution. The results are, however, robust towards extending the sample to include all manufacturing industries. Doing this, the distributions consist of 29 and 234 business units respectively.

deinvest by selling already acquired knowledge. The pattern of optimal investments in this extended version of the model has been examined in some detail by Arrow (1968) and others. Arrow's analysis shows that the basic effect of this extension for the case with an expected rise in R&D costs, e.g. due to the elimination of R&D subsidies, would be that the non-negativity constraint will tend to be binding somewhat earlier, while the option of R&D subsidies still is in place. The intuition is that the firms stop their R&D investment before the subsidy is removed in order to avoid the non-negativity constraint being too costly. Clearly, this result does not make the behavior predicted by the model more realistic, the effect is rather to the contrary, given that firms typically continue their R&D activity also after the R&D subsidy disappears, as shown above.

A more promising suggestion would be to add convex adjustment costs similar to the model used to derive Euler equations for physical capital investment as in Summers (1981). This would make large changes in investment more costly and induce the firms to adjust their level of R&D more slowly. Given a reasonable specification of the profit function, the firms would like to reduce their R&D investments after the R&D subsidies have been eliminated, and they will do it gradually. However, while we find it natural to think about adjustment costs for expanding the R&D activity rapidly, it is less clear to us whether there are similar adjustment costs involved when downscaling an R&D project making it optimal to do it gradually.

Finally, let us make a remark about another, less structural, model of R&D investments, the so-called error-correction model widely used in time-series econometrics. This model also has the equilibrium condition (7) as its point of departure, but suggests that the firms adjust to deviations from this condition with a lag and then only gradually due to some unspecified adjustment costs. Our scepticism about what such adjustment costs are really meant to represent does not need to be repeated; the issue here is that a lagged response of, say, two years does not make much sense for the kind of shocks we are considering. That a firm needs two years to realize or at least to react to an anticipated increase in R&D costs after the grant period has expired, does not seem very convincing.

To sum up, R&D investment models based on variations of the standard model for knowledge accumulation predict that firms will reduce their own R&D investments after an R&D grant has expired or somewhat earlier, possibly down to zero if a non-negativity constraint on R&D is binding. Otherwise, they will rely on adjustment costs that we do not find convincing. These models do not seem appropriate as models of R&D investment behavior, and we now turn to an alternative specification that will induce the somewhat sluggish adjustments we observe in the data and which offers a specific explanation by emphasizing learning and feedback in R&D investments and knowledge accumulation.

6.3 Modeling R&D investments with learning-by-doing

The following accumulation equation for knowledge has been suggested by Hall and Hayashi (1989), Jones (1995), Lach and Rob (1996) and Klette (1996) among others:

$$K_{t+1} = K_t^{\rho-\nu} R_t^{\nu}. \tag{11}$$

ρ is the scale elasticity in knowledge production and ν is a parameter capturing the productiveness of R&D in generating new knowledge (the innovative opportunities of R&D effort).[27] $1 - (\rho - \nu)$ may be considered the depreciation rate, reflecting the depreciation of the private (i.e. the appropriable) part of a firm's knowledge capital. Note that the multiplicative relationship between K_t and R_t on the right hand side of (11) implies positive complimentarity between new R&D investments and already acquired knowledge. This can be thought of as representing learning-by-doing in R&D.

A firm operating from period $t = 0$ to $t = T$, and which wants to maximize its present value, faces the following problem

$$\max_{R_0,\ldots,R_T} PV = \{\pi(K_0) - \overline{w}_0 R_0 + \sum_{t=1}^{t=T} \beta^t [\pi(K_t) - \overline{w}_t R_t]\} \tag{12}$$

subject to (11). $\pi(K_t)$ is the profit function, β is the discount factor, and $\overline{w}_t$ is the firm's average unit cost of R&D. Note that $\beta = 1/(1+r)$ is informative about the firms' *ex ante* returns to R&D. In order to simplify the model and derive comparative static results, we make the following assumptions:

- $T = 2$
- $\rho = 1$ (i.e. constant returns to scale in knowledge production.)

It is trivial to see that $R_2 = 0$ must be part of an optimal R&D investments path as the effect of R_2 does not materialize within the time period considered. We assume for simplicity that the firm's knowledge capital cannot be sold in the market. Given this, the problem reduces to

$$\max_{R_0,R_1} PV = \left\{ [\pi(K_0) - \overline{w}_0 R_0] + \beta [\pi(K_1) - \overline{w}_1 R_1] + \beta^2 \pi(K_2) \right\}. \tag{13}$$

The first order conditions are

$$\begin{aligned} \frac{\partial PV}{\partial R_0} &= -w_0' + \beta\nu\pi'(K_1)\left(\frac{K_0}{R_0}\right)^{1-\nu} \\ &\quad + \beta^2 \nu (1-\nu) \pi'(K_2) K_0^{(1-\nu)^2} R_0^{\nu(1-\nu)-1} R_1^{\nu} = 0 \end{aligned} \tag{14}$$

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[27] The exact formulation is from Klette (1996). We recognize that (11) has the rather extreme and unrealistic implication that a firm which stops its R&D in a single year will lose all its knowledge capital. Alternative specifications that avoid this problem tend to give more complicated estimating equations that we do not explore in this study. However, as most firms have continuous R&D activity, we believe equation (11) can be thought of as a reasonable approximation.

and

$$\frac{\partial PV}{\partial R_1} = -\beta w_1' + \beta^2 \nu \pi' (K_2) \left(\frac{K_1}{R_1} \right)^{1-\nu} = 0 \tag{15}$$

This gives the following expressions for optimal R&D investments

$$R_1 = K_0^{1-\nu} R_0^{\nu} \left(\frac{\beta \nu \pi' (K_2)}{w_1'} \right)^{\frac{1}{1-\nu}} \tag{16}$$

and

$$R_0 = K_0 \left(\frac{\beta \nu}{w_0'} \right)^{\frac{1}{1-\nu}} \left[\pi' (K_1) + \beta (1-\nu) \left(\pi' (K_2) \right)^{\frac{1}{1-\nu}} \left(\frac{\beta \nu}{w_1'} \right)^{\frac{\nu}{1-\nu}} \right]^{\frac{1}{1-\nu}} \tag{17}$$

We are particularly interested in the effects of varying w', the marginal cost of R&D. The relevant derivatives are

$$\frac{\partial R_1}{\partial w_1'} < 0 \qquad \frac{\partial R_0}{\partial w_0'} < 0 \tag{18}$$

$$\frac{\partial R_1}{\partial w_0'} \lesseqgtr 0 \qquad \frac{\partial R_0}{\partial w_1'} \lesseqgtr 0. \tag{19}$$

The algebraic expressions are given in the appendix.

Consider now the effect on R&D of a subsidy which makes investments in R&D cheaper at the margin. The same period effect is given in (18), and, not surprisingly, we see that firms will increase their R&D activity when R&D is subsidized. In this respect, the model performs similarly to the traditional framework, cf. equation (8). The dynamic effects, however, are more interesting. From the leftward derivative in (19) we see that a temporary subsidy at $t = 0$, may induce the firm to undertake more R&D also in the next period even if it is not subsidized then. This contrasts the conventional model of R&D investments, where the dynamic effect of a price decrease will be negative, cf. equation (9). Note also that it is the diminishing returns to knowledge capital which make (19) indeterminate. If we isolate the learning-by-doing feature of our model by assuming that $\pi' (K)$ is constant and thereby that $\pi'' (K) = 0$, we see from the equation (36) in the appendix that the pure effect of learning is positive, i.e. $\frac{\partial R_1}{\partial w_0'} < 0$. The existence of learning-by-doing in R&D is therefore able to explain the empirical results in Table 7. From (19) we also see that a known subsidy at $t = 1$, may induce the firm to increase its R&D activity already at $t = 0$. This is another result which is impossible within the conventional framework built on the analogy between physical capital and R&D. A firm which knows that capital will be subsidized at $t = 1$, and not at $t = 0$, will definitely not increase its investments in the period when capital is not subsidized.

The intuition behind the dynamic behavior of our model is that when there is learning-by-doing in R&D, increased R&D today will make firms more efficient R&D performers in future periods through their increased knowledge capital. This increases the profitability of future R&D. Likewise, if a firm gets to know that the price of R&D will be lowered in the future, it will find it profitable to increase its present R&D, as this will make it a more efficient R&D performer in future periods when it will increase its R&D activity due to the lower price.

Note that a subsidy regime which induces firms to increase their same-period R&D without altering the marginal price will have the same dynamic effects as

$$\frac{\partial R_1}{\partial R_0} \gtreqless 0 \qquad \frac{\partial R_0}{\partial R_1} \gtreqless 0 \tag{20}$$

The rightmost result is derived by treating R_1 as an exogenous variable and using implicit derivation on (14). Once again, going to the appendix and setting $\pi''(K) = 0$ in equations (38) and (39), we find a certain, positive dynamic effect.

7 A structural, econometric analysis of the dynamic effects of R&D subsidies

We now want to pursue a more complete structural modeling of R&D investments suitable for empirical applications, building on the framework of Klette (1996) and Klette and Johansen (1998). First we present the model and extends it by incorporating uncertainty in the knowledge production function, as uncertainty is an important characteristic of R&D investments. Next, we modify the model to handle R&D subsidies, and derive the estimation equation.

7.1 An empirical infinite horizon model with uncertainty in knowledge production

To incorporate uncertainty in the knowledge production function, rewrite (11)

$$K_{t+1} = K_t^{\rho-\nu} R_t^{\nu} \varepsilon_t \tag{21}$$

where ε_t is a mean-one stochastic factor accounting for the randomness in research activities. One way to identify the optimal investment behavior given the accumulation equation above is to consider the Bellman-equation

$$\begin{aligned} V(K_t) &= \max_{R_t} \{\pi_t(K_t) - \overline{w}_t R_t + \beta E_t[V(K_{t+1})]\} \\ &= \max_{R_t} \{\pi_t(K_t) - \overline{w}_t R_t + \beta E_t[\pi_{t+1}(K_{t+1}) - \overline{w}_{t+1} R_{t+1}] \\ &\qquad\qquad + \beta^2 E_t[V(K_{t+2})]\}, \end{aligned} \tag{22}$$

where K_{t+1} is as specified in (21). E_t is the expectation operator, conditioned on the firm's information set available when it makes its decision about the investment R_t.

We can identify an optimal path by considering the marginal change in R_{t+1} induced by a marginal change in R_t such that an optimal path remains unchanged from period $t+2$ onwards, i.e.

$$\begin{aligned} E_t dK_{t+2} &= E_t d\left[(K_t^{\rho-\nu} R_t^{\nu} \varepsilon_t)^{\rho-\nu} R_{t+1}^{\nu} \varepsilon_{t+1} \right] \\ &= E_t \left[\nu \left(\rho - \nu\right) \frac{K_{t+2}}{R_t} dR_t + \nu \frac{K_{t+2}}{R_{t+1}} dR_{t+1} \right] \\ &= E_t \left[\nu K_{t+2} \left\{ \left(\rho - \nu\right) \frac{dR_t}{R_t} + \frac{dR_{t+1}}{R_{t+1}} \right\} \right] = 0 \end{aligned} \tag{23}$$

implying that, in expectational terms,

$$\frac{dR_{t+1}}{dR_t} = -\left(\rho - \nu\right) \frac{R_{t+1}}{R_t}. \tag{24}$$

The first order condition associated with (22), given that K_{t+2} is fixed is

$$w_t' = \beta\, E_t \left[\pi_{t+1}'(K_{t+1}) \frac{\partial K_{t+1}}{\partial R_t} - w_{t+1}' \frac{dR_{t+1}}{dR_t} \right] \tag{25}$$

which, using (21) and (24), can be restated as

$$w_t' R_t = \beta\, E_t \left[\nu \pi_{t+1}'(K_{t+1}) K_{t+1} \right] + \beta(\rho - \nu) E_t \left[w_{t+1}' R_{t+1} \right]. \tag{26}$$

A common specification of the profit function implies that $\pi_t'(K_t) K_t = \gamma\, S_t$, where S_t is sales and γ is a parameter that is informative about the value of the firms' knowledge capital stock relative to sales (see Klette, 1996).[28] Hence, an optimal R&D investment path requires that

$$w_t' R_t = \beta \nu \gamma\ E_t \left[S_{t+1} \right] + \beta(\rho - \nu) E_t \left[w_{t+1}' R_{t+1} \right] \tag{27}$$

The Euler equation (27) gives a tight relationship between R&D expenditures in period t and *expected* sales and *planned* R&D expenditures in period $t+1$.[29]

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[28] More specifically, it is the value of a firms' knowledge capital stock relative to sales for a firm with very low, but positive R&D intensity.

[29] The Euler equation does not have a causal interpretation, hence, one may also express the relationship as $E_t \left[w_{t+1}' R_{t+1} \right] = \frac{1}{\beta(\rho - \nu)} w_t' R_t - \frac{\nu \gamma}{(\rho - \nu)} E_t \left[S_{t+1} \right]$. Interestingly, this relationship is, in terms of variables, identical to one suggested in an early contribution by Mansfield (1962). Mansfield derives his relationship from a simple heuristic model for how managers dermines next years R&D expenditures. His reasoning is inspired by interviews with officials of about 200 US corporations. A notable difference between our structural equation and Mansfield's regression, is that he both expects and estimates a positive coefficient on sales.

7.2 Incorporating "matching grants" R&D subsidies in the empirical model

To incorporate public R&D-subsidies let $R_t = R_t^{PP} + R_t^{PG} + R_t^{G}$. Based on the discussion in section 2, we have three analytically interesting situations which imply different modifications to the Euler equation:

1. If there is full crowding out, we cannot distinguish between the R&D investments of subsidized and non-subsidized firms. The firms cannot be subsidized at the margin, and the Euler equation does not change.
2. If there is less than full crowding out, but not a significant degree of additionality, firms are not likely to be subsidized at the margin. The subsidies do, however, increase the firms' total R&D-investments. A situation where there is significant additionality, but where firms nonetheless are constrained with respect to the size of the subsidized project, will have the same implications with respect to the Euler equation. We will discuss these implications below.
3. If there is significant additionality, and the firms are not constrained with respect to the size of the subsidized project, the marginal cost of R&D is given by equation (3), with $\alpha = 1$ as a limiting case implying that there is full additionality.

In the cases grouped under item 2 above, w' is not affected by the subsidy, hence $w' = \overline{w}$. Furthermore, R^G and R^{PG} are exogenous to our analysis. In these cases, introducing public R&D-subsidies induces two changes in the Bellman equation (22), and these are the replacement of R by R^{PP} as the control variable and the replacement of R by $\left(R^{PP} + R^{PG}\right)$ inside the brace. The first order condition (25), then becomes[30]

$$\overline{w}_t = \beta\, E_t \left[\pi'_{t+1}(K_{t+1}) \frac{\partial K_{t+1}}{\partial R_t^{PP}} - \overline{w}_{t+1} \frac{dR_{t+1}^{PP}}{dR_t^{PP}} \right] \tag{28}$$

which can be rewritten

$$\overline{w}_t R_t = \beta\, \nu E_t \left[\pi'_{t+1}(K_{t+1}) K_{t+1}\right] + \beta(\rho - \nu) E_t \left[\overline{w}_{t+1} R_{t+1}\right]. \tag{29}$$

This equation is, somewhat surprisingly, identical to equation (26). As long as a firm is not subsidized at the margin, therefore, its optimal R&D investment path will follow (26), and hence (27), whether it receives subsidies or not. This, however, is not to say that receiving subsidies is without implications for the firms' investment decision, something which can be seen by rewriting (27) specifying the various components of

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[30] We assume here that $\frac{dR_{t+1}^{PG}}{dR_t^{PP}} = 0$. In a more complete model where one endogenizes the allocation of R&D subsidies, one would want to allow the amount of privately financed R&D invested this year to influence the amount of subsidies received next year. Such a fine point, however, is beyond the scope of this exposition.

R_t and R_{t+1}:

$$\begin{aligned} \overline{w}_t \left(R_t^{PP} + R_t^{PG} + R_t^{G}\right) &= \beta\nu\gamma \, E_t\left[S_{t+1}\right] \\ &\quad + \beta(\rho - \nu)E_t\left[\overline{w}_{t+1}\left(R_{t+1}^{PP} + R_{t+1}^{PG} + R_{t+1}^{G}\right)\right] \end{aligned} \tag{30}$$

We see that a firm which does not receive subsidies at time t (when it decides R_t^{PP}), but which does expect to receive subsidies at time $t+1$, will undertake more R&D at time t than a firm with the same expectations about sales, but which does not expect to receive subsidies in the next period. There is a simple rationale for this: The firm knows that it will receive some additional R&D resources in the next period which, by assumption, cannot be completely crowded out. According to equation (21), these resources can be utilized more efficiently the higher its knowledge capital base, K_{t+1}, at that time. Given this, it is optimal for the firm to "prepare" for the expected R&D-expansion in advance by building up more knowledge through an increase in R_t^{PP}. Due to the same dynamic effect, a firm which receives subsidies at time t, but which does not expect to receive subsidies at time $t+1$, will do more R&D at time $t+1$, than a firm with the same expectations about sales, but which does not receive subsidies at time t. This is because the subsidized firm starts out at time $t+1$ with a larger knowledge capital base than the non-subsidized firm, something which makes it a more efficient "knowledge producer". For this reason the subsidized firm finds it optimal to invest more in R&D at time $t+1$ than it would have done without the subsidy at time t. This will of course also increase its knowledge capital at time $t+2$, relative to the scenario without a subsidy at time t, and consequently we can conclude that a temporary R&D subsidy which is not completely crowded out, will have a lasting positive impact on the firm's future R&D investments. This effect will of course be more significant the less crowding out or more additionality there is associated with the subsidy.

Let us now consider the case described under item 3 above, i.e. the case with additionality and where the firms decide the size of the subsidized projects. In a period where firms are subsidized, their marginal cost of R&D is given by equation (3). We must then distinguish between three different situations;

(i) the firms are subsidized at the margin at time t, but do not expect to be subsidized at the margin at time $t+1$.

(ii) the firms are not subsidized at the margin at time t, but expect to be subsidized at the margin at time $t+1$.

(iii) the firms are subsidized at the margin at time t, and expect to be subsidized at the margin at time $t+1$.

When the firms are not subsidized at the margin, their marginal cost of R&D is $w' = \overline{w}$, and this makes it possible to easily incorporate a fourth category within the framework that we are now building up. This category comprises all other firms, i.e.

(iv) the firms which are not subsidized at the margin at time t, and which do not expect to be subsidized at the margin at time $t+1$.

Using dummy variables to distinguish between firms in different situations, the Euler equation (27), becomes

$$\begin{aligned}\left\{D2 + D4 + (D1 + D3)\,\frac{\alpha}{1+\alpha}\right\}\overline{w}_t R_t = {} & \beta\nu\gamma\, E_t\left[S_{t+1}\right] \\ & +\beta(\rho-\nu)E_t\left[\left\{D1 + D4 + (D2 + D3)\,\frac{\alpha}{1+\alpha}\right\}\overline{w}_{t+1}R_{t+1}\right] \end{aligned} \tag{31}$$

where D1 is one for firms in category (i) and zero otherwise, D2 is one for firms in category (ii) and zero otherwise, D3 is one for firms in category (iii) and zero otherwise, and D4 is one for firms in category (iv) and zero otherwise. Given the application and data collection procedure, cf. footnote 13, it seems likely that the firms are well informed one year in advance about whether or not they will receive subsidies. Assuming, therefore, perfect foresight with respect to next year's subsidies, equation (31) can be reformulated

$$\begin{aligned}\overline{w}_t R_t \;=\; & \beta\nu\gamma\; E_t\left[S_{t+1}\right] + \frac{\beta\nu\gamma}{\alpha}\left\{(D1 + D3)\cdot E_t\left[S_{t+1}\right]\right\} \\ & +\beta(\rho-\nu)E_t\left[\overline{w}_{t+1}R_{t+1}\right] \\ & +\frac{\beta(\rho-\nu)}{\alpha}\left\{D1\cdot E_t\left[\overline{w}_{t+1}R_{t+1}\right]\right\} \\ & -\frac{\beta(\rho-\nu)}{1+\alpha}\left\{D2\cdot E_t\left[\overline{w}_{t+1}R_{t+1}\right]\right\}. \end{aligned} \tag{32}$$

Note that as $\alpha \to 0$, some of the coefficients go to infinity, once again reflecting the fact that firms are not likely to be subsidized at the margin for such values of α, and, thus, that there are not likely to be firms in category (i)-(iii) if α is low. Note also that if some firms are misclassified as belonging to one of the categories (i)-(iii) when belonging to category (iv), these observations still have all the relevant variables included. They do, however, also have non-zero additional variables, namely those involving dummies in (32). From an econometric point of view, this can be interpreted as the inclusion of irrelevant variables, and the estimated coefficients for these variables should be insignificant and close to zero if in fact the majority of firms are not subsidized at the margin. The correct specification in that case is simply

$$\overline{w}_t R_t = \beta\nu\gamma\; E_t\left[S_{t+1}\right] + \beta(\rho-\nu)E_t\left[\overline{w}_{t+1}R_{t+1}\right]. \tag{33}$$

7.3 Estimating the Euler Equation

We start out by assuming that subsidized firms are subsidized at the margin. This hypothesis can be tested. Equation (32) can be estimated and will, given the necessary data, identify the degree of additionality through the parameter α if the hypothesis is correct. If it is wrong, it will be falsified through non-significant parameters for the terms involving dummy variables.

The Norwegian R&D surveys contain information on planned R&D, $E_t\left[\overline{w}_{t+1}R_{t+1}\right]$, but not on expected sales. To circumvent this problem, we have used real sales in the following year as a proxy, and instrumented this variable by its present and lagged value in order to avoid the endogeneity problem thus involved.[31] The sales data are merged in from the manufacturing statistics.

Another problem is to decide which firms belong to which of the four categories determining the values of the dummy variables. Assuming perfect foresight one year ahead is reasonable and helps, but we have annual R&D data only for the period 1982-1985. For the period 1985-1995, the R&D surveys were only conducted every second year, and, hence, for these years we do not know which firms received a subsidy in period $t+1$. One way to proceed, is to assume that firms received subsidies at time $t+1$ if they received subsidies both at time t and $t+2$, as there is positive autocorrelation in subsidy allocation. Likewise, therefore, it seems reasonable to assume that firms did not receive subsidies at time $t+1$ if they did not receive subsidies at time t nor at time $t+2$. Similar reasoning cannot be adopted for firms which received subsidies at t, but not at time $t+2$, or the other way around. These observations, therefore, have to be excluded. Unfortunately, then, there are rather few observations in our data set which can identify the coefficients in front of the last two terms in equation (32), as the majority of the observations are from the period 1985-1995, and it is only a small fraction of the firms that change their subsidy recipient status in the years 1982-1985 . There are 17 observations in category (i), 13 observations in category (ii), 31 observations in category (iii) and 121 observations in category (iv). To correct for heteroscedasticity, all observations are weighted by the square root of inverse sales. Further information about the variable construction can be found in section 3.3.

[TABLE 8 ABOUT HERE]

The estimation results are given in Table 8. The coefficients of equation (32) are reported in column (1). Two of the dummy variable terms are statistically insignificant and have opposite signs to those predicted by theory. The last one is correctly signed and weakly significant. Using the correctly signed and weakly significant coefficient to identify α gives $\widehat{\alpha}=7.45$, a value way outside the theoretical range, $\alpha\in\langle 0,1\rangle$. This means that this coefficient is also too close to zero to have a meaningful interpretation. Taken at face value, these results suggest that matching grants subsidies do not affect the firms' marginal price of R&D, a finding which is to be expected if there is little

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[31] The firms' production function is not shown explicitly in this paper, but production in $t+1$, Q_{t+1} will be a function of the knowledge capital stock,K_{t+1}, and therefore R_t. Sales, $S_{t+1}=P_{t+1}Q_{t+1}$ will then depend on R_t, including any shock, u_t to R in period t. This endogeneity problem is avoided if S_{t+1} is predicted based on the firms' information set at t. Since sales are highly correlated over time, it is natural to use S_t and S_{t-1} as instruments.

or no short run additionality associated with the subsidies.[32] Recall that our analysis of matching grants subsidies at the end of section 2 showed that it is unlikely that firms are subsidized at the margin unless there is a significant degree of additionality associated with the subsidies, and that the short run analysis in section 3.3 showed that there is no crowding out, nor any degree of additionality.

Given the modest size of the data set, the results in column (1) should be considered explorative.[33] If the subsidized firms are not subsidized at the margin, however, all firms should be reclassified to category (iv), and the dummy variable terms will not be part of the regression equation. This simplifies the analysis and also increases the number of observations that can be included in the regression. Table 8, column (2) reports the estimation results based on this assumption. Using this specification (equation 33), both the estimated coefficients are significant at conventional levels. The point estimates are $\beta\nu\gamma = 0.0033$ and $\beta(\rho - \nu) = 0.090$. Unfortunately, none of the structural parameters can be identified separately without strong assumptions as there are two coefficients and four parameters.[34] Something can still be deduced from the estimates, however. The first coefficient tells us that an increase in expected sales has a positive impact on R&D investments as predicted by theory. The second coefficient tells us that there is a positive relationship between R&D this period and planned R&D in future periods. This is consistent with the learning-by-doing framework underlying our theory model.

Finally, let us emphasize that our results do not imply that receiving subsidies is without implications for the firms' investment decision, even if the firms are not subsidized at the margin, cf. the discussion in section 7.2. If our model is correct, a firm which does not receive subsidies at time t, but which does expect to receive subsidies and expand the R&D activity at time $t+1$, will undertake more R&D at time t than a firm with the same expectations about sales, but which does not expect to receive subsidies in the next period. Learning by doing makes it optimal for the firm to "prepare" for the expected R&D-expansion in advance by building up more knowledge. Due to the same dynamic effect, a firm which receives subsidies at time t, but which does not expect to receive subsidies at time $t+1$, will do more R&D at time $t+1$, than a firm with the same expectations about sales, but which does not receive subsidies at time t. This is because the subsidized firm starts out at time $t+1$ with a larger knowledge capital base then the non-subsidized firm, something which makes it a more efficient "knowledge producer". Hence, a temporary R&D subsidy which is not completely crowded out, will have a lasting positive impact on the firm's future

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[32] An alternative explanation for the results is obviously that the Euler equation model is wrong, or that the data do not match the concepts needed very well.

[33] In follow up work, we hope to re-estimate the model on a larger and more recent data set since the Norwegian R&D survey have been conducted annually again since 2001.

[34] Drawing on Klette (1996) and Klette and Johansen (1998) it is possible to derive a performance equation within the same framework. This will allow separate identification of β. We have, however, tried using the estimated parameters in Klette and Johansen (1998) to identify β, but this strategy gives β-estimates that seem implausible low.

R&D investments. This effect will be more significant the less crowding out or more additionality there is associated with the subsidy.

8 Conclusions and future research

Whereas many countries subsidize R&D in private companies through tax credits, subsidies to the Norwegian high-tech industries have mainly been given as “matching grants”, i.e. the subsidies are targeted, and the firms have to contribute a 50 % own risk capital to the projects. It is, however, an open question to what extent this induces firms to increase their total R&D investments as they may reduce non-subsidized R&D activities upon receiving an R&D grant. Our results suggest that grants do not crowd out privately financed R&D, but that subsidized firms do not increase their privately financed R&D either. Hence, the own risk capital in the projects seems to be taken from ordinary R&D budgets, and there is no “additionality” associated with matching grants subsidies.

Our results also suggest that the subsidies most efficiently stimulate R&D investments in small and large firms as opposed to medium size firms. One hypothesis which may explain this is that R&D investments in small firms are liquidity constrained, whereas large firms are so closely monitored by the governmental agencies awarding the subsidies that it is difficult for them to receive support for projects which are profitable without subsidies. A variable measuring the firms’ cash flow does not indicate that small firms are liquidity constrained, however. This might be because this variable rather measures the present success of the firms, something which may be considered a proxy for future success and thereby for the incentive to invest in R&D. Our main result of neither crowding out, nor additionality, seems to be robust both over time and across a wider sample of manufacturing firms than those belonging to the traditional high-tech industries. In addition, there are no clear cut differences between the effects of subsidies awarded by research councils, industry funds and ministries.

We have also investigated possible long-run effects of R&D subsidies, and we have shown that the conventional perpetual inventory model of R&D investments predicts the dynamic effects of subsidies to be negative. There is, however, no empirical evidence supporting this claim. On the contrary, there are indications of a positive dynamic effect, i.e. temporary R&D subsidies seem to stimulate firms to increase their R&D investments even when the grants have expired. We have argued that learning-by-doing in R&D activities is a possible explanation for this, and our theoretical analysis shows that such effects alter the predictions of the conventional models. The intuition behind the dynamic behavior of our model is that with learning-by-doing in R&D, increased R&D in one period makes firms more efficient R&D performers in future periods through increased knowledge capital. This increases the profitability of future R&D.

A structural, econometric model of R&D investments incorporating such learning effects has been estimated with reasonable results. These results suggest that matching grants subsidies do not affect the firms' marginal price of R&D, a finding which is to be expected if there is little or no additionality associated with subsidies in the period in which they are awarded.

In future research, it is our ambition to combine the Euler equation in this paper with the performance equation of Klette (1996), in order to identify the parameters necessary to predict the strength of the dynamic effects, and not least to estimate the returns to private and public R&D investments.

Appendix: Algebraic expressions for the derivatives in section 6.3

$$\begin{aligned}\frac{\partial R_1}{\partial w_1'} &= \{\pi''(K_2)\left(\frac{K_1}{R_1}\right)^{1-\nu}\nu w_1' \\ &\quad -\left[\frac{K_1}{1-\nu}(\beta\nu)^{\frac{1}{1-\nu}}\left(\frac{\pi'(K_2)}{w_1'}\right)^{\frac{\nu}{1-\nu}}\right]^{-1}\}^{-1} < 0\end{aligned} \tag{34}$$

$$\begin{aligned}\frac{\partial R_0}{\partial w_0'} &= -\frac{K_0}{w_0'(1-\nu)}\left(\frac{\beta\nu}{w_0'}\right)^{\frac{1}{1-\nu}} \\ &\quad \cdot\left[\pi'(K_1)+\beta(1-\nu)\left(\pi'(K_2)\right)^{\frac{1}{1-\nu}}\left(\frac{\beta\nu}{w_1'}\right)^{\frac{\nu}{1-\nu}}\right] \\ &\quad \cdot\{1-\frac{K_0}{1-\nu}\left(\frac{\beta\nu}{w_0'}\right)^{\frac{1}{1-\nu}} \\ &\quad \cdot\left[\pi'(K_1)+\beta(1-\nu)\left(\pi'(K_2)\right)^{\frac{1}{1-\nu}}\left(\frac{\beta\nu}{w_1'}\right)^{\frac{\nu}{1-\nu}}\right]^{\frac{1}{1-\nu}} \\ &\quad \cdot\left[\pi''(K_1)\frac{\partial K_1}{\partial R_0}+\beta\left(\frac{\beta\nu}{w_1'}\right)^{\frac{\nu}{1-\nu}}\pi''(K_2)\frac{\partial K_2}{\partial R_0}\right]\}^{-1} < 0\end{aligned} \tag{35}$$

$$\begin{aligned}\frac{\partial R_1}{\partial w_0'} &= \nu\left(\frac{K_0}{R_0}\right)^{1-\nu}\left(\frac{\beta\nu\pi'(K_2)}{w_1'}\right)^{\frac{1}{1-\nu}}\frac{\partial R_0}{\partial w_0'} \\ &\quad +\frac{K_1\pi'(K_2)}{(1-\nu)}\left(\frac{\beta\nu}{w_1'}\right)^2\pi''(K_2)\frac{\partial K_2}{\partial R_0}\frac{\partial R_0}{\partial w_0'} \lesseqgtr 0\end{aligned} \tag{36}$$

$$\begin{aligned}\frac{\partial R_0}{\partial w_1'} &= \frac{\beta K_0}{1-\nu}\left(\frac{\beta\nu\pi'(K_2)}{w_0'}\right)^{\frac{1}{1-\nu}} \\ &\quad \cdot\left[\frac{\beta\nu}{w_1'}\left\{\pi'(K_1)+\beta(1-\nu)\left(\pi'(K_2)\right)^{\frac{1}{1-\nu}}\left(\frac{\beta\nu}{w_1'}\right)^{\frac{\nu}{1-\nu}}\right\}\right]^{\frac{\nu}{1-\nu}} \\ &\quad \cdot\left\{\pi''(K_2)\frac{\partial K_2}{\partial R_1}\frac{\partial R_1}{\partial w_1'}-\frac{\nu}{w_1'}\right\} \gtreqless 0\end{aligned} \tag{37}$$

$$\begin{aligned}\frac{\partial R_1}{\partial R_0} &= \left\{\nu\left(\frac{\beta\nu\pi'(K_2)}{w_1'}\right)^{\frac{1}{1-\nu}}+\frac{\beta\nu}{w_1(1-\nu)}R_0\left(\frac{\beta\nu\pi'(K_2)}{w_1'}\right)^{\frac{\nu}{1-\nu}}\pi''(K_2)\frac{\partial K_2}{\partial R_0}\right\} \\ &\quad \cdot\left(\frac{K_0}{R_0}\right)^{1-\nu} \gtreqless 0\end{aligned} \tag{38}$$

$$
\begin{aligned}
\frac{\partial R_0}{\partial R_1} \quad = \quad & -\beta\left(1-\nu\right)K_0^{(1-\nu)^2}R_0^{1-\nu^2}\left\{\pi''\left(K_2\right)\frac{\partial K_2}{\partial R_1}+\nu R_1^{\nu}\pi'\left(K_2\right)\right\} \\
& \cdot\{\beta\left(1-\nu\right)K_0^{(1-\nu)^2}R_0^{1-\nu^2}\left\{\pi''\left(K_2\right)\frac{\partial K_2}{\partial R_0}-\left(1+\nu^2-\nu\right)\frac{R_1^{\nu}}{R_0}\pi'\left(K_2\right)\right\} \\
& +\pi''\left(K_1\right)K_0^{1-\nu}R_0-\left(1-\nu\right)\pi'K\}^{-1}\gtreqless 0
\end{aligned}
\tag{39}
$$

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Figure 1: The firm's demand curve for R&D

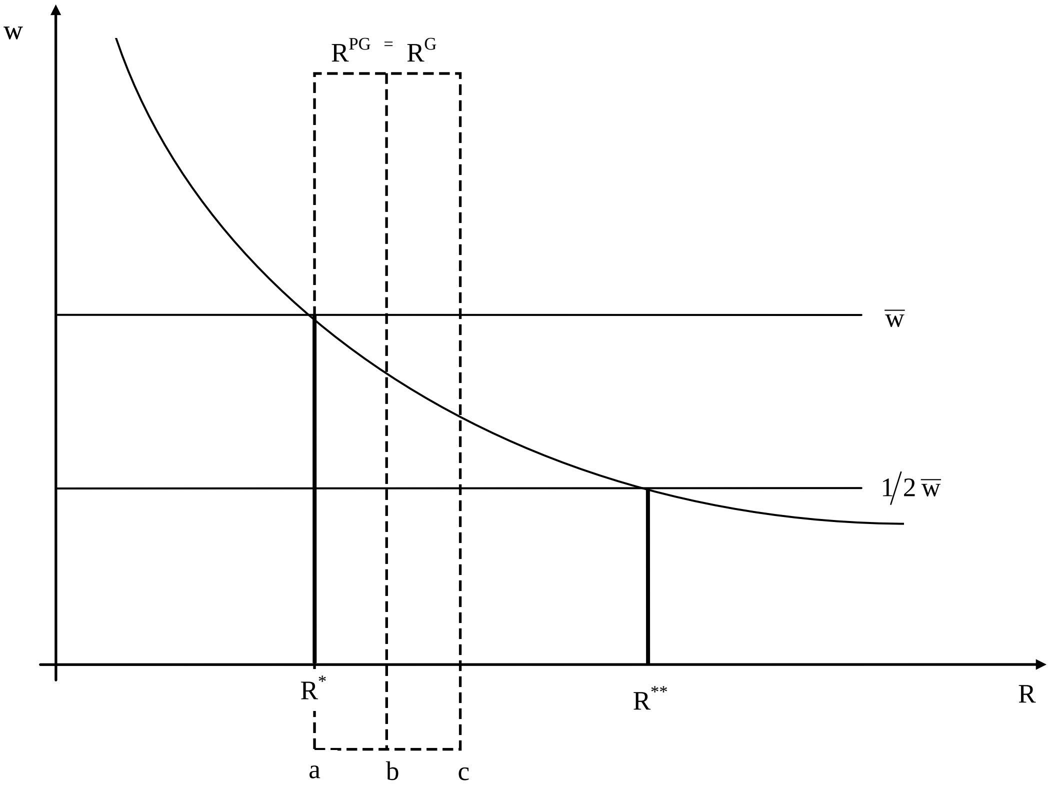

Figure 2: The change in R&D accompanying a subsidy regime change

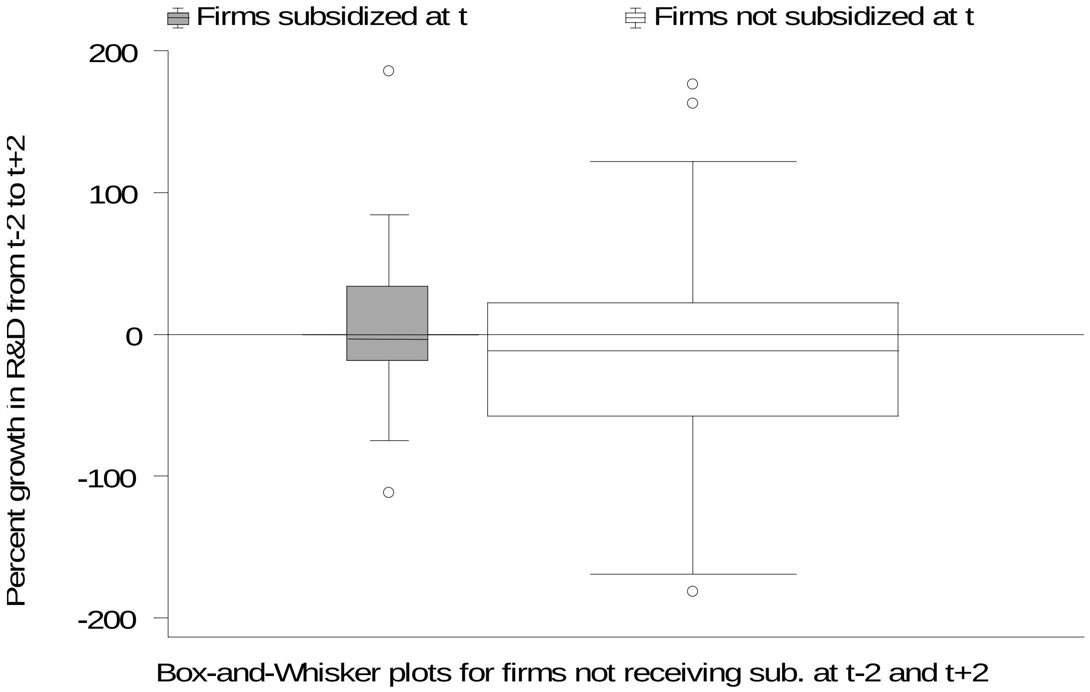

Table 1: Sample Statistics

ISIC 382, 383 and 385	
Total no. of observations	697
no. of business units	192
average no. of observations per business unit	3.6
Observations with subsidies	300
subsidized from research councils	197
subsidized from industry funds	111
subsidized from ministries	98
Observations of small business units (Average no. of workers<25th perc.)	176
Observations of large business units (Average no. of workers>75th perc.)	168
Average no. of workers per business unit	334
25th. Percentile	58
Median	107
75th. Percentile	263
Average R&D intensity	0.07
Median R&D intensity	0.04
Average subsidy share (excluding observations with zero subsidy)	0.23
Median subsidy share (excluding observations with zero subsidy)	0.17

Sample: R&D performing business units in 1982-1995 included in at least two R&D surveys, having at least 20 workers on average, and being successfully merged with the manufacturing statistics. The sample is moderately trimmed. See section 3 for further details.

Table 2: Norwegian interview studies of the crowding out effect of R&D subsidies

Study Sample size Time periode	GF84 54 78-82	HB89 191 80-84	HBW92 213 84-89	HW97 200 90-95	OKOH97 49 92-95	Weighted average
Project done without subsidy	34 %	33 %	15 %	6 %	2 %	18 %
Project delayed or diminished	46 %	45 %	46 %	57 %	28 %	48 %
Project not done without subsidy	20 %	23 %	40 %	37 %	70 %	34 %

Studies: GF84; Grønhaug and Fredriksen (1984), HB89; Hervik and Brunstad (1989), HBW92; Hervik, Berge and Wicksteed (1992), HW97; Hervik and Waagø (1997), OKOH97; Olsen et. al. (1997). Respondents who could not or did not answer are not included.
Only in HB89, where the full sample consisted of 230 projects, was this category of any significance.

Table 3: Correlation coefficients between deviation from planned R&D and change in R&D-subsidy

	Corr.coef.	Sign.level	No. of obs.
One year horizon: Planned R&D in man-years	0.006	0.95	107
Two year horizon: Planned R&D in man-years	0.34	0.00	147
Two year horizon: Planned R&D in kroner	0.17	0.10	99

9 observations in 1991 where deviation from planned R&D measured in man-years and kroner has opposite signs are excluded.

Table 4: The effect of R&D-subsidies on total R&D

	(1)		(2)		(3)	
Functional form	linear		Linear		loglog	
Estimation method	fe		Diff		fe	
Sales	-0.025**	(0.0088)	0.0050	(0.0080)	-0.62	(1.52)
Sales squared	1.5e-8***	(4.7e-7)	-2.9e-10	(5.0e-9)	0.020	(0.046)
Total R&D-subsidy	1.03***	(0.16)	1.06***	(0.17)	0.064***	(0.012)
Cash flow	0.087***	(0.025)	0.097***	(0.033)	0.019	(0.015)
R-Square	0.95		0.39		0.90	
No. of observations	697		379		697	

The observations are weighted by the square root of inverse sales [log of sales in (3)] to correct for heteroskedasticity. Time dummies included in all regressions. The variables have been deflated. Robust standard errors in parenthesis.
* Significant at the 10% level
** Significant at the 5% level
*** Significant at the 1% level

Table 5: The effect of R&D-subsidies on total R&D: Differences between small and large firms

	(1)		(2)		(3)	
Functional form	Linear		linear		Loglog	
Estimation method	Fe		diff		Fe	
Sales	-0.022***	(0.0084)	0.0076	(0.0074)	-0.55	(1.50)
Sales squared	1.3e-8***	(4.8e-9)	-2.6e-9	(5.7e-9)	0.018	(0.046)
Total R&D-subsidy	0.51*	(0.27)	0.47**	(0.22)	0.056***	(0.014)
*small firm dummy	0.48	(0.32)	0.63**	(0.29)	0.022	(0.025)
*large firm dummy	0.74**	(0.36)	0.74**	(0.33)	0.012	(0.032)
Cash flow	0.041*	(0.025)	0.034	(0.025)	0.0093	(0.019)
*small firm dummy	0.028	(0.055)	0.040	(0.059)	0.015	(0.032)
*large firm dummy	0.056	(0.039)	0.077*	(0.047)	0.017	(0.038)
R-Square	0.95		0.41		0.90	
No. of observations	697		379		697	

The observations are weighted by the square root of inverse sales [log of sales in (3)] to correct for heteroskedasticity. Time dummies are included in all regressions. The variables have been deflated. Robust standard errors in parenthesis. Large and small firms are defined as firms with average employment below the 25th percetile and above the 75th percentile respectively.

Table 6: The effect of R&D-subsidies on total R&D: Differences between sources of subsidies

	(1)		(2)		(3)	
Functional form	Linear		linear		Loglog	
Estimation method	Fe		diff		Fe	
Sales	-0.024***	(0.0087)	0.0050	(0.0080)	-0.58	(1.57)
Sales squared	1.4e-8***	(4.8e-9)	-4.8e-10	(5.0e-9)	0.020	(0.048)
Subsidy from research councils	0.95***	(0.23)	1.57***	(0.59)	0.043***	(0.012)
Subsidy from industry funds	0.72***	(0.29)	0.97***	(0.26)	0.029***	(0.011)
R&D grants from ministries	1.17***	(0.25)	1.07***	(0.24)	0.053***	(0.016)
Cash flow	0.085***	(0.024)	0.098***	(0.033)	0.020	(0.015)
R-Square	0.95		0.39		0.89	
No. of observations	697		379		697	

*** Significant at the 1% level
** Significant at the 5% level
* Significant at the 10% level
The observations are weighted by the square root of inverse sales [log of sales in (3)] to correct for heteroskedasticity.
Time dummies are included in all regressions. The variables have been deflated. Robust standard errors in parenthesis.

Table 7: The effect of R&D-subsidies on total R&D: Dynamics

	(1)		(2)		(3)	
Functional form	linear		linear		loglog	
Estimation method	fe		Diff		fe	
Sales	-0.020**	(0.019)	-0.0058	(0.013)	3.38	(3.35)
Sales squared	1.2e-8***	(1.1e-8)	4.4e-9	(9.0e-9)	-0.099	(0.10)
Total R&D-subsidy	1.15***	(0.24)	0.96***	(0.32)	0.051***	(0.020)
Total R&D-subsidy at t-2	0.36*	(0.20)	0.16	(0.15)	-0.019	(0.016)
Cash flow	0.083**	(0.037)	0.087**	(0.035)	0.038	(0.024)
R-Square	0.96		0.29		0.91	
No. of observations	379		181		379	

The observations are weighted by the square root of inverse sales [log of sales in (3)] to correct for heteroskedasticity. Time dummies are included in all regressions. The variables have been deflated. Robust standard errors in parenthesis.
* Significant at the 10% level
** Significant at the 5% level
*** Significant at the 1% level

Table 8: Euler equation estimates

	(1)		(2)	
Expected sales	0.0023*	(0.0013)	0.0033**	(0.0016)
* dummy for subsidy only at time t or both at t and t+1 (D1+D3)	-0.0020	(0.0029)		
Planned R&D	0.82***	(0.017)	0.090***	(0.031)
* dummy for subsidy only at time t (D1)	-0.22	(0.17)		
* dummy for subsidy only at time t+1 (D2)	-0.097*	(0.051)		
Root MSE	5.7		13.6	
No. of observations	182		528	

2SLS regression on nominal values. Sales at period t+1 is used as proxy for expected sales and instrumented with sales in period t and t-1. The observations are weighted by the square root of inverse sales to correct for heteroskedasticity. Robust standard errors in parenthesis.
* Significant at the 10% level
** Significant at the 5% level
*** Significant at the 1% level