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Jarle Møen, Helge Sandvig Thorsen

Institutions: Norwegian School of Economics

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Jarle Møen
Helge Sandvig Thorsen



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Publication bias in the returns to R&D literature

by
Jarle Møen
Helge Sandvig Thorsen

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Publication bias in the returns to R&D literature*

Jarle Møen[†]

Helge Sandvig Thorsen[‡]

September, 2012

Abstract

We conduct a meta-analysis of the private returns to R&D literature and find that 26 % of the results in a hypothetical complete literature are missing. The combined estimate for the marginal returns to R&D falls from 18.2 % to 13.8 % when publication bias is accounted for. The latter estimate is very low, as it is gross of depreciation. One interpretation is that publication bias has contributed to masking the need for a revision of the standard R&D capital model.

Keywords: Returns to R&D, Publication bias, Meta-analysis, Trim-and-fill method

JEL classification: C83, D24, O31

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[†]Corresponding author. Department of Finance and Management Science, Norwegian School of Economics, Helleveien 30, N-5045 Bergen, Norway. Email: jarle.moen@nhh.no.

[‡]Department of Economics, Norwegian School of Economics. Email: helge.thorsen@nhh.no.

1 Introduction

OECD governments spend a substantial amount of public money on programs intended to stimulate innovative activities. The justification for these programs rests on a vast and steadily growing literature that verifies the importance of R&D investments to growth and economic well-being. Much of the returns to R&D literature builds on the R&D capital model formalized in Griliches (1973, 1979), and the literature is reviewed in a number of excellent surveys. Griliches (1992) is an early example, Hall, Mairesse and Mohnen (2010), in a new Elsevier Handbook, is the most recent.¹ All surveys conclude that there are large returns to R&D, although no one computes a combined return estimate using a formal meta-analytic technique.

Most economists have a prior belief that returns to R&D are positive and possibly large, but the returns to R&D literature is prone to problems related to measurement, selection, choice of functional form and appropriate lag lengths. This suggests that there is a real danger of publication bias. Such publication bias may be self-imposed by researchers, or imposed by editors and referees who consider negative, small or non-significant coefficients to be suspicious and of little interest. Studies where the returns to R&D are overestimated are then more likely to end up published than evidence where the returns are underestimated. To the extent that this occurs, the average of estimates from published studies will overestimate the true return. This topic has not been given any attention in previous surveys of the returns to R&D, except for a brief comment by Griliches (1992):

“The estimated social rates of return look surprisingly uniform in their indication of the importance of [...] spillovers. While one must worry whether this is not just the result of self-imposed publication filters, my own involvement in this work and my acquaintance with many of the other researchers in this area leads me to believe in the overall reality of such findings.”

We do not question the “overall reality” of positive returns to R&D, but we complement previous surveys by providing a first analytical investigation of whether the “worry” that Griliches reflects on, is warranted or not. Surveying a related literature on the effectiveness of R&D tax credits, Ientile and Mairesse (2009) find evidence suggesting that “there might be a positive publication bias in the literature on the efficiency of R&D tax credits”.

¹Other surveys include Mairesse and Sassenou (1991), Nadiri (1993), the Australian Industry Commission (1995), Hall (1996), Griliches (1995, 2000) and Wieser (2005).

The literature on the private and social returns to R&D is large. We base our meta analysis on two recent and comprehensive surveys by Wieser (2005) and Hall et al. (2010). Our focus is on the private returns to R&D.² Using both funnel graphs, regressions and the “trim and fill”-method, we find evidence of positive publication bias in the returns to R&D literature. We estimate that 26 % of the results in a hypothetical complete literature are missing. In a subsample that estimate the gross private returns to R&D directly, we find a combined return estimate of 18.2 % before accounting for publication bias. When correcting for publication bias, the combined return estimate drops to 13.8 %. Our analysis, of course, does not imply that 13.8 % is a correct estimate of the true returns to R&D-investments. There are numerous potential biases left that are likely to affect the estimate. In fact, 13.8 % seems implausibly low for a gross rate of return to R&D, as R&D investments are believed to depreciate by at least 15 % per year from a private point of view (Hall et al., 2010). Hence, one interpretation of our finding is that positive publication bias has contributed to masking the need for a revision of the R&D capital model.

2 The R&D capital model

The R&D capital model of Griliches (1973, 1979) has been the ruling paradigm for researchers wanting to estimate the returns to R&D – despite the many weaknesses that Griliches and others have pointed out. A simple representation of the model is:

$$\log Y_{it} = \beta \log X_{it} + \gamma \log K_{it} + \alpha_i + u_{it} \quad (1)$$

where Y_{it} is output of firm i in year t , typically measured by firm revenue, X_{it} is a vector of standard economic inputs such as labor, materials, machinery, equipment etc. K_{it} is one or more measures of accumulated research efforts or “knowledge capital”. The error term is composed of α_i and u_{it} where α_i is a potential firm fixed effect and u_{it} is the idiosyncratic part. The coefficient of main interest is γ , the elasticity of output with respect to knowledge capital. The knowledge capital stock can be constructed as a weighted sum of past investments in R&D. This can be done by the perpetual inventory method, making the necessary assumptions about

²Wieser (2005) conducts a formal meta analysis of the returns to R&D literature, focusing on whether the returns are stable over time, across industries and across different countries. He does not adjust for publication bias, but he acknowledges that it “is generally considered to be one of the merits of the procedure”.

how fast the R&D investments impact production and how fast knowledge depreciates from a private point of view.

Replacing levels with growth rates gives an alternative formulation where the marginal returns to R&D can be estimated directly:

$$\Delta \log Y_{it} = \alpha + \beta \Delta \log X + \rho \frac{R_{it}}{Y_{it}} + \Delta u_{it} \quad (2)$$

In this formulation, $\rho = \frac{dY_{it}}{dK_{it}} = \gamma \frac{Y_{it}}{K_{it}}$ and $\Delta \log K_{it}$ is approximated by $\frac{R_{it}}{K_{it}}$. R_{it} is the net investment in R&D, i.e. net of the depreciation of the previously accumulated knowledge. Under certain assumptions, see e.g. Hall et al. (2010), ρ can be interpreted as the marginal gross internal rate of return to R&D. Subtracting the private R&D depreciation rate one obtains a marginal net rate of return.³

3 Sources of publication bias

Ashenfelter, Harmon and Oosterbeek (1999) point out that if published results are selected because they are significant, this implies that surveys of such results suffer from the same sample selection bias that is emphasized as a concern in all econometric text books. In economics, this idea goes back at least to DeLong and Lang (1992), but it has received considerably more attention in other sciences like medicine. Ashenfelter et al. state that publication bias may arise “because of the tendency in virtually all scientific fields to report statistical results that tend to reject the null hypothesis of no effect.” They stress that “the existence of any such bias is no reflection on any individual scholar, but is instead the natural working of a scientific process designed to discover important new results.”

Card and Krueger (1995) address three potential sources of publication bias. First, scientific journals might favor statistically significant results, as pointed out by DeLong and Lang (1992) and iterated in the quote from Ashenfelter, Harmon and Oosterbeek above. Second, reviewers and editors may use their expectation of the value as an informal test of the validity of estimates. Third, researchers are likely to have an expectation of what the results will look like. Such

³In equation (2), R is the net investment in R&D, while only gross R&D is available in empirical work. Using an R&D measure that is too large, obviously causes ρ to be underestimated. Hall et al. (2010) show that this bias may be substantial. Eberhart, Helmers and Strauss (2012), on the other hand, show that most private returns to R&D estimates suffer from a positive bias as they are based on specifications that ignore the effect of R&D spillovers. R&D spillovers are positively correlated with private R&D investments.

expectations may be important when evaluating findings, and might influence the subsequent choice of empirical specification. Rather than relying on counterintuitive results, researchers might believe there is something wrong with the specification. (This will, of course, be true in many cases.)

The various sources of bias might also reinforce each other. When evaluating their results, researchers will consider the probability of having findings published. This implies that they may not only evaluate results on grounds of their own expectations, but also on their understanding of other researchers' expectations.

4 Data

The returns to R&D have been analyzed at the country level, industry level and firm level. We will focus on results from research at the firm level, as this is the most common approach. Our focus is on private returns, not social returns.⁴ Following Wieser (2005), we exclude studies based on cost functions (the dual approach). The reason is partly that the number of such studies at the firm level is small, and partly that they vary quite a bit with respect to specification. Beyond a reasonable number of studies, a condition for conducting a meta-analysis is that the studies included share some common aspects that make them comparable in a statistical manner.

Our starting point is Wieser (2005), Tables 2, 3 and 4. Table 2 contains “firm level econometric estimates of the rate of return to research and development”, Table 3 contains “estimates of the elasticity of research and development from the level dimensions” (including pooled OLS estimates) and Table 4 contains “estimates of the elasticity of research and development based on the temporal dimensions” (i.e. within and difference estimates). We have updated these tables by cross-checking them against Hall et al. (2010), where Tables 3, 2a and 2b correspond to Wieser’s Tables 2, 3 and 4, respectively. This resulted in the inclusion of estimates based on 38 new samples from 18 additional studies. In Hall et al. (2010), there is not a standard error attached to every reported estimate. There are also examples where the effect estimate is denoted by an interval, rather than a precise number. In these cases, we collect standard errors and exact estimates from the original source. When the two surveys report results from different versions of the same paper, we collect our estimates from the most recent. If a data set

⁴See Karlsson, Warda and Gråsjö (2012) for a formal meta-analysis of the spatial knowledge spillover literature.

is represented by results from different levels of aggregation of the underlying data, e.g. both an overall estimate and estimates by industry or separate time periods, we only include the results based on the most aggregated sample.

All estimates used are listed in Tables A1–A3 in the appendix. For each study and regression result, we record the coefficient of interest (rate of return or elasticity), the standard error of the coefficient, the number of firms in the sample, the time period covered and the country. Some studies are represented by multiple estimates. When these results represent different specifications estimated on the same sample, including all would imply that these samples are overweighted. In order to avoid this problem, we only include the median estimate for each sample reported in Tables A1–A3. Altogether, our analysis uses 94 estimates from 41 studies. Table 1 gives descriptive statistics for the three subsamples we use.

Table 1: Sample statistics

	(1) Rate of return to R&D	(2) Elasticity of R&D Level dimension	(3) Elasticity of R&D Temporal dimension
Number of effect estimates	32	32	30
Mean effect estimate	0.19 (0.15)	0.10 (0.05)	0.07 (0.08)
Median effect estimate	0.210	0.103	0.045
Min effect estimate	-0.475	0.014	-0.003
Max effect estimate	0.420	0.216	0.328
Mean number of firms	700 (1146)	671 (1216)	642 (814)
Median number of firms	269.5	236.5	394
Min number of firms	3	17	17
Max number of firms	5240	6145	3830

Standard errors in parentheses. Elasticity estimates based on the level dimension include pooled OLS. Elasticity estimates based on the temporal dimension account for firm fixed effects. Also the rate of return estimates account for firm fixed effects, as it is based on a first difference specification, cf. equation (2).

5 Detecting publication bias

Light and Pillemer (1984) claim that a “funnel graph” holds information on selection bias in scientific literatures. They plot different estimates of the same parameter into a coordinate system. The horizontal axis denotes the size of the coefficient, whereas the vertical axis denotes the sample size of the study. The idea is that the scatter plot should form a symmetric funnel-

shaped pattern in the absence of publication bias.

Funnel graphs were quickly adopted to examine clinical trial studies. According to Sutton et al. (2000), this is the most commonly used method to detect publication bias in medical research. In economics, funnel graphs have not been much used, but the survey by Stanley and Doucouliagos (2010) illustrates their simplicity and effectiveness. Stanley and Doucouliagos argue that the inverse of an estimate's standard error is a better measure of its precision than the sample size. They claim that the funnel graph has two main implications. First, only the most accurate findings will reveal the true value of an estimate. Second, an asymmetric funnel graph suggests publication bias.⁵ Funnel graph asymmetry can be tested formally, e.g. by simple linear regression and by the non-parametric method of Duval and Tweedie (2000a, 2000b).⁶ We present funnel graphs in section 7.1 and asymmetry tests in section 7.2.

6 Correcting for publication bias

Based on the literature, we want to present a best estimate for the overall returns to R&D. When publication bias is detected, however, a combined meta analysis estimate must account for the effect of missing studies. Several techniques have been suggested, and a common approach is the non-parametric trim-and fill method developed by Duval and Tweedie (2000a, 2000b). Even though this procedure is implemented in all large statistical software packages, it has hardly been used in economics.⁷ The trim-and-fill method is a relatively simple, rank-based augmentation technique, and the simulation studies in Duval and Tweedie (2000a) suggest that it outperforms more sophisticated methods in many situations.

The trim-and-fill method can be considered a formalization of the funnel graph. It starts out estimating the number of "asymmetric" studies on the right-hand side of the funnel by a non-parametric, iterative procedure. (We assume here that it is the small and negative estimates

⁵Strictly speaking, there may also be symmetric publication selection in which case Light and Pillemer (1984) suggest using the 'hollowness' of the funnel graph to indicate selection bias. Symmetric selection is less of a concern, since the mean effect found in meta-analyses will remain largely unbiased.

⁶A common caveat in this literature is that publication bias is only one possible cause of funnel plot asymmetry, see Sterne and Egger (2005). In some settings it is conceivable that small studies have a larger true effect than large studies. This could e.g. happen in medical research if small studies use different populations or different protocols. Such concerns seem less relevant in the returns to R&D literature, but a cautious interpretation of results based on funnel graph asymmetry is to consider them sensitivity analyses showing the potential effect of missing studies.

⁷The only studies we know of are by Abreu, de Groot and Florax (2005) who briefly mention the method and present some results based on it, and a very recent paper by Haelermans and Borghans (2012).

on the left-hand side of the funnel that may have been filtered out.) Asymmetric studies can broadly be thought of as studies that do not have a left-hand side counterpart. In the next step, the asymmetric studies are removed or “trimmed” away, leaving a symmetric remainder that is used to estimate the true center of the funnel by standard meta-analytic methods. Finally, the trimmed studies are replaced and their hypothetical, missing counterparts are imputed as mirror images of the “asymmetric” studies. Using this “filled” sample, an adjusted overall confidence interval can be calculated around the center estimate.⁸

When combining effect estimates to compute the true center of the funnel, one must choose between a fixed effects and a random effects model, see e.g. Borenstein, Hedges and Rothstein (2007). Readers not familiar with meta-analytic models should note that these are not the same as the standard econometric fixed- and random effects models for panel data. The fixed effects model involves the assumption that there is only one true effect size that is shared by all included studies. The combined effect is then an estimate of this fixed or common effect, and the only reason for estimates to vary across studies is random error within studies. With a large enough sample size, this error will tend to zero. Hence, under the fixed effects model, a large study with high precision will be given a large weight, while small studies with low precision will have little influence on the combined estimate. This implies that the effect of publication bias may not be very severe under the fixed effects model, as the missing estimates typically have low precision.

The random effects model, by contrast, allows the true effect to vary between studies. The studies included in the meta analysis are assumed to be a random sample from the relevant distribution of effects. The estimated combined effect is then an estimate of the mean effect in this distribution. Since each study in the meta analysis is informative about a true effect size drawn from the distribution of effects, the random effects model gives more weight to estimates with low precision than the fixed effects model. Formally, the random effects model can be expressed as

$$\hat{\theta}_i = \theta_i + \epsilon_i \quad \text{with } \theta_i \sim N(\theta, \tau^2) \quad \text{and} \quad \epsilon_i \sim N(0, \sigma^2). \quad (3)$$

⁸The algorithm works as follows: The most extreme right-hand side effect sizes are removed one by one. Between each iteration, the overall effect size is estimated, and the procedure goes on until the funnel plot is symmetric around the latest computed overall effect size. This trimming gives an unbiased effect size estimate, but also reduces the variance of the effects. Therefore, the algorithm adds back the original studies and augments the sample with their mirror images before computing the confidence interval.

θ is the overall true effect and $\hat{\theta}_i$ is the effect estimate from study i . The within study variance is σ^2 and the between study variance is τ^2 . With $\tau^2 = 0$, the random effects model transforms to the fixed effects model.

The combined meta analysis estimate of θ is

$$\hat{\theta} = \frac{\sum w_i \hat{\theta}_i}{\sum w_i} \quad \text{where } w_i = (\hat{\sigma}^2 + \hat{\tau}^2)^{-1} \quad \text{and} \quad \text{SE}(\hat{\theta}) = \frac{1}{\sqrt{\sum w_i}} \quad (4)$$

When combining estimates of the return to R&D, it seems obvious that the random effects model is easier to justify than the fixed effects model. The true returns to R&D are likely to vary over time and between industries and countries. In fact, in the introduction to their survey, Hall et al. (2010) explicitly caution the reader that the returns to R&D should not be thought of as an invariant parameter, but the outcome of a “complex interaction between firm strategy, competitor strategy and a stochastic macro-economic environment”. There is therefore “no reason to expect *ex post* returns to be particularly stable”.

7 Results

We start out presenting funnel graphs, and then turn to a formal regression analysis. Finally we present combined estimates based on the random effects model where we use the “trim and fill”-method to correct for publication bias.

7.1 Funnel graphs

7.1.1 Rate of return results

When looking at direct empirical estimates of the rate of return to R&D, i.e. the direct marginal effect of investments from equation (2), we use a total of 32 results from 23 different studies. In Figure 1, we investigate potential publication bias by plotting the different results. We follow Stanley and Doucouliagos (2010) by measuring the size of the estimates on the horizontal axis, and the inverse standard error of the estimates on the vertical axis.

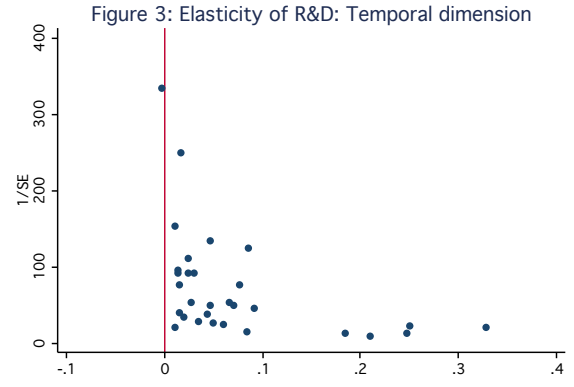
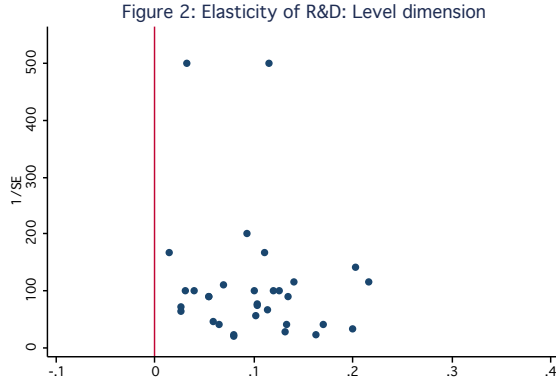


Figure 2 plots 32 results from 23 different studies utilizing the level dimension, and Figure 3 plots 30 results from 18 different studies utilizing the time dimension. A visual inspection of Figure 2 does not suggest serious publication bias, as the plot seems rather symmetric. The elasticity estimates peak around 0.1. A visual inspection of Figure 3, on the other hand, clearly suggests the presence of publication bias. It is striking how the results seem to reach their lower bound around zero. Also, the results tend to get more imprecise as the magnitude of the estimate increases. We will return to the difference between the two plots when we have verified the results using regression analysis.

7.2 Regression analysis

Stanley and Doucouliagos (2010) show by a graphical transformation how the funnel graph corresponds to a simple meta-regression model

$$\text{effect}_i = \beta_0 + \beta_1 SE_i + \epsilon_i \quad (5)$$

where i is an index referring to different empirical estimates.

Running this regression helps us verify or deny our subjective visual inspection of the funnel graphs presented in the previous section. Due to obvious heteroskedasticity, however, a weighted least squares counterpart of the above model is preferable. This can be obtained by weighting the squared errors by the inverse of the estimates' individual variances, $1/SE_i^2$, and is equivalent to dividing the previous expression by SE_i .

$$t_i = \beta_1 + \beta_0(1/SE_i) + \nu_i \quad (6)$$

Here, t_i is the t -value of each reported effect, and the intercept, β_1 , will be zero in the absence of publication bias. This test is widely used in medical research and known as the Egger-test for funnel graph asymmetry after Egger et al. (1997). Simulations in Stanley (2008) show that this procedure provides both an objective approach to identifying publication bias and a test for the presence of a true effect. If publication bias is not present, estimated effects should be independent of their standard errors, i.e. β_1 should be zero. Moreover, if there is an authentic empirical effect beyond the publication selection effect, β_0 should be positive. The results of such meta regressions on the samples plotted in Figure 1, 2 and 3 are reported in Table 1, columns (1), (2) and (3), respectively.

Table 2: Meta-regressions

	(1) Rate of return to R&D	(2) Elasticity of R&D Level dimension	(3) Elasticity of R&D Temporal dimension
Constant (β_1)	1.422*** (0.505)	2.128 (1.920)	2.698*** (0.634)
1/SE (β_0)	0.0877*** (0.0263)	0.0728*** (0.0124)	0.000309 (0.00624)
Observations	32	32	30
R^2	0.270	0.535	0.000

*** is significant at the 1% level, ** is significant at the 5% level. * is significant at the 10% level.

Elasticity estimates based on the level dimension include pooled OLS. Elasticity estimates based on the temporal dimension account for firm fixed effects. Also the rate of return estimates account for firm fixed effects, as it is based on a first difference specification, cf. equation (2).

The tabulated results show that the regressions verify our preliminary conclusions based on the funnel graphs. Both the regressions based on marginal returns to R&D and those based on elasticity estimates from studies utilizing the temporal dimension give β_1 -estimates that are significantly different from 0. This suggests that publication bias is present. The regression based on elasticity estimates from studies utilizing the level dimension, on the other hand, does not give a significant β_1 -estimate. Hence, publication bias appears not to be a problem in these studies, although the estimated coefficient is clearly positive. As for the (1/SE) term, both the rate of return estimates and the specification with elasticities from the level dimension state a significant and positive effect of R&D, while this is not the case for elasticities estimated from the time dimension. One should perhaps not place too much emphasis on the lack of a significant, positive result in column (3), however, as Stanley (2008) shows that β_0 is underestimated when

publication bias is present.

At first sight it is somewhat surprising that publication bias appears to be a problem in two specifications, but not in the third. We believe this can be explained by other biases that are present. Estimates utilizing the time dimension of the data account for firm fixed effects, but it is well known that this amplifies measurement error bias by increasing the noise-to-signal ratio in the data (Griliches and Hausman, 1986). Since R&D data typically are quite noisy, this implies that accounting for fixed effects increases the likelihood of producing small estimates that are candidates to be rejected by the researchers themselves or by referees and editors. Studies utilizing the level dimension of the data do not account for unobserved firm fixed effects. Unobserved firm fixed effects may be due to differences in human capital, management quality, market size, previous patents, strength of brand names etc. These are characteristics that typically correlate positively with R&D. Estimates that do not control for fixed effects are therefore likely to be positively biased. They will hence more easily confirm prior beliefs in the profession concerning high, positive returns to R&D.

7.3 Adjusting for publication bias using the trim-and-fill method

In Table 3 we present combined estimates of the returns to R&D based on the random effects model using the formula in equation (4) as implemented in the “metatrim”-algorithm by Steichen (2001). Metatrim also corrects for publication bias using the trim-and-fill method of Duval and Tweedie (2000a, 2000b) described in section 6. Results for the samples plotted in Figures 1, 2, and 3 are reported in columns (1), (2) and (3), respectively.⁹

From column (1) we see that the combined estimate for the marginal returns to R&D falls from 18.2 % to 13.8 % when publication bias is accounted for. The estimated number of missing studies is 11, i.e. 26 % of the filled sample. Correction for publication bias involves an even larger relative change for the combined elasticity estimates utilizing the temporal dimension. From column (3) we see that the combined elasticity estimate falls from 0.048 to 0.013 when publication bias is accounted for. The estimated number of missing studies is 15, i.e. 33 % of the filled sample. From column (2) we see that the combined elasticity estimates from studies utilizing the level dimension do not change at all that much, although the number of missing

⁹Testing the random effects model against the fixed effects model using the so-called Q-test presented in Shadish and Haddock (1994, p. 266), clearly rejects the fixed effects model in all three samples.

studies from this approach is 8, corresponding to 20 % of the filled sample. Correcting for publication bias reduces the combined elasticity estimate from 0.099 to 0.075. These findings are broadly consistent with the meta-regression results in Table 2, although we did not find significant publication bias in the level dimension-sample there.

Table 3: Combined estimates

	(1) Rate of return to R&D	(2) Elasticity of R&D Level Dimension	(3) Elasticity of R&D Temporal dimension
No correction for publication bias	0.182***	0.099***	0.048***
Correction for publication bias	0.138***	0.075***	0.013*
Original sample size	32	32	30
Filled sample size	43	40	45
Estimated no. of missing studies	11	8	15

*** is significant at the 1 % level, ** is significant at the 5 % level, * is significant at the 10 % level.

The estimates are calculated using the Stata-routine “metatrim” by Steichen (2001).

8 Concluding remarks

Publication bias has previously been detected in the literature on minimum wages by Card and Krueger (1995), in the returns to education literature by Ashenfelter, Harmon and Oosterbeek (1999) and in the literature on spillovers from multinational companies by Görg and Strobl (2001) to mention a few.¹⁰ The meta-analysis presented in this paper shows that publication bias is also present in the returns to R&D literature. Based on a sample of 32 results that directly estimate the gross private returns to R&D, we find a combined estimate of 18.2 % when publication bias is not accounted for. This is reduced to 13.8 % when we use the “trim and fill”-method to adjust for publication bias. The estimated number of missing studies is 11, i.e. 26 % of a hypothetical filled sample. In a sample of 30 studies estimating the elasticity of R&D using the temporal dimension of the data, i.e. accounting for firm fixed effects, we find evidence of even more severe publication bias, as the estimated number of missing studies represents 33 % of a hypothetically filled sample, and the combined elasticity estimate falls from 0.048 to 0.013. In a sample of 32 studies estimating the elasticity of R&D using the level dimension of the data,

¹⁰More examples can be found in Stanley and Doucouliagos (2010). Note that Card and Krueger’s (1995) conclusion was challenged by Neumark and Wascher (1998), but supported by an extended meta-analysis by Doucouliagos and Stanley (2009).

however, we find that publication bias is far less of a problem. Correcting for publication bias using the trim-and-fill method on this sample only reduces the combined elasticity estimate from 0.099 to 0.075, and the Egger test for funnel graph asymmetry shows no significant publication bias at all. When publication bias is less of a problem in studies utilizing the level dimension, it is probably because these studies do not account for firm fixed effects, and therefore are likely to be positively biased at the outset. This implies that they are likely to confirm prior beliefs in the profession concerning high, positive returns to R&D. The two specifications where publication bias is clearly present, on the other hand, control for firm fixed effects and are therefore likely to be negatively biased at the outset because of measurement errors in R&D. Resulting negative and small positive estimates are candidates to be rejected by the researchers themselves, or by referees and editors.

Our combined private returns to R&D estimate of 13.8 % seems implausibly low, as it represents a gross rate of return. R&D investments are believed to depreciate by at least 15 % per year from a private point of view. This suggests that further research on how to estimate the returns to R&D is required, either as refinements of the standard R&D capital framework or through more novel generalizations. This is in line with the final words of Hall et al. (2010) who conclude their extensive assessment of the literature by stating that “further work on the best way to model the R&D input would be extremely desirable.” The main challenges they identify is constructing an R&D capital measure and choosing the appropriate depreciation. They also find that the additive model is not a very good description of knowledge production.¹¹

¹¹A promising example of a study that aims to address these challenges is the structural framework presented in Doraszelski and Jaumandreu (2008).

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Appendix

Table A1. Estimates of the rate of return to R&D

Sample#	Study	Country	Time period	No. of firms	Return	St.dev
1	Bartelsman et al. (1996)	Netherlands	1985-1989	209	0.218	0.085
2	Bartelsman et al. (1996)	Netherlands	1989-1993	159	0.173	0.082
3	Cincera (1998)	World	1987-1994	625	0.38	0.060
3	Cincera (1998)	World	1989-1993	2445 (unbal.)	0.05	0.037
4	Clark & Griliches (1984)	USA	1971-1980	924	0.18	0.005
4	Clark & Griliches (1984)	USA	1971-1980	924	0.18	0.005
4	Clark & Griliches (1984)	USA	1971-1980	924	0.19	0.005
4	Clark & Griliches (1984)	USA	1971-1980	924	0.19	0.005
4	Clark & Griliches (1984)	USA	1971-1980	924	0.20	0.005
4	Clark & Griliches (1984)	USA	1971-1980	924	0.20	0.005
5	Fecher (1990)	Belgium	1981-1983	292	0.04	0.059
6	Goto & Suzuki (1989)	Japan	1976-1984	13	0.42	0.118
7	Goto & Suzuki (1989)	Japan	1976-1984	5	0.22	0.094
8	Goto & Suzuki (1989)	Japan	1976-1984	3	0.33	0.138
9	Griliches & Mairesse (1983)	USA, France	1973-1978	343+185	0.28	0.06
9	Griliches & Mairesse (1983)	USA, France	1973-1978	343+185	0.12	0.06
10	Griliches & Mairesse (1990)	Japan	1973-1980	406	0.56	0.23
10	Griliches & Mairesse (1990)	Japan	1973-1980	406	0.30	0.21
10	Griliches & Mairesse (1990)	Japan	1973-1980	406	0.20	0.21
11	Griliches & Mairesse (1990)	USA	1973-1980	525	0.41	0.09
11	Griliches & Mairesse (1990)	USA	1973-1980	525	0.27	0.10
11	Griliches & Mairesse (1990)	USA	1973-1980	525	0.25	0.10
12	Hall et al. (2009)	USA	1996-1999	1422	0.30	0.08
12	Hall et al. (2009)	USA	1996-1999	1422	0.21	0.07
12	Hall et al. (2009)	USA	1996-1999	1427	0.28	0.07
12	Hall et al. (2009)	USA	1996-1999	1427	0.23	0.08
13	Hall et al. (2009)	USA	2002-2005	1450	0.14	0.03
13	Hall et al. (2009)	USA	2002-2005	1450	0.16	0.04
13	Hall et al. (2009)	USA	2002-2005	1454	0.15	0.04
13	Hall et al. (2009)	USA	2002-2005	1454	0.17	0.05
14	Hall & Mairesse (1995)	France	1980-1987	197	0.231	0.053
14	Hall & Mairesse (1995)	France	1980-1987	197	0.273	0.059
14	Hall & Mairesse (1995)	France	1980-1987	197	0.036	0.053
14	Hall & Mairesse (1995)	France	1980-1987	197	0.065	0.060
15	Harhoff (1998)	Germany	1979-1989	443	0.22	0.04
16	Klette (1991)	Norway	1978-1985	200	0.106	0.026
16	Klette (1991)	Norway	1978-1985	200	0.108	0.026
16	Klette (1991)	Norway	1978-1985	200	0.108	0.026
16	Klette (1991)	Norway	1978-1985	200	0.108	0.026
17	Kwon & Inui (2003)	Japan	1995-1998	3830	0.163	0.041
18	Lichtenberg & Siegel (1991)	USA	1972-1985	5240	0.132	0.021
19	Link (1981)	USA	1971-1976	174	-0.00	0.03
20	Link (1983)	USA	1975-1979	302	0.06	0.04
21	Mansfield (1980)	USA	1960-1976	16	0.275	0.067
22	Medda et al. (2003)	Italy	1992-1994	1008	0.29	0.067
23	Medda et al. (2003)	Italy	1995-1997	689	0.364	0.084
24	Minasian (1962)	USA	1947-1957	18	0.25	0.04
25	Odagiri (1983)	Japan	1969-1981	123	0.256	0.096
26	Odagiri (1983)	Japan	1969-1981	247	-0.475	0.295
27	Odagiri & Iwata (1986)	Japan	1966-1973	135	0.201	0.109
27	Odagiri & Iwata (1986)	Japan	1966-1973	135	0.170	0.135
28	Odagiri & Iwata (1986)	Japan	1974-1982	135	0.169	0.059
28	Odagiri & Iwata (1986)	Japan	1974-1982	135	0.113	0.059

Table A1 (cont.): Estimates of the rate of return to R&D

Sample#	Study	Country	Time period	No. of firms	Return	St.dev
29	Rogers (2010)	UK	1989-2000	466	0.178	0.059
29	Rogers (2010)	UK	1989-2000	466	0.172	0.060
29	Rogers (2010)	UK	1989-2000	66	0.246	0.125
29	Rogers (2010)	UK	1989-2000	66	0.249	0.123
30	Rogers (2010)	UK	1989-2000	223	0.227	0.057
30	Rogers (2010)	UK	1989-2000	223	0.184	0.099
30	Rogers (2010)	UK	1989-2000	20	0.215	0.164
30	Rogers (2010)	UK	1989-2000	20	0.201	0.197
31	Sassenou (1988)	Japan	1973-1981	394	0.69	0.19
31	Sassenou (1988)	Japan	1973-1981	394	0.22	0.11
31	Sassenou (1988)	Japan	1973-1981	394	-0.02	0.07
32	Wakelin (2001)	UK	1988-1996	170	0.29	0.19

The rate of return estimates account for firm fixed effects, as it is based on a first difference specification, cf. equation (2).

Table A2. Estimates of elasticity of R&D, Level dimension

Sample#	Study	Country	Time period	No. of firms	Elasticity	St.dev
1	Bartelsman et al. (1996)	Netherlands	1985-1989	209	0.008	0.016
1	Bartelsman et al. (1996)	Netherlands	1985-1989	209	0.046	0.015
2	Bartelsman et al. (1996)	Netherlands	1989-1993	159	0.043	0.023
2	Bartelsman et al. (1996)	Netherlands	1989-1993	159	0.165	0.004
3	Bond et al. (2003)	Germany	1988-1996	234	0.079	0.042
4	Bond et al. (2003)	UK	1988-1996	239	0.065	0.024
5	Cincera (1998)	World	1987-1994	625	0.11	0.006
5	Cincera (1998)	World	1987-1994	625	0.19	0.008
5	Cincera (1998)	World	1987-1994	625	0.08	0.006
5	Cincera (1998)	World	1987-1990	625	0.09	0.009
5	Cincera (1998)	World	1991-1994	625	0.12	0.008
6	Crepon et al. (1998)	France	1990	6145	0.12	0.01
7	Cunéo & Mairesse (1984)	France	1972-1977	182	0.203	0.007
8	Griffith et al. (2006)	UK	1990-2000	188	0.03	0.01
9	Griliches (1980)	USA	1963	883	0.069	0.009
10	Griliches (1986)	USA	1972	491	0.115	0.018
10	Griliches (1986)	USA	1972	491	0.089	0.017
11	Griliches & Mairesse (1984)	USA	1966-1977	133	0.054	0.011
12	Hall (1993)	USA	1964-1970	1200	0.032	0.002
13	Hall & Mairesse (1995)	France	1980-1987	197	0.180	0.009
13	Hall & Mairesse (1995)	France	1980-1987	197	0.252	0.008
14	Harhoff (1998)	Germany	1979-1989	443	0.14	0.01
14	Harhoff (1998)	Germany	1979-1989	443	0.11	0.01
15	Kafouros (2005)	UK	1989-2002	78	0.04	0.01
16	Kwon & Inui (2003)	Japan	1995-1998	3830	0.10	0.002
16	Kwon & Inui (2003)	Japan	1995-1998	3830	0.13	0.002
17	Los & Verspagen (2000)	USA	1974-1993	485	0.014	0.006
18	Mairesse & Hall (1996)	USA	1981-1989	1073	0.035	0.005
18	Mairesse & Hall (1996)	USA	1981-1989	1073	0.246	0.012
19	Mairesse & Hall (1996)	France	1981-1989	1232	0.090	0.006
19	Mairesse & Hall (1996)	France	1981-1989	1232	0.093	0.006
19	Mairesse & Hall (1996)	France	1981-1989	1232	0.092	0.004
19	Mairesse & Hall (1996)	France	1981-1989	1232	0.165	0.004
20	Minasian (1962)	USA	1948-1957	17	0.113	0.015

Table A2 (cont): Estimates of elasticity of R&D, Level dimension

Sample#	Study	Country	Time period	No. of firms	Elasticity	St.dev
21	O'Mahony & Vecchi (2000)	Europe, USA	1988-1997	783	0.027	0.014
22	Ortega-Argiles et al. (2009)	EU	2000-2005	532	0.104	0.009
22	Ortega-Argiles et al. (2009)	EU	2000-2005	532	0.104	0.017
23	Rogers (2010)	UK	1989-2000	466	0.123	0.008
23	Rogers (2010)	UK	1989-2000	466	0.124	0.009
23	Rogers (2010)	UK	1989-2000	66	0.158	0.013
23	Rogers (2010)	UK	1989-2000	66	0.146	0.013
24	Rogers (2010)	UK	1989-2000	223	0.123	0.013
24	Rogers (2010)	UK	1989-2000	223	0.120	0.014
24	Rogers (2010)	UK	1989-2000	20	0.234	0.034
24	Rogers (2010)	UK	1989-2000	20	0.218	0.036
25	Sassenou (1988)	Japan	1976	394	0.10	0.01
25	Sassenou (1988)	Japan	1976	112	0.16	0.03
25	Sassenou (1988)	Japan	1976	112	0.07	0.02
26	Schankerman (1981)	USA	1963	110	0.104	0.036
26	Schankerman (1981)	USA	1963	110	0.159	0.035
27	Schankerman (1981)	USA	1963	187	0.018	0.022
27	Schankerman (1981)	USA	1963	187	0.099	0.021
28	Schankerman (1981)	USA	1963	101	0.034	0.020
28	Schankerman (1981)	USA	1963	101	0.232	0.029
29	Schankerman (1981)	USA	1963	34	0.069	0.047
29	Schankerman (1981)	USA	1963	34	0.090	0.046
30	Schankerman (1981)	USA	1963	31	0.032	0.033
30	Schankerman (1981)	USA	1963	31	0.292	0.048
31	Schankerman (1981)	USA	1963	41	0.043	0.011
31	Schankerman (1981)	USA	1963	419	0.065	0.011
32	Wang & Tsai (2003)	Taiwan	1994-2000	136	0.20	0.03

Elasticity estimates based on the level dimension include pooled OLS and do not account for firm fixed effects.

Table A3. Estimates of the elasticity of R&D, temporal dimension

Sample#	Study	Country	Time period	No. of firms	Elasticity	St.dev
1	Bartelsman et al. (1996)	Netherlands	1985-1989	209	0.247	0.083
2	Bartelsman et al. (1996)	Netherlands	1989-1993	159	0.185	0.080
3	Bond et al. (2003)	UK	1988-1996	239	-0.296	0.054
3	Bond et al. (2003)	UK	1988-1996	239	0.054	0.072
3	Bond et al. (2003)	UK	1988-1996	239	0.044	0.026
4	Bond et al. (2003)	Germany	1988-1996	234	0.054	0.029
4	Bond et al. (2003)	Germany	1988-1996	234	0.010	0.050
4	Bond et al. (2003)	Germany	1988-1996	234	-0.008	0.044
5	Capron & Cincera (1998)	World	1987-1994	625	0.32	0.04
5	Capron & Cincera (1998)	World	1987-1994	625	0.13	0.05
5	Cincera (1998)	World	1987-1994	625	0.10	0.006
5	Cincera (1998)	World	1987-1994	625	0.33	0.042
5	Cincera (1998)	World	1987-1994	625	0.21	0.094
5	Cincera (1998)	World	1987-1994	625	0.24	0.041
5	Cincera (1998)	World	1987-1990	625	0.38	0.069
5	Cincera (1998)	World	1987-1990	625	0.29	0.069
5	Cincera (1998)	World	1991-1994	625	0.26	0.046
5	Cincera (1998)	World	1991-1994	625	0.24	0.054

Table A3 (continued): Estimates of the elasticity of R&D, temporal dimension

Sample#	Study	Country	Time period	No. of firms	Elasticity	St.dev
5	Cincera (1998)	World	1980-1994	2445 (unbal.)	0.28	0.022
5	Cincera (1998)	World	1980-1994	2445 (unbal.)	0.21	0.010
6	Cunéo & Mairesse (1984)	France	1972-1977	182	0.050	0.039
7	Doraszelski & Jaumandreu (2008)	Spain	1991-1999	289	0.003	0.005
7	Doraszelski & Jaumandreu (2008)	Spain	1991-1999	289	0.025	0.016
8	Doraszelski & Jaumandreu (2008)	Spain	1991-1999	140	0.013	0.006
8	Doraszelski & Jaumandreu (2008)	Spain	1991-1999	140	0.046	0.016
9	Doraszelski & Jaumandreu (2008)	Spain	1991-1999	275	0.018	0.004
9	Doraszelski & Jaumandreu (2008)	Spain	1991-1999	275	0.075	0.011
10	Doraszelski & Jaumandreu (2008)	Spain	1991-1999	132	-0.003	0.008
10	Doraszelski & Jaumandreu (2008)	Spain	1991-1999	132	0.025	0.005
11	Doraszelski & Jaumandreu (2008)	Spain	1991-1999	148	0.009	0.005
11	Doraszelski & Jaumandreu (2008)	Spain	1991-1999	148	0.017	0.017
12	Doraszelski & Jaumandreu (2008)	Spain	1991-1999	304	0.002	0.006
12	Doraszelski & Jaumandreu (2008)	Spain	1991-1999	304	0.046	0.012
13	Doraszelski & Jaumandreu (2008)	Spain	1991-1999	293	0.011	0.008
13	Doraszelski & Jaumandreu (2008)	Spain	1991-1999	293	0.018	0.018
14	Doraszelski & Jaumandreu (2008)	Spain	1991-1999	138	0.018	0.011
14	Doraszelski & Jaumandreu (2008)	Spain	1991-1999	138	0.074	0.030
15	Doraszelski & Jaumandreu (2008)	Spain	1991-1999	160	0.013	0.009
15	Doraszelski & Jaumandreu (2008)	Spain	1991-1999	160	0.041	0.028
16	Griffith et al. (2006)	UK	1990-2000	188	0.024	0.011
17	Griliches (1980)	USA	1957-1965	883	0.076	0.013
18	Griliches & Mairesse (1983)	USA, Japan	1973-1978	343+185	0.02	0.03
19	Griliches & Mairesse (1984)	USA	1966-1977	182	0.091	0.022
20	Hall (1993)	USA	1964-1970	1200	0.06	0.04
21	Hall & Mairesse (1995)	France	1980-1987	197	-0.001	0.036
21	Hall & Mairesse (1995)	France	1980-1987	197	0.069	0.035
22	Harhoff (1998)	Germany	1981-1989	443	0.09	0.02
22	Harhoff (1998)	Germany	1981-1989	443	0.07	0.02
22	Harhoff (1998)	Germany	1981-1989	443	0.1	0.03
23	Kwon & Inui (2003)	Japan	1995-1998	3830	0.084	0.008
23	Kwon & Inui (2003)	Japan	1995-1998	3830	0.087	0.008
23	Kwon & Inui (2003)	Japan	1995-1998	3830	0.149	0.014
23	Kwon & Inui (2003)	Japan	1995-1998	3830	0.147	0.014
23	Kwon & Inui (2003)	Japan	1995-1998	3830	0.053	0.014
23	Kwon & Inui (2003)	Japan	1995-1998	3830	0.052	0.014
24	Los & Verspagen (2000)	USA	1974-1993	485	0.017	0.004
25	Mairesse & Cunéo (1985)	Japan	1974-1979	390	0.21	0.10
26	Mairesse & Hall (1996)	France	1981-1989	1232	-0.003	0.003
26	Mairesse & Hall (1996)	France	1981-1989	1232	-0.003	0.003
26	Mairesse & Hall (1996)	France	1981-1989	1232	-0.005	0.003
26	Mairesse & Hall (1996)	France	1981-1989	1232	0.008	0.011
26	Mairesse & Hall (1996)	France	1981-1989	1232	0.013	0.011
26	Mairesse & Hall (1996)	France	1981-1989	1232	-0.016	0.013
27	Mairesse & Hall (1996)	USA	1981-1989	1073	0.010	0.024
27	Mairesse & Hall (1996)	USA	1981-1989	1073	0.092	0.026
27	Mairesse & Hall (1996)	USA	1981-1989	1073	0.041	0.011
27	Mairesse & Hall (1996)	USA	1981-1989	1073	0.170	0.014
28	Minasian (1962)	USA	1948-1957	17	0.084	0.068
29	O'Mahony & Vecchi (2000)	Europe, USA	1988-1997	783	0.328	0.050
30	Sassenou (1988)	Japan	1973-1981	394	0.04	0.04
30	Sassenou (1988)	Japan	1973-1981	394	-0.01	0.01

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We conduct a meta-analysis of the private returns to R&D literature and find that 26 % of the results in a hypothetical complete literature are missing. The combined estimate for the marginal returns to R&D falls from 18.2 % to 13.8 % when publication bias is accounted for. The latter estimate is very low, as it is gross of depreciation. One interpretation is that publication bias has contributed to masking the need for a revision of the standard R&D capital model.



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**SAMFUNNS - OG
NÆRINGS- OG
LIVSFORSKNING AS**

*Institute for Research in Economics
and Business Administration*

Breviksvæien 40
N-5045 Bergen
Norway
Phone: (+47) 55 95 95 00
Fax: (+47) 55 95 94 39
E-mail: publikasjon@snf.no
Internet: <http://www.snf.no/>

Trykk: Allkopi Bergen