The Impact of Innovation in the Multinational Firm*

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Abstract

What is the private return to innovation? When firms operate production sites in multiple countries, improvements developed at one site may be shared across others for efficiency gain. We develop a dynamic model that accounts for such transfer within the firm, and apply it to measure innovation returns for a comprehensive panel of U.S. multinationals during 1989–2008. We find that the data, which include detailed measures of affiliate-level production and innovation, are consistent with innovation generating returns at firm locations beyond the innovating site. Accounting for cross-plant effects of innovation, our estimates indicate the average firm realizes up to one third of the return to its U.S. parent R&D abroad, suggesting estimates based only on domestic operations may understate firms' gain from innovation.

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1 Introduction

Multinational firms account for the substantial majority of innovation investment in the United States.[1] Moreover, as intrinsically multiplant firms, multinationals may share proprietary technology resulting from innovation investment across multiple firm sites.[2] The extent to which such transmission of technology occurs within the firm—though an essential determinant of both the private return to R&D investment and the welfare effects of multinational production (MP)—is not known, however, as site-specific innovation investment within the boundaries of the firm is rarely observed.

Consider firms in the hard-disk drive industry, for example. Offshore affiliates in this industry perform process innovation to improve efficiency, but are also influenced by innovation performed by the parent. First, parent innovation impacts the quality of an intermediate input that is manufactured by the parent but processed and assembled by affiliates;[3] high levels of parent innovation reduce the rate of input failure, saving affiliates associated loss. Second, parent innovation impacts affiliate productivity through product and process design, as well as through assistance diagnosing and addressing process challenges.[4] Although such within-firm knowledge transfer is an important feature of the multinational firm (e.g. Dunning 1981, Helpman 1984), the actual extent to which innovation investment by a firm in one country impacts its performance at sites abroad is, as an empirical matter, less clear.

This paper uses information on both parent and affiliate-level innovation and production to quantify the impact of innovation within the multinational firm. We develop a dynamic model of firm innovation that accounts for the possibility of intrafirm knowledge transfer across production sites. The model provides a detailed empirical framework that we apply to estimate the private return to innovation investment among U.S.-based multinationals during 1989–2008. We find that the data are consistent with innovation generating returns at firm locations beyond the innovating site within five major manufacturing industries. Specifically, accounting for cross-plant effects of innovation, our estimates indicate that the average multinational firm realizes up to one third of the return to U.S. parent R&D abroad.

In the model, the multinational firm makes a series of optimal production and innovation decisions for each production site based on the costs and expected gains from each activity. The firm determines both location-specific innovation and physical capital investments, as well as subsequent levels of static inputs including labor and materials to be used in production at each site. As in Aw, Roberts, and Xu (2011) and Doraszelski and Jaumandreu

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[1] In 2010, for example, multinational firms' U.S. R&D expenditures accounted for almost all U.S. business R&D and nearly two-thirds of total U.S. R&D expenditures (National Science Board, 2014).

[2] Caves (2007).

[3] Based on firm-specific annual SEC 10-K reports and conversations with a former employee of the hard-disk drive firm Western Digital.

[4] For further details on the industry and its production structure, see Igami (2014) and references therein.

(2013), we assume site-level productivity follows a Markov process that can be shifted by R&D expenditures. Importantly, however, in our model innovation at one site may impact other sites within the same firm, and the impact of innovation on an affiliate may differ depending on whether R&D investment is made by the affiliate, its U.S. parent, or another affiliate within the same firm. We further allow differences between parent and affiliate production and productivity evolution, capturing the possibility that parents and affiliates perform distinct production tasks within the multinational firm, and provide for unobserved, systematic differences in affiliate productivity change across locations and over time.

The model yields general expressions for the firm's optimal input and investment decisions at each production location. Specifically, given an affiliate's current value-added productivity, capital stock, local input prices and aggregate demand conditions, the firm's input and investment decisions solve optimality conditions derived from a standard Bellman equation. We use these optimality conditions directly to estimate parameters of the affiliate production function corresponding to static labor inputs (Gandhi, Navarro, and Rivers 2013). However, to maintain flexibility regarding unknown cost functions for investment in physical capital and in knowledge through R&D, which may differ substantially across countries and the estimation of which is beyond the scope of this paper, we follow Doraszelski and Jaumandreu (2013) by taking an approach for which the precise form of these cost functions is not required.

To recover production and technology parameters determining the firm-wide return to innovation with the estimation strategy implied by our model, we use comprehensive panel data on U.S. multinationals' global activity from the Bureau of Economic Analysis (BEA). Our data include detailed measures of production inputs, output, investment, and innovation expenditures for each firm-country pair during the period 1989–2008, and span multiple industries of which we focus our attention on five prominent manufacturing sectors.[5] Importantly, the data include detailed measures of technological links in both trade and knowledge between U.S. parent firms and each foreign affiliate, enabling our analysis to incorporate an unusually detailed characterization of the firm network. To better isolate the impact of parent and affiliate innovation on productivity, we also introduce data on U.S. state-year level R&D tax credits from Wilson (2009) and intellectual property rights from Ginarte and Park (1997) and Park (2008) as sources of exogenous variation in U.S. R&D expenditures across parent firms located in different U.S. states and in affiliate R&D expenditures across affiliates located in countries with different levels of knowledge appropriability.

These data reveal facts about firms' organization of innovation activity across locations, which is rarely observable. First, for each of the industries we evaluate, almost all (90 percent) multinational firms invest in R&D, and over 99 percent of multinational firms

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[5] The five industries we analyze are Industrial Machinery (SIC 35), Electronic and Other Electrical Equipment (SIC 36), Measuring and Analyzing Instruments (SIC 38), Chemicals and Allied Products (SIC 28), and Transportation Equipment (SIC 37).

investing in R&D do so in part at U.S. parent site. Second, foreign affiliates participate in innovation investment in approximately half of firms, indicating that for a large share of firms, knowledge creation is an international endeavor. However, third, the average multinational firm reports R&D participation by only the minority of its foreign affiliates. And fourth, the R&D intensity of the average U.S. parent operation is three to eight times higher than that of its overall, combined foreign-affiliate operations. That firms fragment innovation across countries to any extent suggests the presence of frictions limiting the communication of technical knowledge across countries (e.g. Arrow 1962, 1969); yet, the fact that the spatial concentration of innovation investment is higher than that of production is consistent with the idea that knowledge is shared across firm locations (Arrow 1975, Teece 1982), as is recent evidence in Atalay, Hortacsu, and Syverson (2014) as well as our estimation results.

Specifically, our empirical analysis indicates R&D investment significantly impacts firm productivity dynamics within U.S. multinationals. Innovation by a U.S. parent has a positive and highly significant impact both on its own productivity and on that of its foreign affiliates. By contrast, innovation by an affiliate has a positive impact on its own productivity, but does not significantly impact other production sites within the firm.

Accounting for both considerations, our estimates reveal that the short-run elasticity of affiliate productivity with respect to a one-year increase in the R&D investment of its U.S. parent ranges between 0.009 and 0.012 percent on average; these effects are compounded by productivity persistence, and imply long-run elasticities of between 0.025 and 0.079 percent. While the short-run elasticities of parent productivity with respect to parent R&D are comparable, the long-run elasticities are larger, ranging between 0.080 and 0.140 percent, due to parents higher estimated productivity persistence. Thus, if parent R&D were the only source of productivity improvement, our estimates would imply parents are significantly more productive than affiliates in the long run, consistent with Tintelnot (2014) and Head and Mayer (2015). We find qualitatively identical results even after instrumenting for both parent and affiliate R&D investment using variation in R&D tax credits across U.S. states and in intellectual property rights across countries.

To measure the firm-level R&D investment return implied by these elasiticities, we proceed by first translating the elasticities described above into derivatives capturing the impact of R&D investment on value added in levels, thereby retrieving estimated local returns (e.g. Hall, Mairesse, and Mohnen 2010, Doraszelski and Jaumandreu 2013). Summing these marginal returns across locations yields a firm-level return to R&D investment; notice that by considering infinitesimal increases in R&D investment, this calculation implicitly holds fixed the capital and input structure of the multinational firm. For the average firm, the estimated short-run, firm-wide return to parent R&D depends on the industry and ranges between 30 and 75 percent and are high relative to estimates surveyed in Hall, Mairesse, and Mohnen (2010); long-run return values are higher and imply returns net of expenditures ranging between 60 and 250 percent.

Relative to the parent-level return to its own R&D investment, these estimates indicate that for the average firm, between 15 and 35 percent of innovation gains are realized among affiliates abroad. This estimated impact share spans a distribution across firms that is influenced by the size of the parent and its foreign affiliates, the number of affiliates, and the R&D participation of each parent firm. Intuitively, returns to parent R&D realized abroad are smaller for multinationals with limited foreign operations. By contrast, our estimates imply that evaluating the impact of parent R&D based only on firms' U.S. operations substantially understates the innovation return for most firms.

This paper contributes to a growing literature investigating the importance of technology within the multinational firm. Our results are consistent with insights formalized in Helpman (1984), as well as recent empirical evidence consistent with centrally-developed technology impacting the distribution of multinational production across countries (Arkolakis et al 2013; Irrazabal, Moxnes, and Opromolla 2013; Keller and Yeaple 2013).[6] In particular, our estimates complement Arkolakis et al (2013), which demonstrates that the relationship between parent and affiliate productivity with firms conditions the equilibrium gains from multinational production in the global economy. The productivity estimates we develop indicate that this relationship is influenced directly by a dynamic process featuring innovation investment and subsequent intrafirm knowledge transfer.

The model and estimation methods applied in this paper are also related to prior empirical studies evaluating the link between innovation and productivity at the plant level. We estimate a dynamic model of endogenous R&D investment and our model is therefore related to Doraszelski and Jaumandreu (2013), Aw, Roberts, and Xu (2011) and Boler, Moxnes, and Ulltveit-Moe (2014). Like these papers, we build directly on insights in Griliches (1979), but focus on R&D expenditures as a proxy for the state of knowledge rather than attempting to construct a stock of knowledge capital from the available data. Our model is distinct from Doraszelski and Jaumandreu (2013), however, and is conceptually closer to Adams and Jaffe (1996), in that it considers the productivity consequences of R&D investment within a multiplant firm, in which productivity gains from the innovation investment of one plant may be realized across multiple production locations within the same firm.

The estimates we recover regarding the impact of innovation across multiple sites support models of the multinational firm featuring operations linked by intangible transfers, and thus complement results in Atalay, Hortacsu, and Syverson (2014), which finds little trade in physical inputs between vertically-linked manufacturing plants. Moreover, in finding a

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[6] See also Javorcik 2004; Branstetter 2006; Branstetter, Fisman, and Foley 2006; McGrattan and Prescott 2010; Branstetter et al 2011; and Bilir 2014.

positive estimated impact of U.S. parent R&D on foreign-affiliate productivity growth within the same firm, our results also contribute to research aimed at evaluating why affiliates of multinational firms are more productive and faster growing than unaffiliated firms (Doms and Jensen 1998, Ramondo 2009, Guadalupe, Kozmina, and Thomas 2012, Branstetter and Drev 2014, National Science Board 2014). Specifically, our estimates suggest affiliates' productivity and growth premium may be related, in part, to innovation investment by parent firms and the positive impact of the resulting knowledge on foreign-affiliate performance.

This latter observation implies a connection between our results and research evaluating technology diffusion across countries. In addition to complementing empirical studies in which multinational firms direct technology and ideas across countries (Branstter, Fisman, and Foley 2006, Branstter 2006), our estimation methodology is related to a wide literature aimed at evaluating the magnitude of productivity spillovers between firms and countries (Jaffe 1986, Bloom et al 2013). However, our emphasis on technological links between affiliates of the same multinational firm, and our results indicating such links between parent and affiliate are economically significant, suggests building active agents and directed technology diffusion into models of international idea diffusion and growth (e.g. Eaton and Kortum 1996, 1999, Buera and Oberfield 2015) may yield important insights regarding the determinants of economic development, productivity growth, and technological change across countries.[7]

The rest of the paper presents our theoretical and empirical analysis. We describe the data in Section 2, and develop a model of production and innovation investment within the multinational firm in Section 3. Section 4 derives our estimation framework from the model and describes how we apply it to evaluate the data. Sections 5 and 6 describe the empirical results, and Section 7 concludes.

2 Data and Descriptive Statistics

Evaluating the link between innovation and productivity change in multinational firms requires measures of production inputs, output, and innovation for each location within the firm at different points in time. These data are described below.

2.1 U.S. Multinational Activity

We use confidential firm-level data on the operations of multinational firms from the Bureau of Economic Analysis (BEA) Survey of U.S. Direct Investment Abroad. These data provide

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[7] Our focus on R&D investment and productivity change within large firms also connects our work with research on innovation, firm size, and industry dynamics (Nelson et al. 1967, Nordhaus 1969, Scherer 1970, Lunn 1982, Klepper and Graddy 1990, Cohen and Klepper 1992, 1996a,b, Klepper 1996, Klette and Kortum 2004), building on Schumpeter (1942).

detailed information on U.S. parent companies and each foreign affiliate on an annual basis.[8] For our analysis, we assemble a new dataset combining both benchmark and annual surveys covering firm operations in 84 countries for each year during 1989–2008.[9] An important feature of the data for our analysis is its detailed information on production and innovation, including parent and affiliate-level R&D expenditures in each firm and year.[10]

Because evaluating the impact of innovation on productivity requires estimating production functions, our empirical analysis proceeds at the industry level. We examine the activity of multinational firms separately in each of five major manufacturing industries: industrial machinery [SIC 35] including separately the computer and disk-drive industry [SIC 357], electronics [SIC 36], instruments and devices [SIC 38], chemicals [SIC 28], and transportation equipment [SIC 37]. Each multinational firm is categorized based on the primary industry classification of its U.S. parent. Even within the same firm and industry, productive tasks performed by foreign affiliates may differ from tasks performed by U.S. parent firms (Oldenski 2012); in our estimation below we therefore follow an approach that allows for such differences between parent and affiliate operations.[11]

The data include detailed affiliate-level information regarding production inputs, outputs, investment, innovation, trade within and outside the firm, and information regarding royalty payments and licensing fees; however, the data do not include a direct measure of material inputs. Table 1 provides a summary of value added, employment, physical capital, and innovation across the sample of firms, affiliates, countries, and industries used in our analysis.

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[8] This survey is conducted by BEA for the purpose of producing publicly available aggregate statistics on the operations of U.S. multinational enterprises. Any U.S. person having direct or indirect ownership or control of 10 percent or more of the voting securities of an incorporated foreign business enterprise or an equivalent interest in an unincorporated foreign business enterprise at any time during the survey fiscal year in question is considered to have a foreign affiliate. However, for small affiliates that do not own another affiliate, parents report only a subset of items requested by the standard survey form. Foreign affiliates are required to report separately unless they are in the same firm, country, and three-digit industry. Each affiliate is considered to be incorporated where its physical assets are located.

[9] In benchmark years 1989, 1994, 1999, and 2004, the BEA's data coverage is nearly complete: in a typical benchmark year, the survey accounts for over 99 percent of affiliate activity. In 1994, for example, participating affiliates accounted for an estimated 99.8 percent of total assets, 99.7 percent of total sales, and 99.9 percent of total U.S. FDI. This reflects the requirement of participation for every U.S. person having a foreign affiliate. Reporting requirements for the annual survey are less restrictive. In certain cases involving missing survey responses, the BEA data may instead report imputed values; these values are coded accordingly, and we exclude from our analysis all such observations. See Appendix A.5 for further details.

[10] R&D expenditure is not recorded for firms' smallest, minority-owned foreign affiliates. Because our estimation below involves evaluating the impact of an affiliates' own R&D on productivity change, in our baseline setting we restrict attention to majority-owned affiliates required to report R&D (Appendix A.5).

[11] At the affiliate level, in all specifications, we exclude from the sample imputed values and small or minority-owned affiliates for which only limited information is reported. We also exclude non-manufacturing affiliates in agriculture, mining, construction, transportation and public utilities, finance, insurance, and real estate, services, and health services for which the mechanism linking R&D investment and plant productivity is unclear. Additional details appear in Appendix A.5.

Measuring Firm Innovation at the Affiliate Level

We report statistics describing innovation expenditures within and across U.S. multinational firms in Tables 2 and 3.[12] Our primary measure of parent and affiliate innovation is R&D investment, which is defined broadly by the survey, including expenditures on basic, applied, product, and process R&D; the measure excludes capital expenditures, routine testing and quality control, market research, and legal patent work, however, and is thus essentially a measure of expenditures on labor and materials used in innovation. While this rules out a model that explicitly distinguishes the efficiency impact of product innovation from that of process innovation as in Cohen and Klepper (1996b) and Dhingra (2013), we will adopt a model and estimation framework able to accommodate symmetrically both forms of innovation in sections 3 and 4 below.

It is important to note that, although the firm must report any research and development activity performed by each affiliate, this leaves open the possibility that an affiliate either a) performs R&D paid for by another firm or affiliate, or b) performs and pays for R&D that is nevertheless done primarily on behalf of another firm or affiliate. Data from the benchmark-year surveys indicate neither a) nor b) is commonly observed. In 2004, for example, 96 percent of the R&D performed by affiliates was also paid for by the performing affiliate. Of the R&D performed by affiliates, 83 percent was for the performing affiliate's own account, 14 percent was for another affiliate of the same firm, and only 3 percent was for an unaffiliated firm (U.S. Bureau of Economic Analysis 2008). Accordingly, the model in section 3 below considers the case in which each affiliate location in a firm performs and pays for its own R&D, while the technological knowledge resulting from R&D may be shared across locations in the same firm.

2.2 Patterns of Innovation Within the Firm

Several strong patterns emerge from descriptive observation of the data corresponding to each industry. It is clear from Table 2 that almost all multinational firms invest in R&D, and also that nearly all firms' innovation investment involves expenditures by the U.S. parent operation. In the industrial machinery sector, for example, 90 percent of firms invest in innovation, and of these firms, over 99 percent innovate with the involvement of the U.S. parent (Table 2, column 1). However, foreign affiliates participate in innovation investment in only approximately half of firms; in the industrial machinery sector, 45 percent of firms report R&D investment by at least one foreign affiliate. Third, the average multinational firm

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[12] These statistics pertain to U.S. firms and their foreign affiliate operations in 1994. The 1994 benchmark-year survey is exceptionally comprehensive in its innovation measures, with all U.S. parent firms reporting R&D regardless of size, and all foreign affiliates above a low size threshold of $3 million reporting R&D; this period therefore provides an unusually complete representation of activity corresponding to the universe of U.S.-based multinational firms in 1994.

reports R&D participation by only the minority of its foreign affiliates, with, for example, just 24 percent of affiliates in industrial machinery performing R&D. Accordingly, the R&D intensity (R&D/sales ratio) for the average U.S. parent operation is higher than that of its overall foreign-affiliate operations; in industrial machinery, the parent is on average 8.4 times as R&D intensive as foreign affiliates. This indicates innovation activity is substantially less dispersed across locations than production in multinational firms, with parents investing disproportionately in R&D.

Firms' offshore R&D performance does, however, vary substantially across firms. On average, Table 3 indicates a firm's foreign affiliates account for between 10 and 13 percent of its global R&D expenditures, but the standard deviation ranges between 19 and 21 percentage points, and the shape of the distribution is such that the 95th percentile firm locates the majority of its global R&D investment within offshore affiliates.

That firms fragment innovation across countries to any extent suggests the presence of frictions limiting the communication of technical knowledge across countries (e.g. Arrow 1962, 1969), however, the sharp differences between observed parent and affiliate R&D participation and the high degree of R&D concentration relative to production concentration is consistent with classic theories of the multinational firm featuring both concentrated knowledge production and intrafirm technology transfer (Helpman 1984). Data on intrafirm royalty and license payments also strongly suggest parent firms share technology extensively with foreign affiliates, while affiliates share relatively less with parents: among manufacturing firms in 2004, aggregate royalty and license fees for the use of intangible intellectual property paid by foreign affiliates to U.S. parents within multinationals were approximately 15 times higher than payments in the reverse direction (U.S. Bureau of Economic Analysis 2008).

Statistics reported in Table 3 further indicate U.S. multinationals concentrate a large share of foreign production and innovation in a relatively narrow set of countries. The United Kingdom and Mexico are among the top five locations for U.S. firms' employment abroad in each of the industries considered here, followed closely by Canada and Germany; Brazil, France, Japan, and Malaysia also account for a large share of firms' offshore employment. Germany and France are the most important offshore R&D locations for U.S.-based firms, followed by the United Kingdom, Canada, and Japan; Belgium, Brazil, Ireland, and Singapore are also within the top-five R&D locations for at least one industry.[13] This under-

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[13] A U.S. multinational's decision to perform R&D in a foreign country may be influenced by investment conditions abroad including the corporate tax rate and opportunities for R&D tax incentives (see, for example, Hines 1994, 1995). In the data, we find a low correlation of between -2 and 2 percent across FDI host countries between affiliate R&D investment and the corporate tax rate incidence; nevertheless, our estimation framework below includes two sets each of country-by-year and sector-by-year fixed effects, one corresponding to affiliates with positive R&D expenditures and the other corresponding to non-innovating affiliates. These effects capture any unobserved factors that differ across locations—including corporate tax

lying distribution of activity across countries is an important determinant of the distribution of within-firm gains from U.S.-parent R&D investment (section 6).

3 Theory

We develop an empirical model of endogenous R&D investment in multinational firms. The model provides estimating equations that enable us to use the data described in Section 2 above to estimate technology parameters determining both the affiliate-level and firm-wide returns to innovation reported in Sections 5 and 6 below.

3.1 Setup

A multinational firm is composed of a parent and one or more affiliates located in other countries. In our model, all multinational firm parents are located in a single country of origin h and belong to the same industry s.[14] We define the set of h-based multinational firms in period t by $I(t) = \{1, \ldots, I_t\}$, and the set of firm-$i$ affiliates by $J(i,t) = \{0, \ldots, J_{it}\}$ in period t. We use the sub-index i for multinational firms, $j = 0$ to denote the parent in country h, and $j > 0$ to denote affiliates located outside h; these affiliates may potentially operate in sectors other than s.

Each multinational firm i makes parent- and affiliate-specific investment decisions in physical capital, and in knowledge through R&D investment. Firm i also determines the amount of labor and materials to be used for production at each site. We assume these investment and input choices are made in discrete time with the goal of maximizing the firm-wide expected net present value of future cash flows.

To capture possible differences between parent and affiliate operations, in what follows we allow all structural parameters to differ between the parent and its affiliates abroad. This is consistent with models of the multinational firm in which parents and affiliates perform distinct production tasks (e.g. Helpman 1984). We assume that all foreign affiliates in a firm share identical structural parameters, but allow the relevant input prices and demand conditions these affiliates face to differ across affiliates depending on the country in which they are located and the sector in which they operate.

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rates and policy incentives—that may influence the productivity evolution of affiliates independently of the R&D decision.

[14] In the estimation, an industry is defined at either the two-digit or three-digit SIC level.

3.2 Production

In period t, firm i's affiliate j combines inputs to create output Q_{jt} according to the following production technology[15]

$$Q_{jt} = \mathcal{H}(L_{jt}, K_{jt}; \alpha^H)^{1-\alpha_m} M_{jt}^{\alpha_m} \, \Omega_{jt}, \tag{1}$$

where

$$\mathcal{H}(L_{jt}, K_{jt}) = \exp[h(l_{jt}, k_{jt}; \alpha^H)], \tag{2a}$$

$$h(l_{jt}, k_{jt}; \alpha^H) = \alpha_l l_{jt} + \alpha_k k_{jt} + \alpha_{ll} l_{jt}^2 + \alpha_{kk} k_{jt}^2 + \alpha_{lk} l_{jt} k_{jt}, \tag{2b}$$

and where $\alpha^H = (\alpha_l, \alpha_k, \alpha_{ll}, \alpha_{kk}, \alpha_{lk})$ and $\alpha = (\alpha^H, \alpha_m)$. In equation (1) above, Q_{ijt} is total output, L_{ijt} is the number of workers, K_{ijt} is effective units of capital, M_{ijt} is materials, and Ω_{ijt} denotes the physical productivity of firm i's affiliate j during period t.[16] An advantage of the translog production function $\mathcal{H}$ specified above is its flexibility: output elasticities may vary across sites and over time within a firm, even under identical production coefficients α^H. This flexibility is important in our setting because the affiliates of a given multinational may operate across countries with different factor-market conditions, and may thus differ in the optimal relative usage of labor and capital in production.[17] We assume parent and affiliates take input prices for labor P^l_{ijt}, capital P^k_{ijt}, and materials P^m_{nt} as given. However, these prices may differ across affiliates and time periods t.

3.3 Demand

Each affiliate j produces a single variety; we therefore use the index j to identify both an affiliate and the variety it produces.[18] Firm i's affiliate j faces the following demand function at period t

$$q_{jt} = q_{nt} - \sigma p_{jt} + \sigma p_{nt} + (\sigma - 1)\xi_{jt}, \tag{3}$$

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[15] To keep the notation simple below, we omit the firm index i and use lower-case letters to denote the logarithm of the corresponding upper-case variable.

[16] We assume the production function of the parent firm has the same functional form as that of its affiliates but allow the parameter vector α to differ.

[17] The assumption that the elasticity of substitution between materials and the joint output of labor and capital is equal to one is driven by data availability. Because affiliate materials use is not observed in the data, we cannot identify the parameters of a production function that is translog in labor, capital and materials.

[18] Within firm i, different affiliates may produce different goods or different varieties of the same good, allowing the model to capture the possibility that multinationals may also be multiproduct firms.

where $\sigma > 1$ is the elasticity of substitution across varieties, n is the market in which affiliate j is located, p_{jt} is the log output price set by affiliate j of firm i at t, and ξ_{jt} is a demand shock (or quality shock) that is unobserved to the econometrician but known to the firm when making its input and output choices at period t. Market-level variables p_{nt} and q_{nt} denote the log of the price index and total demand for firms operating in market n.[19] Notice that affiliates need not sell all output to the local domestic market; instead, affiliates located in the country-sector market n are assumed to face the same aggregate price and quantity indices.[20] We assume U.S. parent firms also face a demand function of the form in equation (3) above, allowing for differences in the demand elasticity σ and in market-level indices p_{ht} and q_{ht}.

3.4 Revenue and Value Added

We use $Y_{jt} = P_{jt}Q_{jt}$ to denote the total revenue of affiliate j during period t. Given the production and demand functions described in Sections 3.2 and 3.3 above, the revenue function for firm i's affiliate j is

$$y_{jt} = p_{nt} + q_{nt}/\sigma + \frac{\sigma - 1}{\sigma}\,[(1 - \alpha_m)h(l_{jt}, k_{jt}; \alpha^H) + \alpha_m m_{jt} + \psi_{jt}],$$

where ψ_{jt} is the sum of affiliate j's physical productivity level and its demand shock: $\psi_{jt} \equiv \omega_{jt} + \xi_{jt}$. As described in Section 2, we do not directly observe usage of material inputs by either parent or affiliates in the data. However, assuming firms take the prices of material inputs as given and optimally determine the amount of materials used in production by each affiliate j in period t by maximizing the static profits of j at t, we can rewrite y_{jt} as

$$y_{jt} = \kappa^1_{nt} + h(l_{jt}, k_{jt}; \beta) + \kappa^2 \psi_{jt}, \tag{4}$$

where κ^1_{nt} is a function of the parameters α_m and σ, the price of materials, the output price, and total expenditure in market n at period t. In addition, $\beta = \alpha^H \kappa_2(1 - \alpha_m)$, and[21]

$$\kappa^2 = \frac{(\sigma - 1)}{\sigma - \alpha_m(\sigma - 1)}.$$

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[19] In the empirical analysis below, we define the market n of an affiliate j as the intersection of the country and the three-digit SIC sector in which affiliate j operates.

[20] Reliable data on aggregate consumption and average prices by country-sector for the large set of countries and years in our dataset is not available. Our empirical analysis therefore considers p_{nt} and q_{nt} as variables observed by the firm but not by the econometrician.

[21] Given that $\sigma > 1$ and $0 < \alpha_m < 1$, $0 < \kappa_2(1 - \alpha_m) < 1$ and, therefore, the parameters of the revenue function, β, are always smaller in absolute value that the parameters of the production function α.

The term $\kappa^2\psi_{jt}$ denotes affiliate j's period-t revenue productivity. Similarly, defining the log of the value added function as $va_{jt} = y_{jt} - p^m_{jt} - m^*_{jt}$, where m^*_{jt} denotes the optimal consumption of materials, we derive an expression for affiliate-level value added va_{jt} as

$$va_{jt} = \kappa^3_{nt} + h(l_{jt}, k_{jt}; \beta) + \kappa^2\psi_{jt}, \tag{5}$$

where κ^3_{nt} is defined in Appendix A.1.[22]

As we show in Section 6 below, in order to compute the return to R&D investment, it is enough to know the revenue function parameter vector β. It is not necessary to know the production function parameters α. As is immediate from equations (4) and (5), we may use information on value added, together with information on labor and capital usage, to identify β.

3.5 The Productivity Process

The value-added productivity ψ_{jt} of firm i's affiliate j is assumed to evolve over time according to the following stochastic process

$$\psi_{jt} = \psi^e_{jt-1} + \eta_{jt}, \tag{6}$$

with

$$\psi^e_{jt-1} = (1 - d_{jt-1})(\mu_{1nt} + \rho_1\psi_{jt-1}) + d_{jt-1}(\mu_{2nt} + \rho_2\psi_{jt-1}) + g(\mathbf{r}_{t-1}; \mu_r), \tag{7}$$

and where $\mathbf{r}_{t-1} \equiv (r_{0t-1}, r_{1t-1}, ..., r_{jt-1}, ..., r_{J_t t-1})$ is the vector of location-specific R&D investments within multinational firm i. Specifically, r_{0t-1} is the log R&D expenditure of the firm's parent, and r_{jt-1} for $j > 0$ is the R&D expenditure of its corresponding affiliate j. The dummy variable $d_{jt-1} \equiv \mathbb{1}\{R_{jt-1} > 0\}$ takes the value 1 if affiliate j performs a positive amount of R&D during period $t-1$, and is zero otherwise. We estimate several variants of the model, but assume in our baseline setting that the function capturing the impact of R&D investment on productivity change $g(\cdot)$ is defined as follows

$$g(\mathbf{r}_{t-1}; \mu_r) = \mu_a r_{jt-1} + \mu_p r_{0t-1}.$$

Notice that the specification in equation (6) is consistent with investment in R&D having both an *expected* impact on productivity, as captured by the ψ^e_{jt}, and an *unexpected* impact that is accounted for by the term η_{jt}, the productivity innovation. This productivity innovation captures exogenous temporary changes in the economic environment that affect the

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[22] See Appendix A.1 for additional details on the derivation of equations (4) and (5).

production process of a firm, such as strikes or extreme weather events, as well as uncertainties inherent to the R&D process. To estimate the model, we assume η_{jt} is mean independent of ψ_{jt-1}, and is also mean independent of the R&D investment $\mathbf{r}_{t-1}$ corresponding to the parent and each affiliate j at $t-1$. However, we allow η_{jt} to be correlated both across affiliates j and between affiliates and the parent firm of the same firm i.

Equation (7) incorporates a flexible characterization of the expected impact of R&D on productivity. First, through the parameters μ_{1nt} and μ_{2nt}, (7) accounts for the possibility that the productivity impact of performing any innovation activity (R&D > 0), relative to those affiliates adopting the corner solution of zero R&D, varies across countries, sectors, and years. These parameters also capture any differences across countries, sectors, and years in underlying rates of productivity change, including those which may differ depending on whether affiliates perform innovation tasks. This is particularly important if, for example, countries differ in the strength of patent protection or the abundance of skilled labor (e.g. in certain countries, weak patent laws might allow the firm to only partially appropriate the returns to R&D investment; similarly, differences in the relative supply of skilled workers across countries may induce differences in variable R&D costs), sectors are differentially exposed to basic scientific developments that impact productivity change, and time periods are characterized by different underlying macroeconomic conditions that may be country- or sector- specific.

Second, through the parameters ρ_1 and ρ_2, equation (7) allows for a different persistence of productivity ψ_{jt} when affiliate j adopts the corner solution of zero R&D and when it chooses a positive R&D level. This explicitly accounts for the possibility that innovative firms have productivity shocks that are more or less persistent than non-innovating firms.[23]

Third, the specification in equation (7) accounts for the possibility that affiliate j's expected productivity change depends not only on its own R&D expenditure r_{jt-1}, but also on the R&D investment r_{0t-1} of its parent firm. While (7) assumes the impact of parent R&D investment on affiliate productivity change is symmetric to that of the affiliate's own innovation investment, the magnitude of these two effects may differ.[24]

We assume that parent-level value-added productivity follows a stochastic process similar

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[23] According to the specification in equation (7), the effect of R&D investment on productivity exclusively depends on a binary variable capturing whether an affiliate does any investment in R&D at all. In Section 5.4, we generalize this specification by allowing for interactions between an affiliate's lagged productivity and R&D investment to influence its productivity evolution. We also consider other sources of nonlinearity in that section.

[24] In Section 5.4, we evaluate specifications in which parent and affiliate R&D may influence productivity directly over a period of multiple years, which may be important if innovation investment does not result in immediate efficiency improvement but instead requires refinement over a period of years.

to that in equations (6) and (7):

$$\psi_{0t} = \psi^e_{0t-1} + \eta_{0t}, \tag{8}$$

with

$$\psi^e_{0t-1} = \mu_{02t} + \rho_{02}\psi_{0t-1} + \mu_{0p} r_{0t-1}. \tag{9}$$

Note that we have introduced two asymmetries between parent and affiliates specification of the expected innovation in productivity ψ^e_0. First, equation (9) assumes that parent firms perform a positive amount of R&D in every time period. Second, while equation (7) allows innovation investment by the parent firm to potentially affect the evolution of foreign-affiliate productivity, affiliate R&D in (9) does not impact the productivity of parent firms.[25]

3.6 Firm Optimization

In each period t, firm i determines its optimal levels of employment, physical capital investment, R&D investment, and material input use both for the parent company and its foreign affiliates $j = 1, \ldots, J_{it}$. These decisions are taken after innovations to revenue productivity η_{jt} have been realized for every affiliate within the multinational firm i. The Bellman equation associated with firm i's dynamic optimization problem is, accordingly,

$$V(S_{it}) = \max_{I_{it}, L_{it}, M_{it}, R_{it}} \sum_{j=0}^{J_{it}} \Big\{ \Pi(S_{jt}, I_{jt}, L_{jt}, M_{jt}) + \delta \mathbb{E}[V(S_{jt+1}) | S_{jt}, I_{jt}, R_{it}] \Big\} \tag{10}$$

where $\Pi(\cdot)$ is the profit function, $V(\cdot)$ is the value function, δ is the discount factor, and S_{it} is the state vector for firm i. We define $S_{it} = (S_{0t}, S_{1t}, \ldots, S_{J_{it}t})$ with

$$S_{jt} = (\psi_{jt}, Q_{nt}, P_{nt}, P^m_{nt}, P^l_{jt}, P^k_{jt}, K_{jt}),$$

for every $j = 0, \ldots, J_{it}$ in firm i. The choice variables are investment in physical capital I_{it}, number of workers employed L_{it}, amount of material inputs M_{it}, and the level of R&D expenditure R_{it}.[26] The profit function of firm i's affiliate j at period t in equation (10) above is

$$\Pi(s_{jt}) = Y_{jt} - P^l_{jt} L_{jt} - P^m_{nt} M_{jt} - C_k(P^k_{jt}, I_{jt}, K_{jt}) - C_r(R_{jt}), \tag{11}$$

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[25] Both characterizations are strongly consistent with the data, as our estimates based on alternative and more flexible forms of equations 5 through 8 indicate in Section 5 below.

[26] Section 5.4 considers estimates that account for firms' optimal choice over the set of affiliates J_{it} as a function of the state vector S_{it}.

where C_k and C_r are general cost functions of investment in physical capital and knowledge. Knowing the exact functional forms for C_k and C_r is important for determining the optimal capital and innovation investment for firm i's affiliate j. These cost functions are, however, not observable in practice. An advantage of our estimation approach is therefore that it does not require explicit functional forms for C_k or C_r, provided that *there exist* some functions C_k and C_r that rationalize firms' observed investments in capital and R&D in the data.[27]

We assume labor and materials are both fully flexible (static) inputs. Conversely, physical capital at period t is determined by investment in physical capital in all periods previous to t according to the following law of motion

$$K_{jt} = \delta K_{jt-1} + I_{jt-1}.$$

4 Empirical Strategy

We apply the structure introduced in Section 3 to derive an estimating equation that depends exclusively on observed ouput, choice variables (L_{it}, K_{it}, R_{it}), and parameters of interest. In what follows, we present results using value added as our preferred measure of output.

Allowing for measurement error in observed value added, the value added function (5) may be generalized as follows

$$va_{jt} = \kappa^3_{nt} + h(l_{jt}, k_{jt}; \beta) + \kappa^2 \psi_{jt} + \varepsilon_{jt}, \tag{12}$$

where ε_{jt} captures measurement error, and we assume that $\mathbb{E}[\varepsilon_{jt}|S_{js}, L_{js}] = 0$, for any s.[28] Combining equation (12) with equations (6) and (9), we obtain the following baseline estimating equation

$$\begin{aligned} va_{jt} = h(l_{jt}, k_{jt}; \beta) + (1 - d_{jt-1})[\gamma_{1nt} + \rho_1(va_{jt-1} - h[l_{jt-1}, k_{jt-1}; \beta])] + \\ d_{jt-1}[\gamma_{2nt} + \rho_2(va_{jt-1} - h[l_{jt-1}, k_{jt-1}; \beta])] + \gamma_a r_{jt-1} + \gamma_p r_{0t-1} + u_{jt} \end{aligned} \tag{13}$$

where $\gamma_a = \kappa^2 \mu_a$, $\gamma_p = \kappa^2 \mu_p$, $\gamma_{1nt} = \kappa_2 \mu_{1nt} + \kappa^3_{nt} - \rho_1 \kappa^3_{nt-1}$, $\gamma_{2nt} = \kappa_2 \mu_{2nt} + \kappa^3_{nt} - \rho_2 \kappa^3_{nt-1}$, and $u_{jt} = \kappa^2 \eta_{jt} + \varepsilon_{jt} - \rho_1(1 - d_{jt-1})\varepsilon_{jt-1} - \rho_2 d_{jt-1} \varepsilon_{jt-1}$. The parameters γ_a and γ_p capture the elasticities of revenue productivity with respect to R&D investment by affiliate j and its parent, respectively. The market-year fixed effects μ_{1nt} and μ_{2nt} capture both the unobserved

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[27] For example, costs for each investment could simply be linear $C_k(P^k_{nt}, I_{jt}, K_{jt}) = P^k_{nt} I_{jt}$ and $C_r(R_{jt}) = R_{jt}$. However, in practice, the cost of buying I_{jt} effective units of capital is likely to be heterogeneous across firms due to financial frictions (Midrigan and Xu 2012) or adjustments costs of capital. Similarly, the cost of investing a fixed amount of dollars into R&D is also likely to differ across firms due to grants, subsidized loans or tax credits.

[28] For convenience, va_{jt} denotes both the theoretical and the observed firm-j value added during period t.

quantity and price indices (embedded in the terms κ^3_{nt} and κ^3_{nt-1}) as well as the market-year specific changes in revenue productivity, μ_{1nt} and μ_{2nt}. Finally, the unobserved component u_{jt} captures both the shock to revenue productivity $\kappa^2\eta_{jt}$ as well as lagged and current values of the measurement error.

The complete parameter vector we estimate is $(\beta, \rho_1, \rho_2, \gamma_r, \{\mu_{1nt}\}, \{\mu_{2nt}\})$, where $\beta = (\beta_l, \beta_k, \beta_{ll}, \beta_{kk}, \beta_{lk})$ captures parameters of the value added function, and, for $x = 1, 2$, $\{\mu_{xnt}\}$ denotes the set of effects μ_{xnt} for every nt pair in which there is at least one observation identifying such effect. Estimating this set of parameters using nonlinear least squares (NLS) in equation (13) will result in biased estimates unless we assume that labor is predetermined (i.e. l_{jt} is determined at period $t-1$, before η_{jt} is realized) and value added is measured without error (i.e. $\varepsilon_{jt-1} = 0$).[29] If the amount of labor hired by firm j at period t is at least partially determined after productivity innovations have been observed by firm i, then l_{jt} will be correlated with η_{jt} and this will give rise to an endogeneity issue known as transmission bias (e.g., Griliches and Mairesse 1998). Similarly, if our measures of value added suffer from classical measurement error, va_{jt-1} will be correlated with ε_{jt-1} and this will generate standard attenuation bias. In order to simultaneously address the potential problems of transmission bias and attenuation bias, we estimate the parameters of interest in two steps (see Gandhi, Navarro, and Rivers 2013). In the first step, we exploit information about the production function that is contained in the firms' first order condition for labor. This allows us to recover consistent estimates of $(\beta_l, \beta_{ll}, \beta_{lk})$ and an structural proxy for ε_{jt} for every period t. In the second step, conditional on these first stage estimates, we estimate $(\beta_k, \beta_{kk}, \rho_1, \rho_2, \gamma_r, \{\gamma_{1nt}\}, \{\gamma_{2nt}\})$. Specifically, in this second step, we first apply the Frisch-Waugh-Lovell theorem to control for the fixed effects $(\{\gamma_{1nt}\}, \{\gamma_{2nt}\})$ and then use NLS or GMM to estimate $(\beta_k, \beta_{kk}, \rho_1, \rho_2, \gamma_r)$. Additional estimation details appear in Appendix A.2.

5 Empirical Results

This section applies the estimation procedure described in section 4 above to evaluate the impact of innovation on affiliate-level productivity change within the multinational firm. Estimates in this section correspond to multinational firms in the computer industry and the industrial machinery sector; analogous results for firms in other industries are summarized in Section 5.4 below.

5.1 Baseline estimates

Computers

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[29] We consider these alternative assumptions in Section 5.4.

Table 4 provides estimates corresponding to equation (13) for multinational firms in the computer industry.[30] Columns 1 and 2 evaluate the impact of innovation investment on value added productivity among U.S. parent firms, while columns 3–6 correspond to their foreign affiliates. All estimates are based on the full sample of majority-owned, manufacturing affiliates that are associated with a U.S. parent firm in the industry under evaluation.

Estimates in columns 1 and 2 indicate parent innovation has a strong, positive impact on parent value-added productivity in subsequent periods. The estimated coefficient on parent R&D in column 1 ($\hat{\gamma}_{0p} = 0.0109$, standard error $= 0.0043$) suggests raising parent innovation by 1 percent during period t—while holding all other production inputs fixed—would lead to an increase in parent value added of 0.0109 percent, on average. This immediate, short-run impact of innovation on productivity is further compounded over time through the high degree of estimated U.S. parent productivity persistence ($\hat{\rho}_{02} = 0.9200$, standard error $= 0.0244$), which implies a long-run value added elasticity of 0.136 percent. Column 2, however, indicates R&D performed at a firm's affiliated foreign locations has, on average, only a negligible effect on the productivity of the corresponding U.S. parent.

By contrast, columns 3–6 suggest parent and foreign-affiliate innovation are both important determinants affiliates' subsequent productivity change. Specifically, the estimates in column 3 indicate an affiliate's own R&D expenditure significantly impacts its future productivity, independently of innovation performed elsewhere within the firm ($\hat{\gamma}_a = 0.0159$, standard error $= 0.0040$). This immediate impact is again magnified over time through the high degree of estimated productivity persistence $\hat{\rho}_2$ and $\hat{\rho}_1$ among affiliates; although the model allows flexible differences in productivity persistence depending on whether the affiliate performs R&D or not, the data indicate these differences are not statistically important for the specifications considered in Table 4.[31]

Column 4 evaluates a specification that also includes the R&D expenditure of each affiliate's corresponding U.S. parent. This specification is thereby able to evaluate the influence of parent innovation on productivity and value added increases realized abroad within the same multinational firm; as such, these estimates may be of particular interest from a policy perspective. Specifically, it may be important for governments considering policies aimed at stimulating local innovation to understand the impact of such policies not only on domestic productivity growth, but also on growth in foreign countries realized through technology transfer within the multinational firm. The value of policies aimed at attracting foreign direct investment may likewise hinge on the extent to which domestic affiliates realize their well-

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[30] The computer industry [SIC 357] includes computer hardware and disk-drive firms and thus forms a narrow subset of the industrial machinery sector [SIC 35] discussed below. As constructed, the computer industry is defined at the full extent of industry disaggregation possible in the data.

[31] The estimates $\hat{\rho}_1$ and $\hat{\rho}_0$ are statistically indistinguishable in columns 3–6. However, because estimates in specifications below suggest the presence of statistically important differences in productivity persistence, we nevertheless provide this flexibility throughout the analysis.

documented productivity premium (e.g. Guadalupe, Kuzmina, and Thomas 2012) through the transfer of valuable technology developed abroad, rather than through foreign firms selecting the most productive inputs and existing production plants. The estimates in column 4 strongly suggest the importance of parent R&D investment as a highly significant determinant of affiliate productivity change ($\hat{\gamma}_p = 0.0105$, standard error = 0.0040). Columns 5 and 6 confirm that these estimates are robust to controlling for the total R&D investment of other affiliates in the same firm; estimates corresponding to other-affiliate R&D are not statistically different from zero and are thus suppressed.[32]

Column 4 also indicates that $\hat{\gamma}_a$ exceeds $\hat{\gamma}_p$. This pattern, which indicates affiliate productivity is on average more responsive to a marginal increase in its own innovation than to an increase in its U.S. parent innovation, is consistent with the presence of knowledge frictions that limit firms' ability to transmit parent knowledge to distant affiliates (e.g. Arrow 1962, 1969); the observation is also consistent with a vertical firm structure in which parent and affiliate operations perform distinct tasks that, accordingly, require distinct forms of innovation. Notice also that the impact of parent innovation on affiliates is comparable to the local impact of parent R&D on parents' productivity, on average. It would thus seem these estimates support the idea that the documented productivity gap between multinational parents and their generally less-productive foreign affiliates (e.g. Tintelnot 2014) may be driven largely by differences in the long-run impact of R&D, as determined by parents' higher productivity persistence, rather than their short-run impact.

Across all six columns of Table 4, production function coefficients β further indicate the importance of both labor and capital inputs as determinants of affiliate output levels. Table 4 describes the scaled input elasticities implied by $\hat{\beta}$ given the sample distribution of labor and capital; the estimated scaled labor elasticity is 0.45, while estimates span a narrow range around 0.17 for capital inputs. The importance of labor relative to capital inputs is larger among U.S. parents.

Notice that specifications 3–6 in Table 4 include a full set of country-year and sector-year fixed effects, in addition to a second set of country-year and sector-year fixed effects that are interacted with an indicator for whether the affiliate performs R&D $d_{jt} = \mathbb{1}\{R_{jt} > 0\} = 1$, as indicated in section 4. These fixed effects are important for several reasons. First, affiliate value added y_{ijt} in the model is a function of the aggregate price P_{nt} and demand level Q_{nt} in the affiliate's local (country-sector) market n during period t. Because our panel spans such a large set of countries and years, it is not possible to obtain direct proxies for P_{nt} and Q_{nt} corresponding to the full set of observations for each industry considered.[33] By relying

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[32] Innovation investment and productivity growth rates may be persistent and correlated across firms, raising the question of whether unobserved firm characteristics drive both. [What would we like to say here?]

[33] Data are available that would enable us to construct these proxies for certain countries and years. While

instead on fixed effects, we are able to recover all relevant technology parameters within the complete sample of countries and years.

Second, the fixed effects approach has the significant further advantage of controlling for any systematic component of affiliate value added, as well as any systematic component of affiliate productivity growth, that may depend on local conditions and may differ across innovating and non-innovating affiliates. These conditions include, for example, local taxes and subsidies, intellectual property rights, the quality of R&D inputs available, productivity spillovers from domestic research universities and firms, infrastructure quality, and so on. Local taxes and subsidies may, in particular, impact firms' incentives to engage in strategic revenue relocation across affiliate countries (Hines and Rice 1994, Hines 1997, Blouin, Robinson, and Seidman 2013); we further evaluate the robustness of our results to this possibility below, but notice that as a baseline, the market-year fixed effects already capture systematic differences in affiliate profitability across locations and periods—including differences that may be pronounced among affiliates investing in R&D.

Industrial machinery

Table 5 extends the analysis presented in Table 4 to also include firms in the broader industrial machinery sector, of which the computer industry is a part.

Estimates across columns 1–6 match the qualitative pattern of results in Table 4. Columns 1 and 2 both indicate parent innovation has a positive and highly significant impact on the subsequent value added and value-added productivity of the parent. The estimated coefficient on parent R&D in column 1 is both larger and more precisely estimated $\hat{\gamma}_{0p} = 0.0145$, standard error $= 0.0015$) than its analog in Table 4, and implies an immediate, short-run impact of parent R&D that is compounded by the persistence in parent-level productivity ($\hat{\rho}_{0p} = 0.8384$, standard error $= 0.0105$). The resulting long-run elasticity of output with respect to parent R&D is 0.90 percent.

Columns 3–6 again indicate parent and foreign-affiliate innovation are both important determinants affiliates' subsequent productivity change. Specifically, column 4 includes the affiliate's own R&D and its U.S. parent R&D investment. The estimates in column 4 strongly suggest the importance of parent R&D investment as a determinant of affiliate productivity change ($\hat{\gamma}_p = 0.0105$, standard error $= 0.0040$), even after controlling for affiliates' own R&D investment. However, to a greater extent than in the computer industry above, it is apparent that the local impact of R&D investment is significantly larger than the impact of R&D on other sites within the same firm: parent innovation has a larger impact on parent productivity than on affiliate productivity ($\hat{\gamma}_{0p} > \hat{\gamma}_p$) and affiliate innovation has a

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doing so would have the advantage of freeing our estimation approach from handling a large number of fixed effects, it would also preclude evaluation of firms' full set of production locations, thus limiting our ability to correctly estimate innovation returns.

greater impact on affiliate productivity than it has on parent productivity ($\hat{\gamma}_a > \hat{\gamma}_{0a}$). Again, this pattern of results is consistent with the presence of knowledge frictions (Arrow 1962, 1969), as well as R&D differentiation. It is also apparent that the productivity of affiliates performing any R&D decays over time significantly more rapidly than the productivity of affiliates not performing R&D ($\hat{\rho}_2 = 0.6638 < 0.7377 = \hat{\rho}_1$).[34] Columns 5 and 6 confirm that these estimates are robust to controlling for the total R&D investment of other affiliates in the same firm.

5.2 Heterogeneous effects of parent R&D

The models estimated above presume multinational affiliates within an industry share common technology parameters, including that governing the impact of U.S. parent R&D on subsequent changes in productivity and output. However, it is possible that observable characteristics of countries, firms, and affiliates condition the influence of innovation on affiliate productivity change. We therefore evaluate simple extended versions of the model (13) that accommodate heterogeneity. Specifically, we define

$$g(\mathbf{r}_{t-1}; \gamma_r) = \gamma_a \, r_{jt-1} + \gamma_p \, r_{0t-1} + \gamma_x \, r_{0t-1}\chi_{ijt-1} + \delta \, \chi_{ijt-1}, \tag{14}$$

where χ_{ijt-1} is a characteristic of interest that may influence the overall impact of parent R&D r_{0t-1} on affiliate-j productivity. For example, an affiliate located industrially close to its U.S. parent, in that both share not only the same primary industry, but also demonstrate substantial overlap in secondary and tertiary activities, may receive systematically more gains from U.S. parent technology investment than an affiliate with a lower degree of observed industrial overlap with its parent. Tables 6 and 7 evaluate linear models featuring such forms of heterogeneity in the impact of parent R&D on affiliate productivity for computer and industrial machinery firms, respectively.

Intrafirm transactions

Estimates in Tables 6 and 7, column 1 suggest the importance of intrafirm trade in intangible technology assets for firms in both industries. Building on Tables 4–5, the estimates in column 1 account for observed technology transactions between affiliates and U.S. parent firms by defining $\chi_{ijt} = \text{Royalties}_{ijt}$, the log value of royalties paid by firm i's affiliate j to its parent, in (14) above.

In the data, affiliates report royalties and license fees paid for the use of proprietary

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[34] These estimates are consistent with Bilir (2014), which finds a negative correlation across industries between R&D intensity (the ratio of R&D to sales) and the average length of product lifecycles, which reflect technology obsolescence rates among U.S. patents. Doraszelski and Jaumandreu (2013) also finds evidence of higher knowledge persistence among non-R&D performing plants than among R&D performers.

intellectual property and intangible assets owned by the U.S. parent. The existence of such payments between a parent-affiliate pair is thus strongly suggestive of within-firm technology transfer that is directed from a U.S. parent to its foreign affiliate (see also Branstetter et al 2006). In line with estimates in Tables 4–5, which indicate a significant impact of parent innovation on affiliate productivity, the data show that a substantial share of sample affiliates in the computer (52 percent) and industrial machinery (40 percent) sectors pay technology-related royalties to the U.S. parent. Moreover, affiliates with $\text{Royalties}_{ijt} = 0$ report lower average levels of value added, assets, employment, and plant, property and equipment, consistent with the idea that such affiliates receive relatively less value from U.S. parent innovation and that differences in intangible technology trade may capture meaningful variation in technology received. The estimates in column 1 indicate that the elasticity of affiliate value added with respect to parent R&D invested during the previous period is indeed systematically increasing in intrafirm royalty and license fees paid by affiliate j to its U.S. parent ($\hat{\gamma}_x = 0.0019$, standard error $= 0.0005$, Table 6, mean elasticity 0.0103).

U.S. parent technology may be transferred to foreign affiliates in either embodied or disembodied forms (Keller and Yeaple 2014). While Royalties_{ijt} captures the latter, the former is related to trade in tangible goods. To evaluate the importance of this channel we define $\chi_{ijt} = \text{Imports}_{ijt}$, the value of imported goods purchased by firm i's affiliate j from the U.S. parent, in column 2, Tables 6 and 7. The estimates in both industries indicate the elasticity of affiliate value added with respect to parent R&D invested during the previous period systematically increases in intrafirm imports received by affiliate j from its U.S. parent ($\hat{\gamma}_x = 0.0009$, standard error $= 0.0005$, Table 6, mean elasticity 0.0070). The data are thus consistent with the idea that affiliates receiving imports from the U.S. parent benefit systematically more from its R&D investment.[35]

Distance between parent and affiliate

At the industry level, data on multinational activity is consistent with the idea that knowledge flowing from parent to affiliate in embodied form—for example, through a physically traded input—declines with the geographic distance between parent and affiliate (Keller and Yeaple 2014). Similarly, it is natural to hypothesize that the impact of parent innovation on an affiliate may be related to the industrial distance separating the two operations, where industrial distance reflects the extent of overlap between parent and affiliate production tasks. To evaluate the importance of these two forms of distance, we evaluate specifications in Tables 6 and 7 in which $\chi_{ijt} = \text{Geographic Distance}_{ijt}$ and $\chi_{ijt} = \text{Industrial Distance}_{ijt}$ where each form of distance is that between firm i's affiliate j and its U.S. parent; Industrial

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[35] If intrafirm imports are not priced competitively, the assumption placed on M_{ijt} pricing in section 3 above is not upheld. Below, we therefore confirm that the results are qualitatively robust to restricting the sample to affiliates with below-median imports as a share of intermediates.

Distance is the simple Euclidean norm between the distribution of parent and affiliate activity across their respective top five industries. The results indicate that in both industries, affiliates located far from the U.S. parent in industry space experience a smaller impact of parent R&D on productivity change. Unsurprisingly, in the relatively broad industrial machinery sector, the coefficient $\hat{\gamma}_x$ is more strongly negative than in the narrow computer industry, in which the scope for industry variation is relatively limited. By contrast, the data do not appear to support a systematic influence of geographic distance on the impact of parent innovation.

Complementarity between parent and affiliate R&D

The baseline model in section 3 implicitly considers parent and affiliate R&D as substitutes in determining affiliate productivity change. We also evaluate a specification that considers whether the data instead indicate complementarity in innovation investment across firm locations. Specifically, in Tables 6 and 7, column 4 evaluates (14) defining $\chi_{ijt} = r_{ijt}$, so that the specification includes an interaction between parent and affiliate R&D investment. In both industries, the estimates indicate parent innovation has a productivity impact that increases in affiliates' own R&D investment. Moreover, including this interaction in both cases reduces the independent effect of affiliate R&D. The estimated complementarity between parent and affiliate R&D is higher in the narrowly-defined computer industry; this suggests the possibility either that complementarity is stronger in the computer industry, or that within a narrowly-defined industry, parent and affiliate innovation are more likely targeting related product and process challenges, and are thus inherently more complementary.

Nonlinear productivity process

To further evaluate sources of heterogeneity across firms in the impact of innovation on productivity change, we consider an extended set of specifications featuring multiple forms of nonlinearity. Define the following process for affiliate-level productivity

$$\begin{aligned}\psi^e_{jt-1} = (1-d_{jt-1})(\mu_{1nt} + \rho_1\psi_{jt-1}) + d_{jt-1}(\mu_{2nt} + \rho_2\psi_{jt-1}) + \rho_3\psi_{jt-1}r_{jt-1} \\ + \rho_4\psi^2_{jt-1} + \mu_a r_{jt-1} + \mu_p r_{0t-1} + \rho_5 r_{0t-1}\psi_{jt-1} \qquad (15)\end{aligned}$$

which is to be evaluated in place of (7) for firms in the computer and industrial machinery sectors. In (15) above, notice that the expected period-t productivity of affiliate j depends on its past productivity through both linear and squared terms, as well as through interactions between productivity at $t-1$ and affiliate-j R&D investment r_{jt-1} and parent R&D investment r_{0t-1}. This nonlinear specification is thus able to account for flexible forms of heterogeneity in the influence of R&D on productivity change, whereby the impact of parent or affiliate R&D investment may differ across affiliates depending on their initial productivity level.

Corresponding estimates for both parents and affiliates in each industry appear in Appendix Tables A.1 and A.2. The estimates imply empirical distributions for affiliate-level productivity persistence, as well as for the impact of parent and affiliate R&D on productivity change; these distributions appear in panels A, B, and C of Figures 1 and 2. In both sectors, relatively productive affiliates are found to receive larger gains from parent R&D than less productive locations. Accordingly, the impact of parent R&D on affiliate productivity change follows a distribution with mean 0.0033 for computer firms and 0.0060 for industrial machinery firms. For affiliates with the initial productivity levels around the 95th percentile, the impact rises to 0.0122-0.0136, while affiliates with the smallest levels of initial productivity report a slightly negative impact of parent innovation. The results continue to support the conclusion that an affiliate's own innovation, and its parent firm's innovation, are important sources of productivity gain.

5.3 Endogenous R&D investment

The estimates above rely on an assumption that multinationals' R&D investment choices in period t are independent of the productivity innovation realized in period $t+1$, η_{t+1}. However, this assumption may not be upheld if firms make other investments at t that influence productivity and are correlated with R&D choices, but that are unobserved in the data. For example, firms may choose to raise future productivity by acquiring new technologies from external sources rather than developing them internally; firms may also actively substitute between technology acquisitions and internal development through R&D investment, leading to a correlation between the two; but while R&D is observed in our dataset, private technology acquisitions are not. In this setting, R&D would be correlated across firms and periods with an omitted variable that influences future productivity change η, thus posing an interpretation challenge for the estimates above

To isolate the independent influence of parent R&D on subsequent productivity while allowing for the possibility of these alternative forms of investment, we introduce variation in location-specific innovation incentives faced by firms in the data. Specifically, the multinational firms in our dataset operate headquarters located in one U.S. state, which has a prevailing state-year level R&D tax credit that impacts R&D costs; as in Bloom et al (2013), we rely on a Hall-Jorgenson user cost of R&D based on state-year level R&D tax credit information in Wilson (2009). Using the address of the U.S. headquarters for each firm in our dataset, we build the relevant state-year user cost of R&D and rely on variation in this as an instrument for U.S. parent R&D investment. The data reveal strong correlations between a parent's R&D investment and its associated user cost of R&D; in the computer industry, conditional and unconditional correlations are -6.98 and -6.52, respectively.

While state tax incentives provide a natural source of variation in R&D investment for parent firms in the United States, foreign affiliates of U.S. multinationals operate in locations that differ substantially in other forms of institutional quality that also influence innovation choices. Specifically, affiliates in countries with strong intellectual property rights protection may be more attractive locations for R&D investment, as such protections condition firms' ability to appropriate the returns to innovation (Grossman and Lai 2004, Bilir 2014). As such, firms may be inclined to view affiliates located in strong institutional environments as closer substitutes for a firm's U.S. headquarters when determining the level and allocation of R&D investments to pursue. A firm facing a significant decline in the generosity of its headquarters research credit may, for example, decrease its headquarters innovation investment and increase its investment among affiliates in strong-patent countries. We thus interact the relevant state-year user cost of R&D faced by each firm-year with the strength of intellectual property rights for each affiliate country-year (Ginarte and Park 1997, Park 2008) and use variation in this interaction as an instrument for foreign-affiliate R&D investment. The data indeed reveal strong correlations between an affiliate's R&D investment and the interaction between the affiliate's local intellectual property protection and the user cost of R&D faced by its U.S. parent; in the computer industry, conditional and unconditional correlations are 1.41 and 0.70, respectively.

Tables 8 and 9 replicate the specifications appearing in Tables 4 and 5, but rely on an GMM estimator that corrects for endogeneity in R&D investments using the policy instruments described above. The resulting estimates are qualitatively identical to those in Tables 4 and 5. The influence of parent innovation on both parent and affiliate productivity change is positive and statistically significant. Similarly, foreign affiliate R&D investment significantly impacts affiliate productivity change, and both parent and affiliate operations exhibit considerable persistence in productivity over time. It is apparent in Tables 8 and 9 that in both the computer and industrial machinery sectors, the estimated importance of R&D investment is increased by correcting for the endogeneity of innovation investment.[36]

5.4 Robustness and Alternative Specifications

We subject our estimation results above to a series of robustness checks and alternative specifications to evaluate their stability. First, because our setting involves multinational firms, concerns arise regarding the use of reported affiliate-level value added y_{ijt} as a measure of output given multinationals' profit-shifting motives documented in Hines and Rice (1994), Hines (1997), Blouin, Robinson, and Seidman (2013), and elsewhere. While the inclusion of

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[36] These increases are consistent with a strong negative correlation between firms' observed R&D investment and any other correlated, but unobservable investments.

an extensive set of market-year fixed effects and their interaction with indicators for affiliate R&D performance likely captures most variation across affiliates in transfer pricing motives, concerns may nevertheless remain. In an additional set of tests, we re-estimate Tables 4–5 excluding counties known to have policies that encourage revenue relocation across borders: the list of excluded countries is from Gravelle (2015).[37] U.S. multinationals may also engage in intrafirm input trade at non-competitive input prices, contrary to the assumption on M_{ijt} pricing in section 3 above. We therefore reevaluate all results within a sample restricted to affiliates receiving low or zero intrafirm imports. To account for the further possibility that parent innovation is measured with error, we replicate all results above clustering standard errors at the firm-year level. In addition, we replicate our analysis above for four other manufacturing sectors: chemicals [SIC 28], electronics [SIC 36], transportation equipment [SIC 37], and instruments and devices [SIC 38]. We also replicate results using an alternative dataset for each industry that includes both manufacturing and retail affiliates. Finally, we consider an alternative timing assumption whereby labor inputs are predetermined and thus not subject to endogeneity concerns; under this assumption, all β parameters of the production function may be estimated in a single step. With the exception of this last adjustment, we find qualitatively identical results under each of these alternative specifications.

Because the full impact of parent innovation may occur over a period lasting longer than one year, we also consider an alternative timing assumption by allowing parent R&D investment summed over the previous five years to influence affiliate productivity evolution,

$$g(\mathbf{r}_{t-1,t-5};\gamma_r) = \gamma_a\, r_{jt-1} + \gamma_{p5}\, r_{0t-1t-5}, \tag{16}$$

where $r_{0t-1t-5} \equiv \log(\sum_{s=t-5}^{t-1} R_{0s})$. This approach is conceptually related to Griliches (1979), though our aim is not to build a stock of knowledge capital, but rather to allow for the possibility that the impact of R&D may be realized multiple years after it is performed. The estimates reveal qualitatively similar results to those appearing in Tables 4 and 5, but with larger point estimates. Similar to Aw, Roberts, and Xu (2008), we further extend our estimation approach to allow parent innovation to impact affiliate productivity flexibly for up to four years, with separate parent R&D variables corresponding to investment in period $t-1$, $t-2$, and so on. This exercise indicates parent innovation tends to have a positive impact as far back as period $t-2$. However, the impact of affiliate's own local innovation

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[37] This list was prepared by the U.S. Congressional Research Service and is closely based on OECD and GAO lists, as well as that appearing in Dharmapal and Hines (2009). The list of countries excluded is: Andorra, Bahamas, Bahrain, Barbados, Bermuda, Costa Rica, Cyprus, the Dominican Republic, French Islands - Pacific, French Islands - Indian Ocean, French Islands, Gibraltar, Hong Kong, Ireland, Jordan, Lebanon, Liechtenstein, Luxembourg, Macau, Maldives, Malta, Mauritius, Monaco, Netherlands, Netherlands Antilles, Panama, Seychelles, Switzerland, Singapore, United Kingdom Islands - Caribbean, and Virgin Islands. These locations account for 15% of sample observations in the computer industry, and 11% in industrial machinery.

appears shorter-lived, primarily occurring within the first year after investment.

6 Implications for the Multinational Firm

In this section, we use the estimates reported in Section 5 to compute estimated return to innovation investment by U.S. parent firms. We first determine the elasticity—holding all other production inputs fixed—of parent and affiliate value-added productivity with respect to parent R&D. Second, we evaluate the effect of a infinitesimal increase in parent R&D on productivity and output levels by parent, affiliate, and firm, again holding other inputs and firm structure fixed. Finally, using the latter estimates, we determine how much U.S. parent R&D increases firm productivity and output abroad relative to its overall impact, and characterize the empirical distribution of this foreign impact share across U.S.-based multinational firms.

6.1 Output elasticities with respect to innovation

The evolution of parent productivity $\tilde{\psi}_0$, which jointly reflects parent physical productivity and product quality, is described in section 3, equations (8) and (9). This process, along with the production technology and demand function, implies the elasticity of expected parent value added in year t with respect to parent R&D investment during period $t-1$ is

$$\frac{\partial \mathbb{E}[va_{0t}|S_{it-1}]}{\partial r_{0t-1}} = \gamma_{0p}.$$

Notice that γ_{0p} is also the elasticity of expected value-added productivity in year t with respect to parent R&D, and corresponds to the estimated coefficient on r_{0t-1} appearing in columns 1 and 2 of Tables 4 and 5, where r_{0t-1} is the log of U.S. parent R&D investment at $t-1$ and va_{0t} is the log of U.S. parent value added at t. Similarly, for each foreign affiliate j of firm i, the elasticities of period-t expected affiliate value added, or value-added productivity, with respect to parent and affiliate R&D investment during period $t-1$ are

$$\frac{\partial \mathbb{E}[va_{jt}|S_{it-1}]}{\partial r_{0t-1}} = \gamma_p, \quad \text{and} \quad \frac{\partial \mathbb{E}[va_{jt}|S_{it-1}]}{\partial r_{jt-1}} = \gamma_a,$$

respectively, which are the coefficients on parent R&D r_{0t-1} and affiliate R&D r_{jt-1} appearing in columns 3–6 of Tables 4 and 5. As reviewed above, the estimated elasticities with respect to parent R&D range between 0.085 and 0.145, while that with respect to affiliate R&D ranges between 0.0140 and 0.165 depending on the specification.

Comparison with previous estimates

The estimates γ_{0p} and γ_a may be compared, up to a scalar, with magnitudes from the existing literature. Notice that estimating equation described in section 4 provides a method for recovering $\gamma_{0p} = \kappa^2 \mu_{0p}$ and $\gamma_p = \kappa^2 \mu_p$, where κ_2 is scalar that depends on the demand and production parameters σ and α_m (section 3.4). The key distinction between the μ and γ parameters is that while μ captures the elasticity of $\tilde{\psi}$, the sum of physical productivity and product quality, with respect to innovation, γ is the elasticity of value-added productivity, and of value added, with respect to innovation.

Comparing our estimates with those in Doraszelski and Jaumandreu (2013), which uses observed prices and material inputs to estimate productivity process parameters directly, thus requires scaling recovered elasticities by $(\hat{\kappa}^2)^{-1}$. Applying their estimate of $\hat{\alpha}_m = 0.691$ for Agriculture and Industrial Machinery, the closest of the ten industries considered to the industrial machinery sector evaluated here, it is possible to compare their estimated mean elasticity (see their Table 7) against those in Table 5 above; their Table 7 reports a mean elasticity of output with respect to R&D of 0.005 in Agriculture and Industrial Machinery. Using the Broda and Weinstein (2006) elasticities, we construct an estimated $\hat{\sigma} = 2.95$, somewhat above the cross-industry average estimate $\hat{\sigma} = 2$ reported in Doraszelski and Jaumandreu (2013). Multiplying their elasticity estimate by $\hat{\kappa}^2 = 1.216$ results in a value-added elasticity of 0.0061 that may be compared with both affiliate $\hat{\gamma}_a = 0.0085$ (Table 5, column 6) and parent $\hat{\gamma}_p = 0.0132$ (Table 5, column 2) estimates. The estimated elasticity corresponding to U.S. firms' foreign affiliates in the industrial machinery sector are remarkably close to that reported in Doraszelski and Jaumandreu (2013), which is perhaps not surprising given that their estimation is based on a panel of Spanish plants that are not likely parents of a multinational firm. However, the estimated elasticities corresponding to U.S. parent firms are more than twice as large, possibly indicating the exceptional nature of innovation within the headquarters of a large multinational firm. The 'plant-level' estimates in Tables 4 and 5 also fall within the range of elasticities surveyed in Hall, Mairesse, and Mohnen (2010), despite distinct differences between the econometric technique considered here and that applied in the surveyed articles, with the exception of Doraszelski and Jaumandreu (2013).

6.2 The private return to innovation

Plant-level R&D returns

To determine the short-run return to R&D investment, we proceed by translating the elasticities described above into derivatives that capture the impact of R&D investment on value added in levels; this approach is standard in the literature (e.g. Hall, Mairesse, and Mohnen 2010, Doraszelski and Jaumandreu 2013). The short-run return to parent R&D

investment that is realized by the innovating parent is

$$\frac{\partial \mathbb{E}[\mathrm{VA}_{0t}|S_{it-1}]}{\partial R_{0t-1}} = \gamma_{0p}\mathrm{VA}_{0t}/R_{0t-1},$$

and likewise, the short-run returns to parent and affiliate R&D investment realized by foreign affiliate j are

$$\frac{\partial \mathbb{E}[\mathrm{VA}_{jt}|S_{it-1}]}{\partial R_{0t-1}} = \gamma_p \mathrm{VA}_{jt}/R_{0t-1}, \quad \text{and} \quad \frac{\partial \mathbb{E}[\mathrm{VA}_{jt}|S_{it-1}]}{\partial R_{jt-1}} = \gamma_a \mathrm{VA}_{jt}/R_{jt-1},$$

respectively. Long-run innovation returns, which are more easily compared with rates of return to other forms of investment, are a function not only of output elasticities, but also of estimated productivity persistence ρ in the Markov processes (6) and (8). Specifically, the long-run return to parent R&D investment that is realized by the parent is

$$\lim_{s\to\infty} \frac{\partial \sum_{u=0}^{s} \mathbb{E}[\mathrm{VA}_{0t+u}|S_{it-1}]}{\partial R_{0t-1}} = \frac{\gamma_{0p}\mathrm{VA}_{0t}}{(1-\rho^0)R_{0t-1}},$$

and the long-run returns to parent and affiliate R&D investment realized by its foreign affiliate j are

$$\lim_{s\to\infty} \frac{\partial \sum_{u=0}^{s} \mathbb{E}[\mathrm{VA}_{jt+u}|S_{it-1}]}{\partial R_{0t-1}} = \frac{\gamma_p \mathrm{VA}_{jt}}{[1-\rho(j)]R_{0t-1}},$$

and

$$\lim_{s\to\infty} \frac{\partial \sum_{u=0}^{s} \mathbb{E}[\mathrm{VA}_{jt+u}|S_{it-1}]}{\partial R_{jt-1}} = \frac{\gamma_a \mathrm{VA}_{jt}}{[1-\rho(j)]R_{jt-1}},$$

respectively, where the productivity persistence $\rho(j) \equiv d_{ijt}\,\rho_1 + (1-d_{ijt})\rho_0$ takes on different values depending on whether or not affiliate j performs R&D during period t.

The top panel of Figure 3 plots estimated parent-level returns to parent R&D for computer firms. The estimates reveal substantial heterogeneity in both local short-run and local long-run rates of return to parent innovation. For the median firm, the return to parent R&D realized by the parent itself is just 8.6 percent, 19.0 percent after correcting for endogeneity, in the short run; long run values for the median firm are 43.9 percent and 96.2 percent, respectively. This latter estimate indicates a 1 percent increase in parent R&D generates, on average, a 0.962 percent increase in parent value added. However, for firms at the upper end of the distribution of parent value added to R&D investment, the estimated return to innovation is substantially higher; for firms at the lower end, it approaches zero.

A similar pattern of local returns to parent innovation may be observed within industrial machinery firms (Figure 4, top panel), though effects are generally higher than in the computer industry. For the median firm, the short-run return to parent R&D realized by the parent itself is 17.7 percent, 70.2 percent after correcting for endogeneity; long-run values are higher, at 19.9 percent and 100.0 percent, respectively.

The foreign affiliate-level return to parent R&D also follows a distribution across affiliates, but one with substantially smaller magnitudes. The short-run return to parent R&D realized by the median affiliate in the computer industry is just 0.014 percent, 0.087 percent after correcting for endogeneity; long run values are 0.078 percent and 0.44 percent, respectively. Affiliate returns to affiliate R&D are larger at 42.3 percent in the short run, with comparable values within industrial machinery firms.

The firm-level R&D return

The firm-level return to parent innovation reflects the combined impact of R&D on both parent and foreign affiliates within the same firm. Specifically, summing the marginal returns above across firm locations, the short-run firm-level return to parent R&D is

$$\frac{\partial \mathbb{E}[\mathrm{VA}_{it}|S_{it-1}]}{\partial R_{0t-1}} = \frac{\partial \mathbb{E}[\sum_j \mathrm{VA}_{jt}|S_{it-1}]}{\partial R_{0t-1}} = (\gamma_{0p}\mathrm{VA}_{0t} + \gamma_p \sum_{j\neq 0} \mathrm{VA}_{jt})/R_{0t-1},$$

where VA_{it} is firm i value added accounting for all affiliated locations. The center panels in Figures 3 (computers) and 4 (industrial machinery) plot the distribution of these firm-level returns across firms as well as their long-run analog. The median returns are higher, at 9.68 percent for computer firms, 23.1 after correcting for endogeneity, in the short run; long-run firm-level returns are also higher at 49.3 percent, and 1.19 percent after correcting for the endogeneity of R&D. The distribution of returns is skewed, with firms at the upper range earning exceptionally high returns to R&D. For the average firm, the short-run return to parent R&D is 30.9 percent, while the long-run return is 162 percent, even before correcting for endogeneity. Magnitudes are similar for innovation returns in industrial machinery. Moreover, median-firm long-run rates of return are high relative to, but within the range of, other existing estimates in Hall et al (2010) and Jones and Williams (1997); long-run returns for the average firm are consideraly higher.

The distribution of firm-level returns to U.S. parent R&D is similar in shape to that of parent-level returns. But the higher magnitudes across the distribution are due to the impact that parent R&D has on the productivity and value added of multinational affiliates abroad. The lower panels of Figures 3 and 4 plot the cross-firm distribution in the share of firm-level returns to U.S. parent R&D that is realized among firm foreign affiliates. In the computer industry, the estimated return share ranges as high as 45 percent in the short run (50 percent in the long run), and as high as 70 percent after correcting for the endogeneity of both parent and affiliate R&D investment. The median share of returns earned abroad is approximately 15 percent, and is closer to 30 percent once endogeneity is accounted for. According to these estimates, most U.S.-based multinational firms earn a substantial share of innovation returns abroad.

6.3 The impact of U.S. parent innovation on value added abroad

The estimates in section 5 indicate innovation investment by U.S. parents has a significant, positive impact on productivity and value added, not only for the parent, but also for its affiliates abroad. An implication of this empirical result is that U.S. R&D investment performed by multinational parents, which as noted in the introduction accounts for nearly all private U.S. R&D investment and is eligible for U.S. research subsidies, increases both the productivity and earned value added of foreign firms. For countries abroad that host a large population of multinational affiliates, our results indicate this cross-border productivity link translates into an economically significant impact of U.S. R&D on value added, or GDP, in these foreign-affiliate host countries.

Figures 5 and 6 (top panel) provide maps indicating the distribution of the market-level, one-period ahead return to U.S. parent R&D across host countries for firms in the computer and industrial machinery sectors. For each industry, one-period ahead return for country n is

$$\frac{\partial \mathbb{E}[\sum_{j\in n} \mathrm{VA}_{jt}|S_{it-1}]}{\partial R_{0t-1}} = \gamma_p \sum_{j\in n} \mathrm{VA}_{jt}/R_{0t-1}.$$

Darker shades in Figures 5 and 6 correspond to systematically higher country-level returns for computers and industrial machinery, respectively; countries shaded white do not host U.S. multinational affiliates in these industries. The five countries receiving the largest industry-level impact of U.S. parent R&D are the United Kingdom, Germany, Canada, Japan, and France in the computer industry; for industrial machinery, Germany, the United Kingdom, France, Canada, and Mexico receive the largest gains in sector-level GDP from a marginal increase in U.S.-parent R&D investment.

The market-level return above is based on the marginal impact on value added of an infinitesimal increase in parent R&D. To instead obtain a proxy for the overall impact of observed parent R&D levels relative to host-country GDP, suppose that the marginal impact of R&D is comparable across each dollar of parent R&D spent, and that the marginal impact is equal to that estimated in section 5 above. The total market-specific impact of U.S. parent innovation investment relative to aggregate GDP in host-country n is then

$$\frac{\partial \mathbb{E}[\sum_{j\in n} \mathrm{VA}_{jt}|S_{it-1}]}{\partial R_{0t-1}} \frac{R_{0t-1}}{\mathrm{GDP}_{nt}} = \gamma_p \sum_{j\in n} \mathrm{VA}_{jt}/\mathrm{GDP}_{nt}.$$

The lower panel combines the country-level impact with aggregate GDP in the host country, and shows the distribution across countries in the ratio of the impact of parent R&D investment to host-country GDP. Top countries are Malaysia, Canada, UK, Belgium, Sweden, Finland in industrial machinery; Swaziland, Malaysia, Canada, UK, Denmark for computers.

7 Conclusion

This paper uses detailed information on parent and affiliate-level innovation and production to measure the private return to multinational firms' innovation investment. We develop a dynamic model of firm innovation that explicitly accounts for intrafirm knowledge transfer across production sites. The model provides a detailed empirical framework that we apply to estimate innovation returns within a comprehensive panel of U.S. multinationals during 1989–2008. We find that the data are consistent with innovation generating returns at firm locations beyond the innovating site within five major manufacturing industries. Specifically, accounting for cross-plant effects of innovation, our estimates indicate conservatively that firms realize between 30 and 40 percent of the return to U.S. parent R&D abroad, suggesting single-plant estimates may understate firms' gain from innovation.

Government industrial policy—including innovation and production incentives—is likely to be a key force shaping multinationals' activity across countries (Hines 1994, 1995). Many countries including the United States subsidize private R&D to encourage local innovation and growth. Our results indicate that local policies aimed at stimulating innovation may indirectly contribute to productivity gains abroad. Evaluating the implications of this effect for policies including the R&D tax credit and intellectual property reform is an important area for future research.

Finally, our estimates are connected to a literature that has examined the equilibrium relationship between international technology diffusion and economic growth across countries. The results presented here reveal that multinational activity systematically influences the diffusion of ideas across countries through a within-firm channel. Our estimates thus indicate the potential importance of future research aimed at building active agents and directed technology diffusion into models of international idea diffusion and growth.

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Table 1: Summary Statistics by Industry, 1989-2008

Industry	Industrial Machinery	Electronics	Instruments and Devices	Chemicals	Transportation Equipment
Affiliate-Level Variables					
Log value added, mean	10.43	10.45	10.37	10.47	10.57
Standard deviation	1.23	1.18	1.11	1.18	1.29
Log labor (number of employees), mean	5.94	6.12	5.81	5.74	6.25
Standard deviation	1.31	1.35	1.29	1.25	1.43
Log capital, mean	9.74	9.96	9.79	10.06	10.17
Standard deviation	1.78	1.82	1.78	1.81	1.81
Log R&D expenditure, mean	7.21	7.60	7.53	7.24	7.70
Standard deviation	1.97	2.01	1.90	1.97	2.02
U.S. Parent-Level Variables					
Log value added, mean	14.26	14.20	13.82	14.52	14.97
Standard deviation	1.55	1.55	1.62	1.44	1.70
Log labor (number of employees), mean	9.63	9.62	9.21	9.53	10.47
Standard deviation	1.42	1.46	1.53	1.28	1.47
Log capital, mean	15.78	15.46	15.18	16.37	16.56
Standard deviation	2.93	2.84	2.96	2.64	3.28
Log R&D expenditure, mean	12.08	12.18	12.04	12.43	12.90
Standard deviation	1.96	1.90	1.76	1.83	2.18

Notes: This table summarizes multinational activity for five industries during 1989 through 2008. All variables are from the Bureau of Economic Analysis Survey of U.S. Direct Investment Abroad, and pertain to U.S. outward foreign direct investment reported annually during this sample period. Labor is the number of employees. Values are in log thousands of U.S. dollars in 2004.

Table 2: Descriptive Evidence, Innovation in Multinational Firms

Industry	Industrial Machinery	Electronics	Instruments and Devices	Chemicals	Transportation Equipment
Industry-Level Variables					
Fraction of firms with total R&D > 0	0.9091	0.8896	0.9251	0.9325	0.9167
Fraction of firms with parent R&D > 0	0.8864	0.8734	0.9031	0.9241	0.9091
Fraction of firms with total affiliate R&D > 0	0.4545	0.5065	0.5507	0.5654	0.5227
Firm-Level Variables					
R&D Intensity (R&D / Sales)					
Firm, mean	0.0362	0.0443	0.0607	0.0534	0.0314
Standard deviation	0.0526	0.0506	0.0540	0.1610	0.0474
Parent, mean	0.0580	0.0585	0.0859	0.0675	0.0368
Standard deviation	0.1372	0.0651	0.0733	0.1790	0.0528
Affiliates, mean	0.0069	0.0110	0.0128	0.0216	0.0095
Standard deviation	0.0160	0.0249	0.0256	0.1863	0.0245
Share of affiliates with R&D > 0, mean	0.2371	0.2826	0.2659	0.2901	0.2329
Standard deviation	0.3365	0.3621	0.3383	0.3314	0.2937
Affiliate share in firm R&D expenditure, mean	0.1056	0.1030	0.1226	0.1186	0.1108
Standard deviation	0.2093	0.1983	0.2186	0.1933	0.1989

Notes: This table summarizes multinational activity for five industries in the benchmark year 1994. All variables are from the Bureau of Economic Analysis Survey of U.S. Direct Investment Abroad, and pertain to U.S. outward foreign direct investment reported annually during this sample period.

Table 3: Descriptive Evidence, Average Characteristics of The Firm, by Industry

Industry	Industrial Machinery	Electronics	Instruments and Devices	Chemicals	Transportation Equipment
Number of affiliates	7.83	7.52	7.82	14.62	11.38
Number of affiliates with R&D > 0	1.81	1.91	1.91	4.95	3.07
Total R&D expenditure	$69.1 million	$86.7 million	$69.2 million	$121 million	$309 million
Affiliate share of total R&D	10.56%	10.30%	12.26%	11.85%	11.08%
Top affiliate locations, by employment					
	United Kingdom	Mexico	Japan	Mexico	Mexico
	France	United Kingdom	United Kingdom	United Kingdom	Germany
	Japan	Germany	Germany	Germany	Canada
	Canada	Malaysia	France	Canada	United Kingdom
	Mexico	Canada	Mexico	France	Brazil
Top affiliate locations, by R&D					
	Germany	Germany	United Kingdom	Japan	Germany
	France	Japan	France	United Kingdom	United Kingdom
	Ireland	United Kingdom	Germany	France	Canada
	Japan	France	Japan	Germany	France
	Singapore	Canada	Canada	Belgium	Brazil

Notes: This table summarizes average characteristics of the multinational firm for five industries during 1994. All values are computed using data from the Bureau of Economic Analysis Survey of U.S. Direct Investment Abroad, and pertain to U.S. outward foreign direct investment. Number of affiliates, Number of affiliates with R&D > 0, Total R&D expenditure, and Affiliate share of total R&D are unweighted averages across firms in the regression sample. Top affiliate locations, by employment, lists the five countries with the highest number of affiliate employees in our regression sample, ranked from first to fifth. Top affiliate locations, by R&D, is analogous but based on total affiliate R&D expenditures in the industry and country.

Table 4: Parent and Affiliate R&D Investment and Productivity Change, Computer Industry

	(1)	(2)	(3)	(4)	(5)	(6)
	Parent firms		Foreign affiliates			
Productivity (t-1), ρ_{02}	0.9200	0.9212				
	0.0244***	0.0248***				
Productivity (t-1), R&D > 0, ρ_2			0.8720	0.8537	0.8714	0.8545
			0.0255***	0.0273***	0.0258***	0.0273***
Productivity (t-1), R&D = 0, ρ_1			0.8447	0.8327	0.8443	0.8330
			0.0263***	0.0273***	0.0264***	0.0273***
Parent R&D (t-1), γ_{0p}, γ_p	0.0109	0.0111		0.0105		0.0115
	0.0043**	0.0044**		0.0040***		0.0043***
Total affiliate R&D (t-1), γ_{0a}		-0.0005				
		0.0019				
Affiliate R&D (t-1), γ_a			0.0159	0.0140	0.0158	0.0144
			0.0040***	0.0040***	0.0040***	0.0040***
Labor elasticity, mean	0.8157	0.8157	0.4509	0.4509	0.4509	0.4509
Labor elasticity, standard dev.	0.0219	0.0219	0.0674	0.0674	0.0674	0.0674
Capital elasticity, mean	0.0976	0.0976	0.1649	0.1668	0.1651	0.1661
Capital elasticity, standard dev.	0.0228	0.0232	0.0226	0.0224	0.0226	0.0224
Year FE	Y	Y	−	−	−	−
Market-Year FE	−	−	Y	Y	Y	Y
Market-Year x 1{R&D > 0} FE	−	−	Y	Y	Y	Y
Other affiliate R&D (t-1)	−	−	N	N	Y	Y
N	536	536	3,290	3,290	3,290	3,290
R^2	0.8724	0.8712	0.8923	0.8928	0.8923	0.8929

Notes: ** $p < 0.05$, *** $p < 0.01$. This table provides GMM estimates of the parameters in equation (12) for foreign affiliates, and estimates of an analogous equation for U.S. parents in the computer industry, SIC 357, during 1989−2008. All specifications measure the impact of R&D investment on value added and productivity change. Columns 1 and 2 evaluate the full sample of U.S. parents; columns 3 through 6 evaluate corresponding majority-owned, manufacturing affiliates located abroad. Labor (number of employees), capital (plant, property and equipment), value added, and R&D expenditure for parents and each foreign affiliate are from the Bureau of Economic Analysis Survey of U.S. Direct Investment Abroad, and pertain to U.S. outward foreign direct investment reported annually during this sample period. The estimated mean elasticities of value added with respect to labor and capital are reported above along with respective standard deviations. Standard errors clustered by firm-year appear below each point estimate.

Table 5: Parent and Affiliate R&D Investment and Productivity Change, Industrial Machinery

	(1)	(2)	(3)	(4)	(5)	(6)
	Parent firms		Foreign affiliates			
Productivity (t-1), ρ_{02}	0.8384	0.8341				
	0.0105***	0.0106***				
Productivity (t-1), R&D > 0, ρ_2			0.6744	0.6671	0.6699	0.6658
			0.0135***	0.0135***	0.0136***	0.0136***
Productivity (t-1), R&D = 0, ρ_1			0.7253	0.7204	0.7213	0.7191
			0.0130***	0.0130***	0.0131***	0.0130***
Parent R&D (t-1), γ_{0p}, γ_p	0.0145	0.0132		0.0094		0.0085
	0.0015***	0.0016***		0.0019***		0.0020***
Total affiliate R&D (t-1), γ_{0a}		0.0034				
		0.0012***				
Affiliate R&D (t-1), γ_a			0.0161	0.0153	0.0153	0.0150
			0.0031***	0.0031***	0.0031***	0.0031***
Labor elasticity, mean	0.7271	0.7271	0.5442	0.5442	0.5442	0.5442
Labor elasticity, standard dev.	0.0376	0.0376	0.0779	0.0779	0.0779	0.0779
Capital elasticity, mean	0.1220	0.1185	0.1794	0.1718	0.1788	0.1723
Capital elasticity, standard dev.	0.0397	0.0371	0.0328	0.0295	0.0319	0.0294
Year FE	Y	Y	−	−	−	−
Market-Year FE	−	−	Y	Y	Y	Y
Market-Year x 1{R&D > 0} FE	−	−	Y	Y	Y	Y
Other affiliate R&D (t-1)	−	−	N	N	Y	Y
N	2,609	2,609	5,016	5,016	5,016	5,016
R^2	0.9583	0.9584	0.8460	0.8468	0.8463	0.8469

Notes: ** $p < 0.05$, *** $p < 0.01$. This table provides GMM estimates of the parameters in equation (12) for foreign affiliates, and estimates of an analogous equation for U.S. parents in the industrial machinery sector, SIC 35, during 1989−2008. All specifications measure the impact of R&D investment on value added and productivity change. Columns 1 and 2 evaluate the full sample of U.S. parents; columns 3 through 6 evaluate corresponding majority-owned, manufacturing affiliates located abroad. Labor (number of employees), capital (plant, property and equipment), value added, and R&D expenditure for parents and each foreign affiliate are from the Bureau of Economic Analysis Survey of U.S. Direct Investment Abroad, and pertain to U.S. outward foreign direct investment reported annually during this sample period. The estimated mean elasticities of value added with respect to labor and capital are reported above along with respective standard deviations. Standard errors clustered by firm-year appear below each point estimate.

Table 6: R&D Investment and Affiliate Productivity Change, Computer Industry, Heterogeneity

	(1)	(2)	(3)	(4)
	Foreign affiliates			
Productivity (t-1), R&D > 0, ρ_2	0.7929	0.8299	0.8543	0.8348
	0.0172***	0.0163***	0.0160***	0.0171***
Productivity (t-1), R&D = 0, ρ_1	0.8105	0.8204	0.8331	0.8374
	0.0130***	0.0131***	0.0130***	0.0131***
Parent R&D (t-1), γ_p	0.0021	0.0002	0.0135	0.0059
	0.0029	0.0034	0.0035***	0.0029**
Parent R&D x Royalties (t-1), γ_x	0.0019			
	0.0005***			
Parent R&D x Imports (t-1), γ_x		0.0009		
		0.0005*		
Parent R&D x Industrial Distance (t-1), γ_x			-0.0087	
			0.0067	
Parent R&D x Affiliate R&D (t-1), γ_x				0.0019
				0.0006***
Affiliate R&D (t-1), γ_a	0.0150	0.0103	0.0140	-0.0125
	0.0037***	0.0037***	0.0037***	0.0094
Labor elasticity, mean	0.4509	0.4509	0.4509	0.4509
Labor elasticity, standard dev.	0.0674	0.0674	0.0674	0.0674
Capital elasticity, mean	0.1556	0.1575	0.1673	0.1686
Capital elasticity, standard dev.	0.0218	0.0220	0.0225	0.0224
Market-Year FE	Y	Y	Y	Y
Market-Year x 1{R&D > 0} FE	Y	Y	Y	Y
N	3,290	3,290	3,290	3,290

Notes: ** $p < 0.05$, *** $p < 0.01$. This table provides GMM estimates of the parameters in equation (12) modified by (13) for foreign affiliates of U.S. parents in the computer industry, SIC 357, during 1989−2008. Columns 1 through 4 evaluate heterogeneity in the impact of parent R&D on affiliate value added and productivity change. In column 3, industrial distance is the Euclidean distance between parent- and affiliate-specific vectors of sales across their respective five reported industries. Labor (number of employees), capital (plant, property and equipment), value added, R&D expenditure, royalties paid to the U.S. parent, and imports received from the U.S. parent for each foreign affiliate are from the Bureau of Economic Analysis Survey of U.S. Direct Investment Abroad, and pertain to U.S. outward foreign direct investment reported annually during this sample period. The estimated mean elasticities of value added with respect to labor and capital are reported above along with respective standard deviations. Standard errors clustered by firm-year appear below each point estimate.

Table 7: R&D Investment and Affiliate Productivity Change, Computer Industry, Heterogeneity

	(1)	(2)	(3)	(4)
	Foreign affiliates			
Productivity (t-1), R&D > 0, ρ_2	0.6571	0.6605	0.6681	0.6657
	0.0136***	0.0136***	0.0135***	0.0136***
Productivity (t-1), R&D = 0, ρ_1	0.7139	0.7160	0.7204	0.7216
	0.0129***	0.0130***	0.0130***	0.0130***
Parent R&D (t-1), γ_p	0.0040	0.0002	0.0164	0.0110
	0.0021*	0.0034	0.0028***	0.0047**
Parent R&D x Royalties (t-1), γ_x	0.0017			
	0.0004***			
Parent R&D x Imports (t-1), γ_x		0.0012		
		0.0003***		
Parent R&D x Industrial Distance (t-1), γ_x			-0.0161	
			0.0048***	
Parent R&D x Affiliate R&D (t-1), γ_x				0.0003
				0.0003
Affiliate R&D (t-1), γ_a	0.0154	0.0103	0.0152	0.0080
	0.0031***	0.0037***	0.0031***	0.0022***
Labor elasticity, mean	0.5442	0.5442	0.5442	0.5442
Labor elasticity, standard dev.	0.0779	0.0779	0.0779	0.0779
Capital elasticity, mean	0.1562	0.1623	0.1703	0.1715
Capital elasticity, standard dev.	0.0248	0.0271	0.0289	0.0295
Market-Year FE	Y	Y	Y	Y
Market-Year x 1{R&D > 0} FE	Y	Y	Y	Y
N	5,016	5,016	5,016	5,016

Notes: ** $p < 0.05$, *** $p < 0.01$. This table provides GMM estimates of the parameters in equation (12) modified by (13) for foreign affiliates of U.S. parents in the industrial machinery sector, SIC 35, during 1989−2008. Columns 1 through 4 evaluate heterogeneity in the impact of parent R&D on affiliate value added and productivity change. In column 3, industrial distance is the Euclidean distance between parent- and affiliate-specific vectors of sales across their respective five reported industries. Labor (number of employees), capital (plant, property and equipment), value added, R&D expenditure, royalties paid to the U.S. parent, and imports received from the U.S. parent for each foreign affiliate are from the Bureau of Economic Analysis Survey of U.S. Direct Investment Abroad, and pertain to U.S. outward foreign direct investment reported annually during this sample period. The estimated mean elasticities of value added with respect to labor and capital are reported above along with respective standard deviations. Standard errors clustered by firm-year appear below each point estimate.

Table 8: Parent and Affiliate R&D Investment and Productivity Change, Computer Industry, Endogeneity

	(1)	(2)	(3)	(4)	(5)	(6)
	Parent firms		Foreign affiliates			
Productivity (t-1), ρ_{02}	0.8860	0.8878				
	0.0297***	0.0297***				
Productivity (t-1), R&D > 0, ρ_2			0.7373	0.6535	0.7446	0.6673
			0.0521***	0.0748***	0.0499***	0.0705***
Productivity (t-1), R&D = 0, ρ_1			0.8559	0.7961	0.8584	0.8029
			0.0121***	0.0217***	0.0124***	0.0199***
Parent R&D (t-1), γ_{0p}, γ_p	0.0239	0.0257		0.0544		0.0606
	0.0088***	0.0086***		0.0186***		0.0220***
Total affiliate R&D (t-1), γ_{0a}		-0.0018				
		0.0016				
Affiliate R&D (t-1), γ_a			0.0937	0.0795	0.0944	0.0827
			0.0290***	0.0330***	0.0288***	0.0332***
Labor elasticity, mean	0.8157	0.8157	0.4509	0.4509	0.4509	0.4509
Labor elasticity, standard dev.	0.0219	0.0219	0.0674	0.0674	0.0674	0.0674
Capital elasticity, mean	0.0976	0.0976	0.1324	0.1477	0.1311	0.1450
Capital elasticity, standard dev.	0.0146	0.0148	0.0248	0.0286	0.0247	0.0281
Year FE	Y	Y	−	−	−	−
Market-Year FE	−	−	Y	Y	Y	Y
Market-Year x 1{R&D > 0} FE	−	−	Y	Y	Y	Y
Other affiliate R&D (t-1)	−	−	N	N	Y	Y
Instruments for parent R&D	Y	Y	−	Y	−	Y
Instruments for affiliate R&D	N	N	Y	Y	Y	Y
N	536	536	3,290	3,290	3,290	3,290

Notes: ** $p < 0.05$, *** $p < 0.01$. This table provides GMM estimates of the parameters in equation (12) for foreign affiliates, and estimates of an analogous equation for U.S. parents in the computer industry, SIC 357, during 1989−2008. All specifications measure the impact of R&D investment on value added and productivity change. The instrument for parent innovation is the user cost of R&D, which reflects the state-level R&D tax credit, prevailing in the U.S. state corresponding to the parent address; the instrument for affiliate innovation is the interaction between the parent user cost of R&D and the quality of intellectual property institutions in the affiliate host country. Data on R&D tax credits and the user cost of R&D by state-year are from Wilson (2009); intellectual property rights by country-year are from (Ginarte and Park 1997) and Park (2008). Conditional and unconditional correlations between innovation and each instrument are strong; the nonlinearity of the estimating equation precludes a formal first-stage test. Columns 1 and 2 evaluate the full sample of U.S. parents; columns 3 through 6 evaluate corresponding majority-owned, manufacturing affiliates located abroad. Labor (number of employees), capital (plant, property and equipment), value added, and R&D expenditure for parents and each foreign affiliate are from the Bureau of Economic Analysis Survey of U.S. Direct Investment Abroad, and pertain to U.S. outward foreign direct investment reported annually during this sample period. The estimated mean elasticities of value added with respect to labor and capital are reported above along with respective standard deviations. Standard errors clustered by firm-year appear below each point estimate.

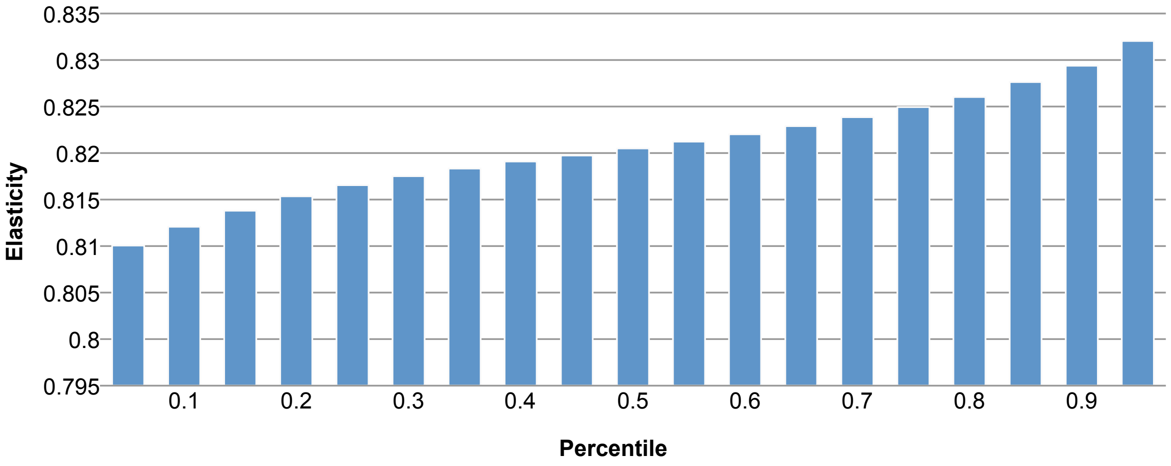
Table 9: Parent and Affiliate R&D Investment and Productivity Change, Industrial Machinery, Endogeneity

	(1)	(2)	(3)	(4)	(5)	(6)
	Parent firms		Foreign affiliates			
Productivity (t-1), ρ_{02}	0.7556	0.7662				
	0.0540***	0.0558***				
Productivity (t-1), R&D > 0, ρ_2			0.5990	0.5466	0.6023	0.5551
			0.0431***	0.0479***	0.0424***	0.0456***
Productivity (t-1), R&D = 0, ρ_1			0.8692	0.7089	0.8667	0.7202
			0.0270***	0.0355***	0.0280***	0.0352***
Parent R&D (t-1), γ_{0p}, γ_p	0.0478	0.0469		0.0734		0.0866
	0.0127***	0.0155***		0.0160***		0.0186***
Total affiliate R&D (t-1), γ_{0a}		-0.0029				
		0.0031				
Affiliate R&D (t-1), γ_a			0.0888	0.0538	0.0875	0.0603
			0.0179***	0.0206***	0.0180***	0.0219***
Labor elasticity, mean	0.7271	0.7271	0.5442	0.5442	0.5442	0.5442
Labor elasticity, standard dev.	0.0376	0.0376	0.0779	0.0779	0.0779	0.0779
Capital elasticity, mean	0.0696	0.0756	0.1149	0.0978	0.1157	0.0879
Capital elasticity, standard dev.	0.0338	0.0354	0.0221	0.0353	0.0221	0.0359
Year FE	Y	Y	−	−	−	−
Market-Year FE	−	−	Y	Y	Y	Y
Market-Year x 1{R&D > 0} FE	−	−	Y	Y	Y	Y
Other affiliate R&D (t-1)	−	−	N	N	Y	Y
Instruments for parent R&D	Y	Y	−	Y	−	Y
Instruments for affiliate R&D	N	N	Y	Y	Y	Y
N	2,609	2,609	5,016	5,016	5,016	5,016

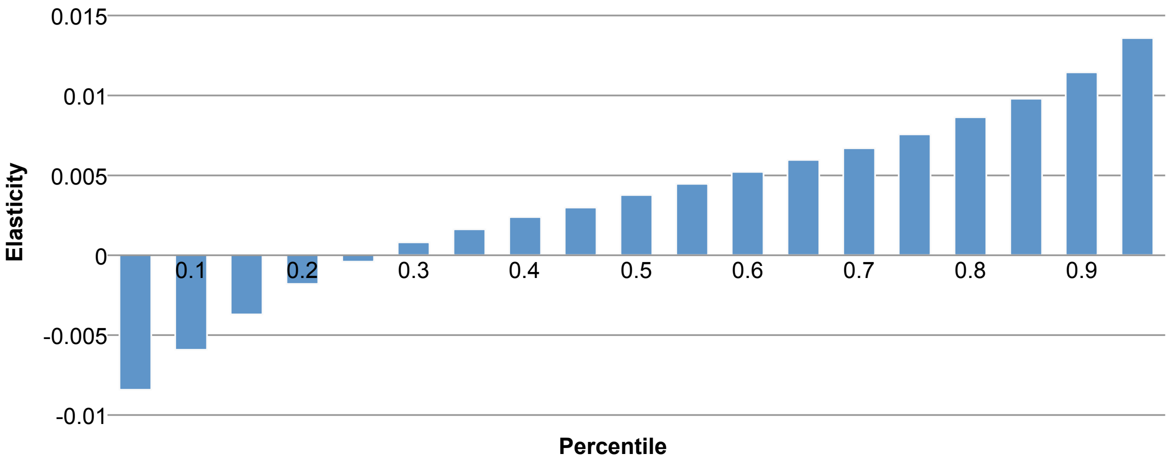
Notes: ** $p < 0.05$, *** $p < 0.01$. This table provides GMM estimates of the parameters in equation (12) for foreign affiliates, and estimates of an analogous equation for U.S. parents in the industrial machinery sector, SIC 35, during 1989−2008. All specifications measure the impact of R&D investment on value added and productivity change. The instrument for parent innovation is the user cost of R&D, which reflects the state-level R&D tax credit, prevailing in the U.S. state corresponding to the parent address; the instrument for affiliate innovation is the interaction between the parent user cost of R&D and the quality of intellectual property institutions in the affiliate host country. Data on R&D tax credits and the user cost of R&D by state-year are from Wilson (2009); intellectual property rights by country-year are from (Ginarte and Park 1997) and Park (2008). Conditional and unconditional correlations between innovation and each instrument are strong; the nonlinearity of the estimating equation precludes a formal first-stage test. Columns 1 and 2 evaluate the full sample of U.S. parents; columns 3 through 6 evaluate corresponding majority-owned, manufacturing affiliates located abroad. Labor (number of employees), capital (plant, property and equipment), value added, and R&D expenditure for parents and each foreign affiliate are from the Bureau of Economic Analysis Survey of U.S. Direct Investment Abroad, and pertain to U.S. outward foreign direct investment reported annually during this sample period. The estimated mean elasticities of value added with respect to labor and capital are reported above along with respective standard deviations. Standard errors clustered by firm-year appear below each point estimate.

Figure 1: Parent and Affiliate R&D Investment and Productivity Change, Computer Industry, Nonlinearity

Panel A − Affiliate productivity persistence, empirical distribution across affiliates



Panel B − The productivity impact of parent R&D, empirical distribution across affiliates



Panel C − The productivity impact of affiliate R&D, empirical distribution across affiliates

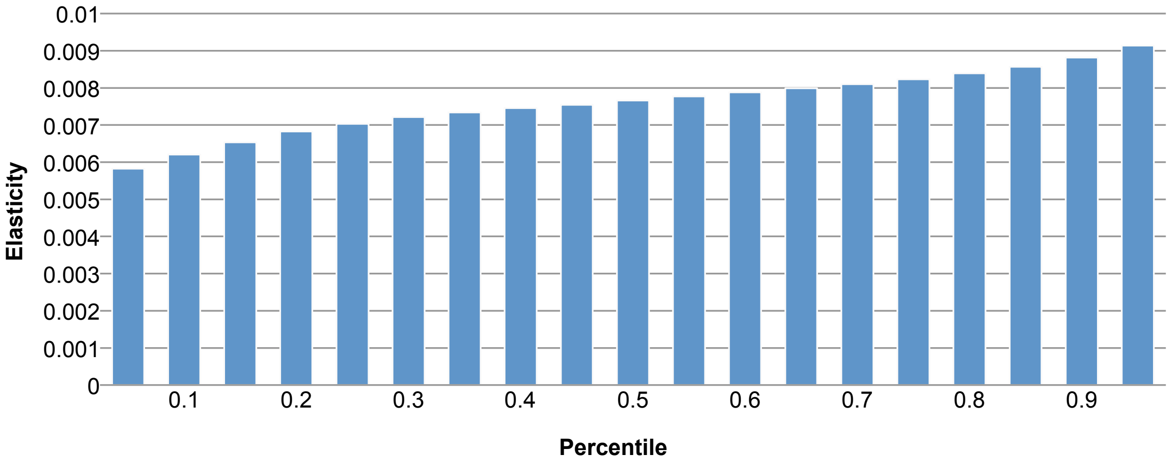
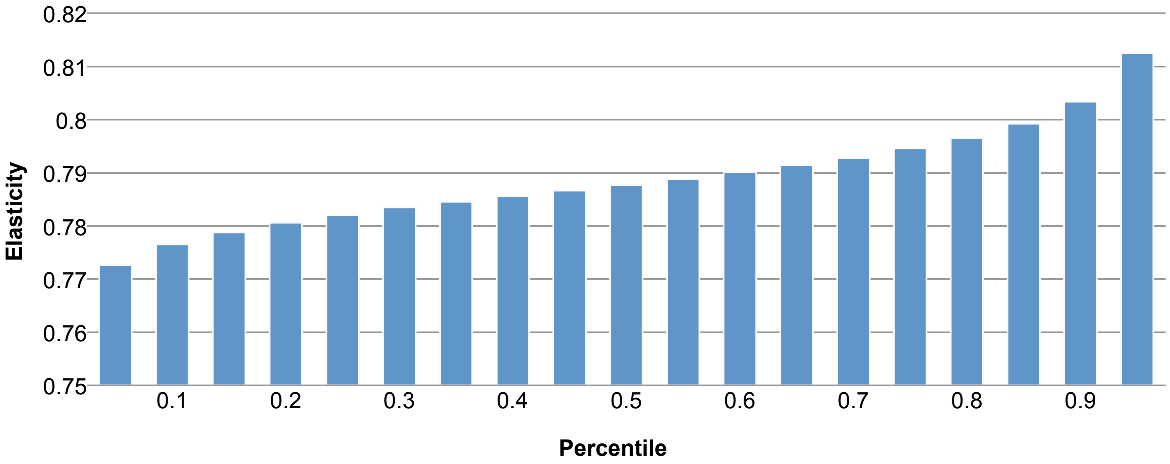
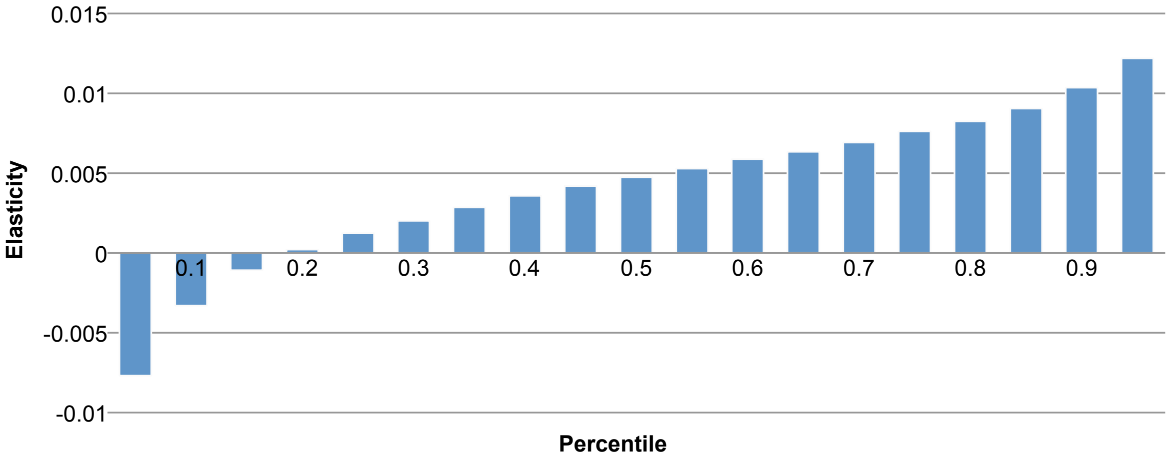


Figure 2: Parent and Affiliate R&D Investment and Productivity Change, Industrial Machinery, Nonlinearity

Panel A − Affiliate productivity persistence, empirical distribution across affiliates



Panel B − The productivity impact of parent R&D, empirical distribution across affiliates



Panel C − The productivity impact of affiliate R&D, empirical distribution across affiliates

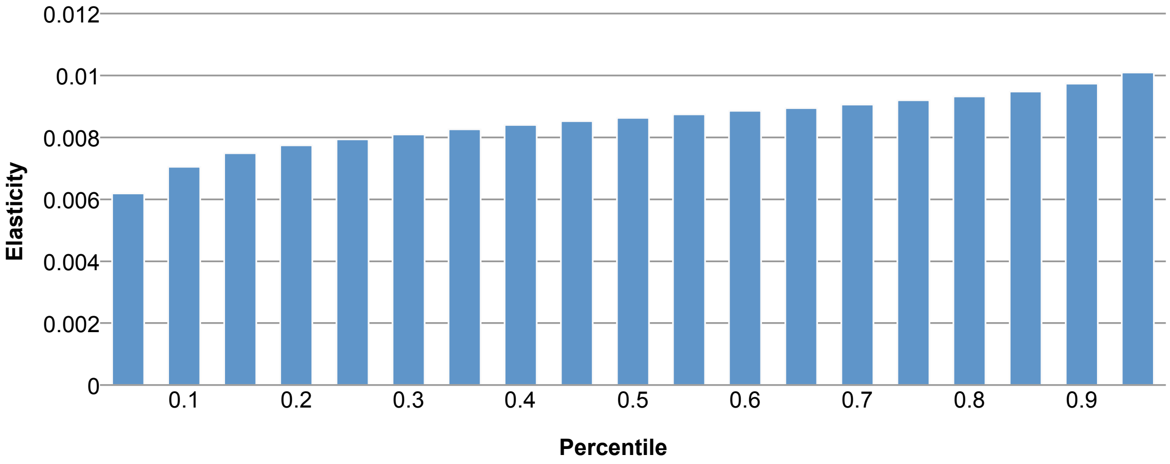
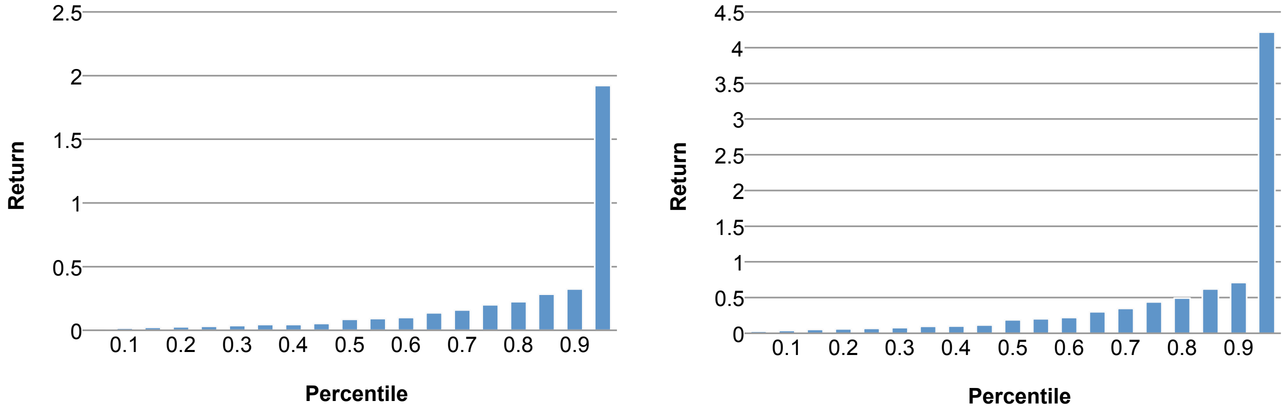


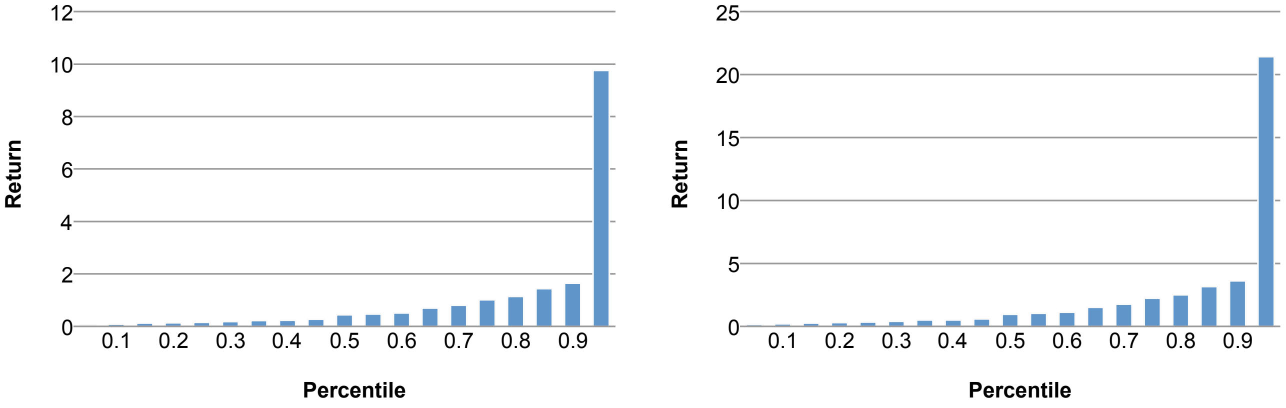
Figure 3: Parent and Affiliate R&D Investment and Productivity Change, Computer Industry, Nonlinearity

Panel A − Parent-level returns to parent R&D, distribution across firms



Private return, one period ahead, distribution across firms

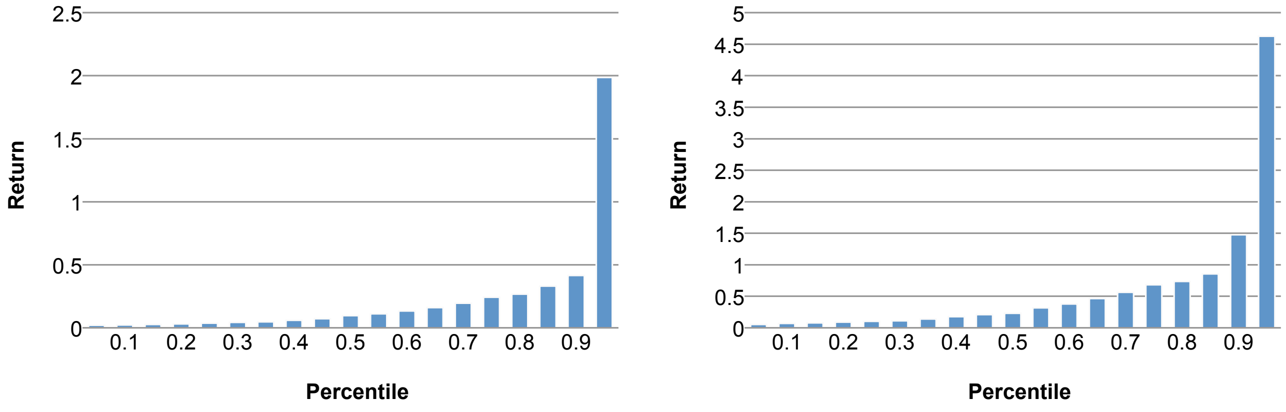
Private return, one period ahead, distribution across firms, endogeneity



Private return, long run, distribution across firms

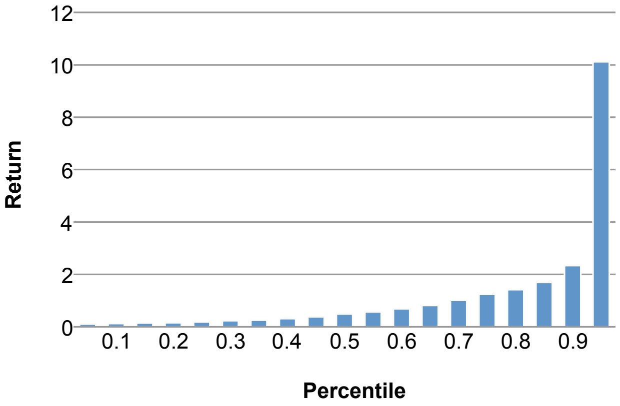
Private return, long run, distribution across firms, endogeneity

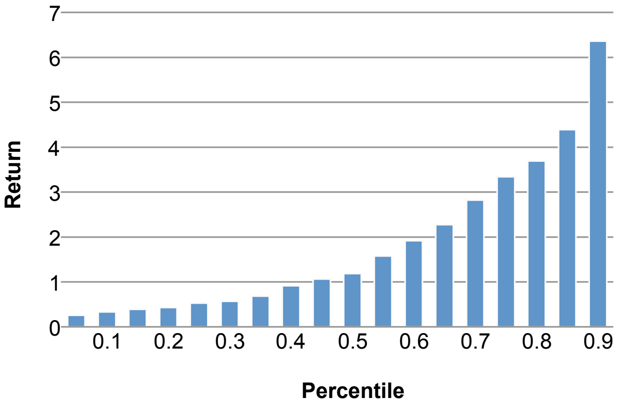
Panel B − Multinational firm-level returns to parent R&D, distribution across firms



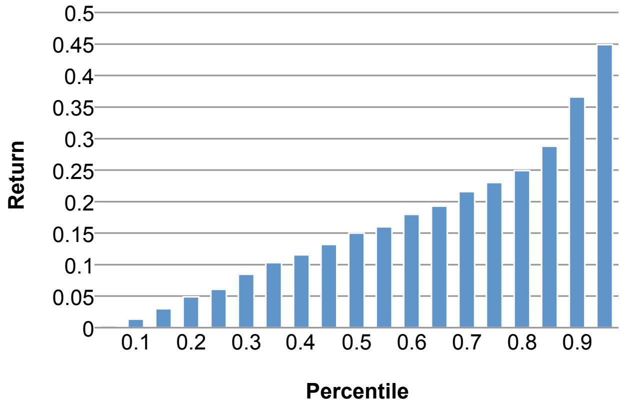
Private return, one period ahead, distribution across firms

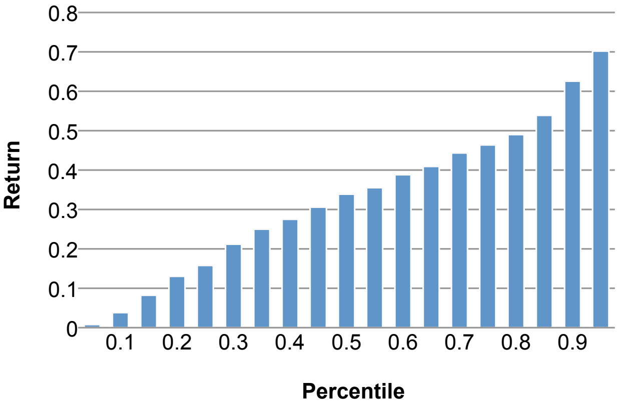
Private return, one period ahead, distribution across firms, endogeneity

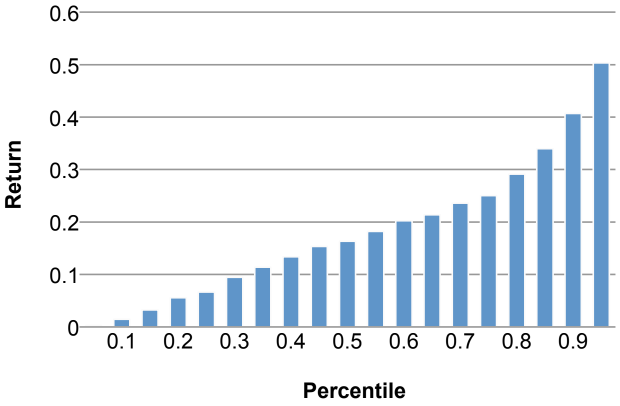

Private return, long run, distribution across firms


Private return, long run, distribution across firms, endogeneity

Panel C − Share of multinational firm-level return to parent R&D earned by foreign affiliates, distribution across firms


Private return, one period ahead, distribution across firms


Private return, one period ahead, distribution across firms, endogeneity


Private return, long run, distribution across firms

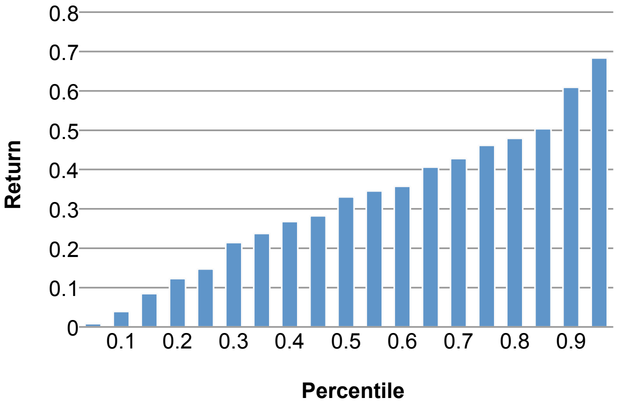

Private return, long run, distribution across firms, endogeneity

Figure 4: Parent and Affiliate R&D Investment and Productivity Change, Industrial Machinery, Nonlinearity

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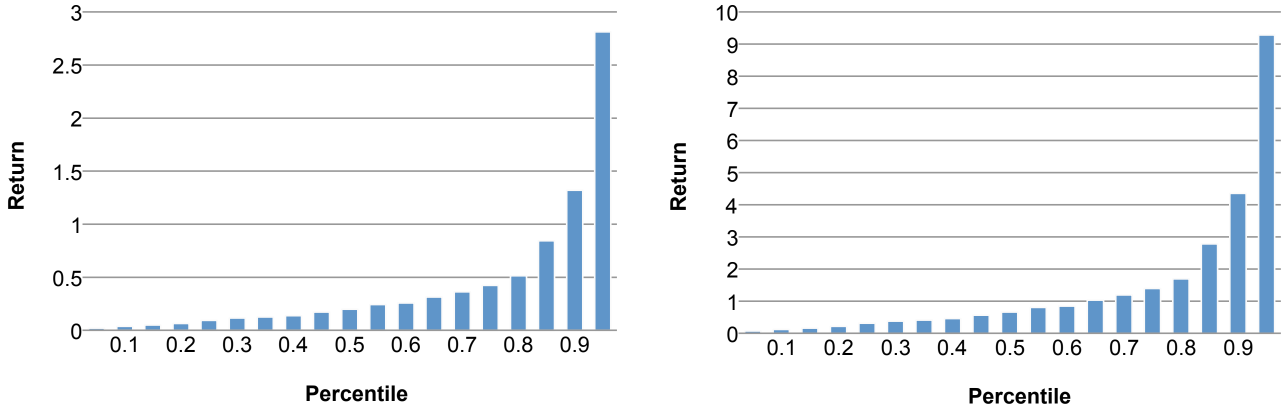
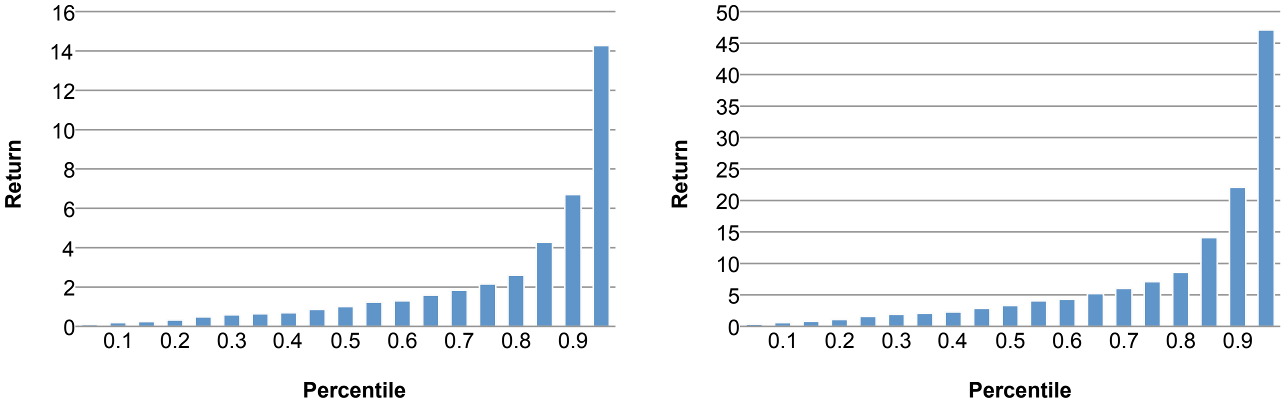
Panel A − Parent-level returns to parent R&D, distribution across firms



Private return, one period ahead, distribution across firms

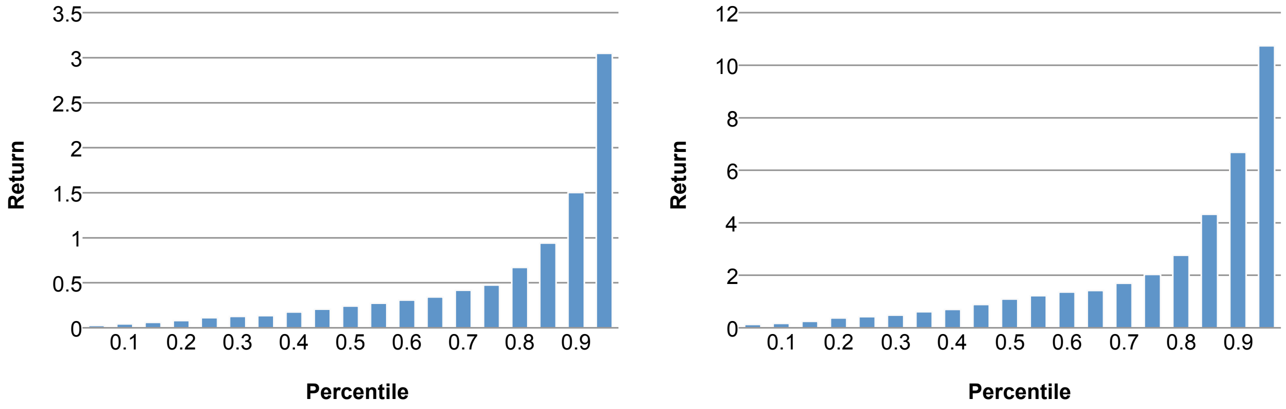
Private return, one period ahead, distribution across firms, endogeneity



Private return, long run, distribution across firms

Private return, long run, distribution across firms, endogeneity

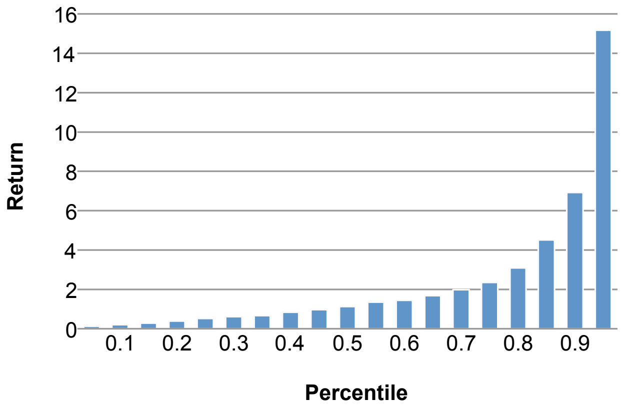
Panel B − Multinational firm-level returns to parent R&D, distribution across firms



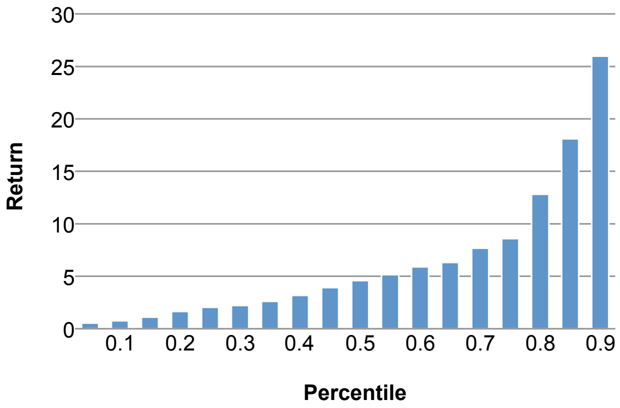
Private return, one period ahead, distribution across firms

Private return, one period ahead, distribution across firms, endogeneity

Private return, long run, distribution across firms

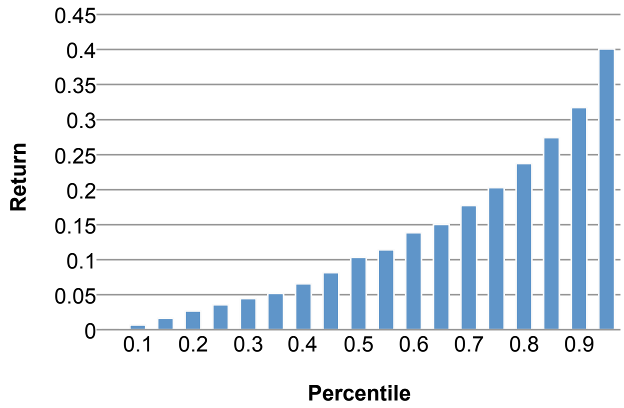


Private return, long run, distribution across firms, endogeneity

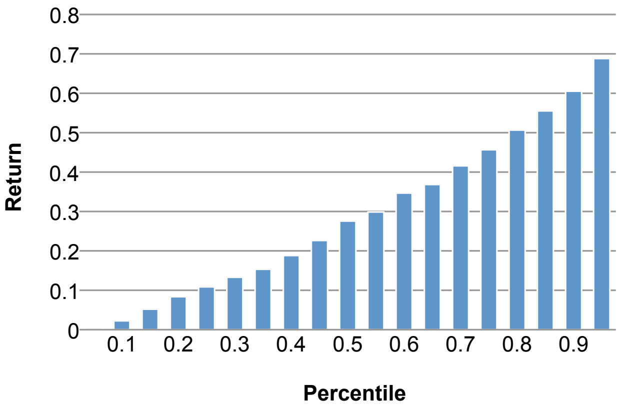


Panel C − Share of multinational firm-level return to parent R&D earned by foreign affiliates, distribution across firms

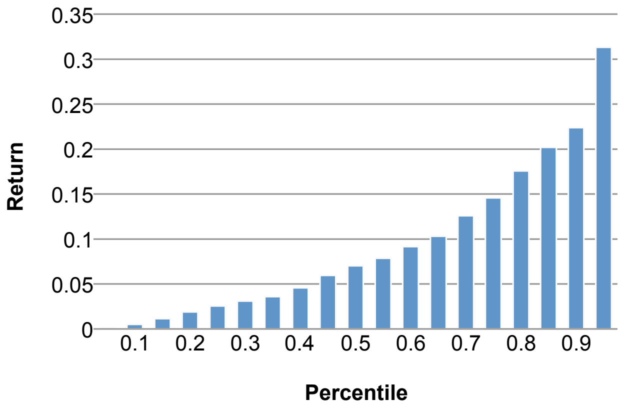
Private return, one period ahead, distribution across firms



Private return, one period ahead, distribution across firms, endogeneity



Private return, long run, distribution across firms



Private return, long run, distribution across firms, endogeneity

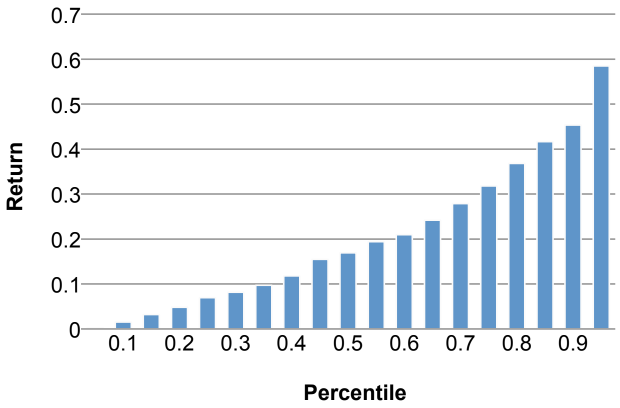
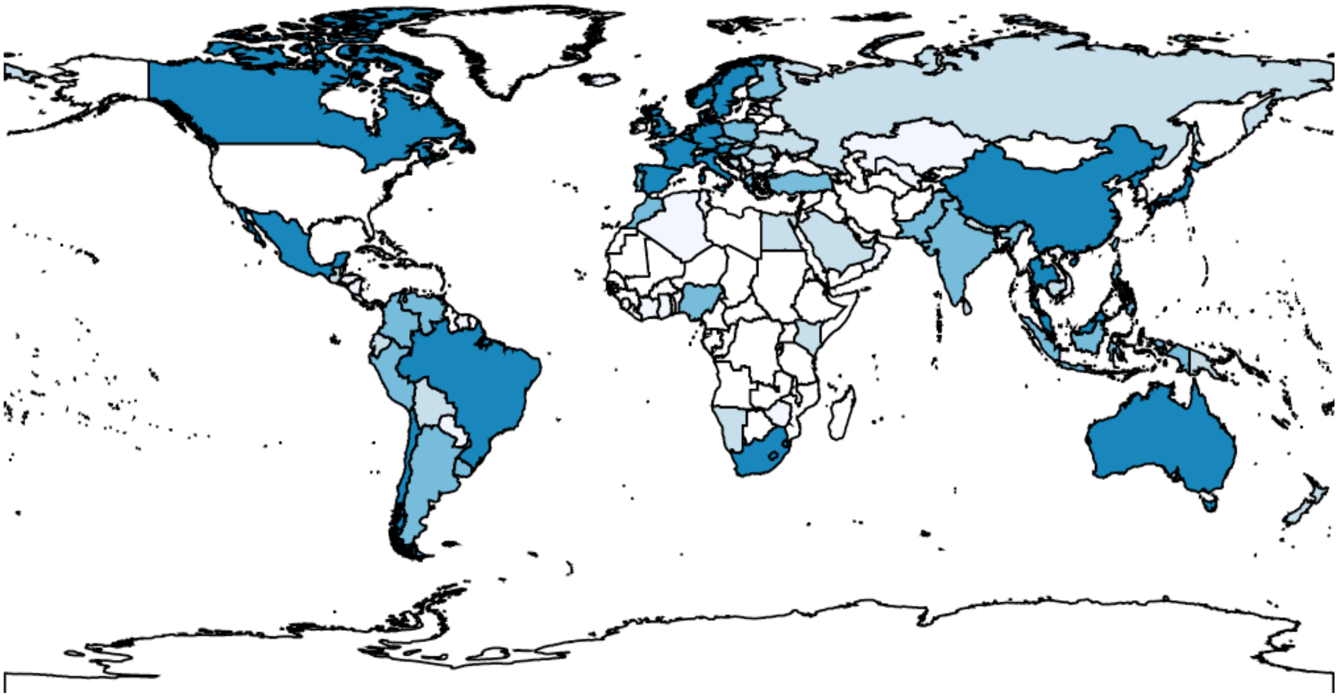


Figure 5: The Impact of U.S. Parent R&D on R&D by Country, Computer Industry

Panel A − The country-level impact of parent R&D on value added, distribution across countries



Panel B − The country-level impact of parent R&D on value added relative to GDP, distribution across countries

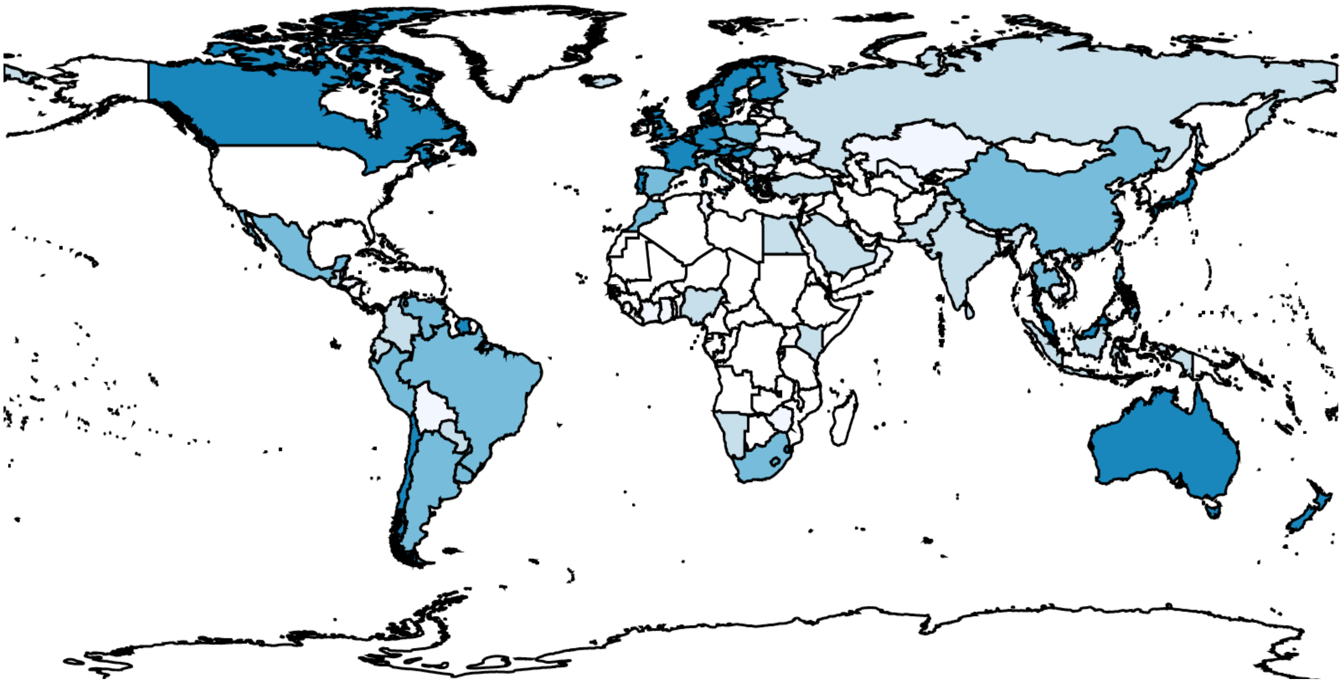


Figure 6: The Impact of U.S. Parent R&D on R&D by Country, Industrial Machinery

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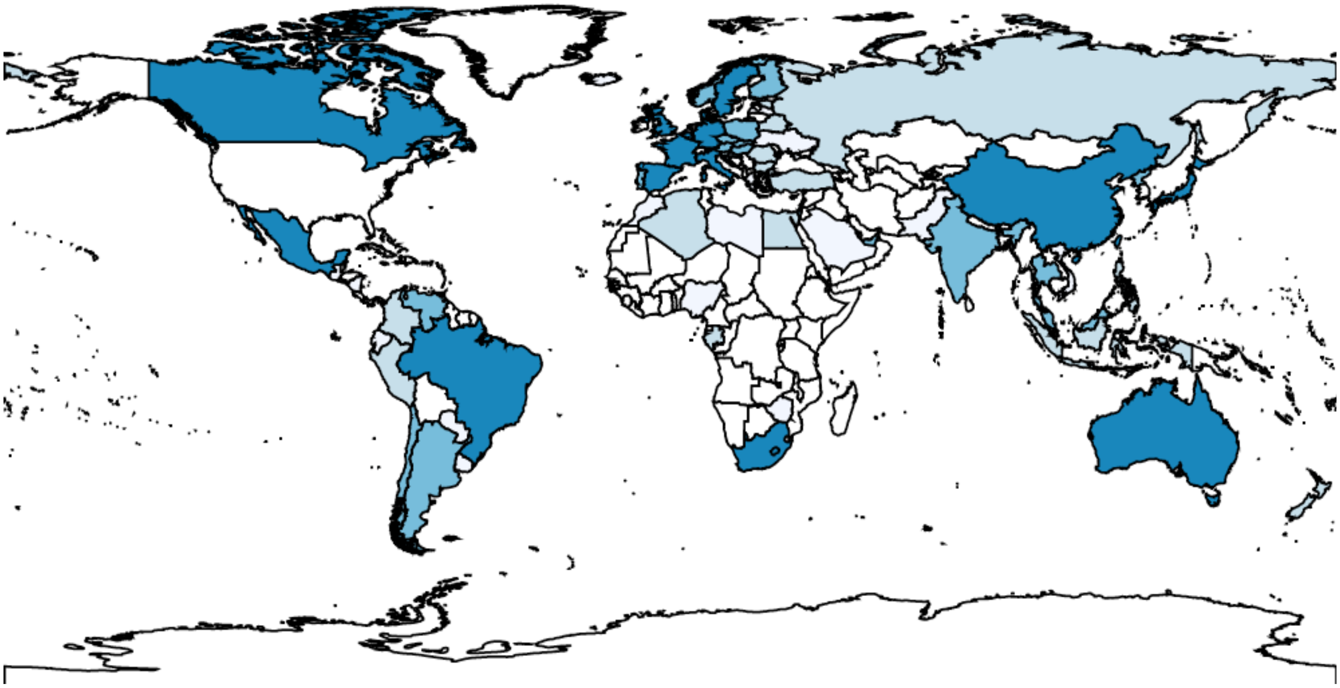
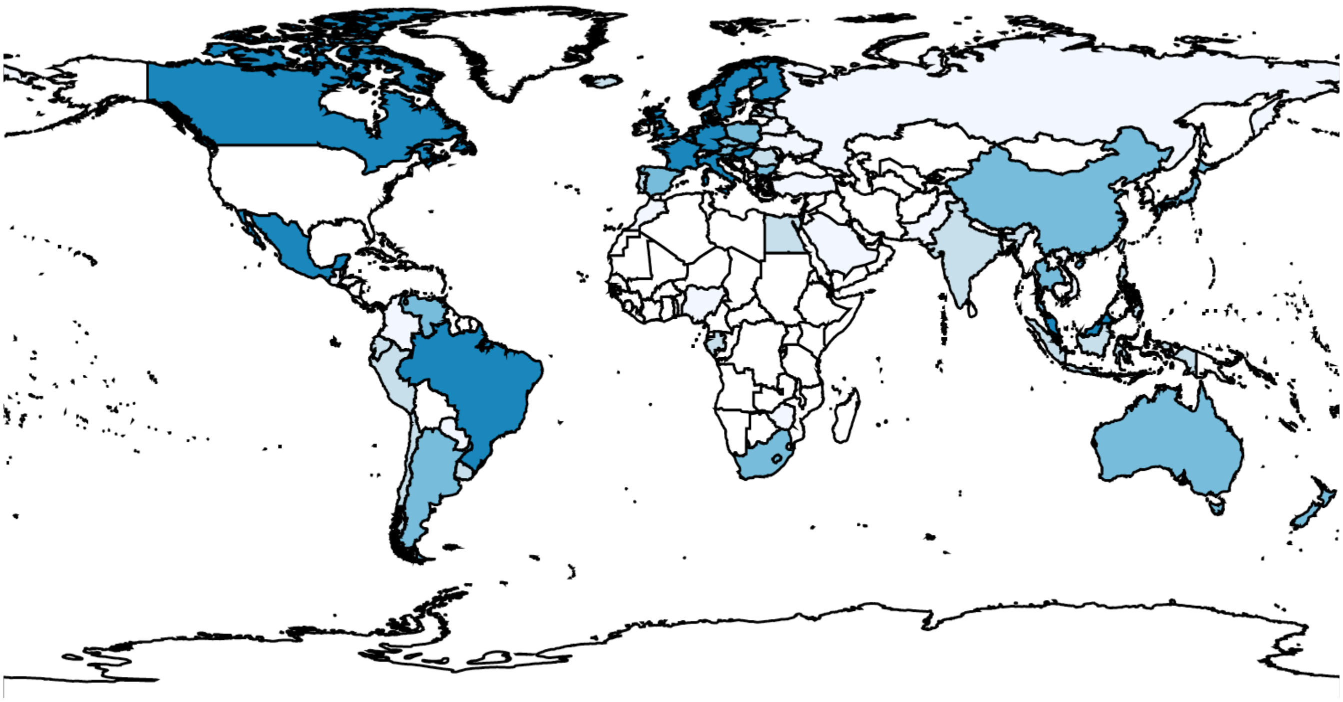
Panel A − The country-level impact of parent R&D on value added, distribution across countries



Panel B − The country-level impact of parent R&D on value added relative to GDP, distribution across countries



Appendix

A.1 Deriving Revenue and Value-Added Functions

We can write the optimization problem that determines the optimal usage of materials by affiliate j at period t as:

$$\max_{M_{jt}} \ M_{jt}^{\frac{\alpha_m(\sigma-1)}{\sigma}} \exp(-\sigma p_{nt} + \frac{1}{\sigma} q_{nt} + \frac{\sigma-1}{\sigma}((1-\alpha_m)h(l_{jt}, k_{jt}; \alpha) + \omega_{jt} + \xi_{jt})) - P_{nt}^m M_{jt}$$

From the first order condition, the log of the optimal quantity of materials, m_{jt}^*, should satisfy the following equation

$$\begin{aligned}
\frac{\alpha_m(\sigma-1)}{\sigma} m_{jt}^* = & \frac{\alpha_m(\sigma-1)}{\sigma - \alpha_m(\sigma-1)} \ln\Big(\frac{\alpha_m(\sigma-1)}{\sigma}\Big) - \frac{\alpha_m(\sigma-1)}{\sigma-\alpha_m(\sigma-1)} p_{nt}^m \\
& + \frac{\alpha_m(\sigma-1)(1-\alpha_m)(\sigma-1)}{\sigma(\sigma-\alpha_m(\sigma-1))} h(l_{jt}, k_{jt}; \alpha) - \frac{\sigma\alpha_m(\sigma-1)}{\sigma-\alpha_m(\sigma-1)} p_{nt} \\
& + \frac{\alpha_m(\sigma-1)}{\sigma(\sigma-\alpha_m(\sigma-1))} q_{nt} + \frac{\alpha_m(\sigma-1)(\sigma-1)}{\sigma(\sigma-\alpha_m(\sigma-1))}(\omega_{jt} + \xi_{jt}).
\end{aligned}$$

Therefore, assuming that firms choose their consumption of materials optimally, we can rewrite the revenue function as

$$\begin{aligned}
y_{jt} = & \frac{\alpha_m(\sigma-1)}{\sigma-\alpha_m(\sigma-1)} \ln\Big(\frac{\alpha_m(\sigma-1)}{\sigma}\Big) - \frac{\alpha_m(\sigma-1)}{\sigma-\alpha_m(\sigma-1)} p_{nt}^m - \frac{\sigma^2}{\sigma-\alpha_m(\sigma-1)} p_{nt} \\
& + \frac{1}{\sigma-\alpha_m(\sigma+1)} q_{nt} + \frac{(1-\alpha_m)(\sigma-1)}{\sigma-\alpha_m(\sigma-1)} h(l_{jt}, k_{jt}; \alpha) + \frac{(\sigma-1)}{\sigma-\alpha_m(\sigma-1)}(\omega_{jt} + \xi_{jt}),
\end{aligned}$$

or, equivalently in a more compact notation,

$$y_{jt} = \kappa_{nt}^1 + \kappa^2((1-\alpha_m)h(l_{jt}, k_{jt}; \alpha) + \psi_{jt}),$$

where

$$\begin{aligned}
\kappa_{nt}^1 &= \kappa^2 \Big(\alpha_m \ln\Big(\frac{\alpha_m(\sigma-1)}{\sigma}\Big) - \alpha_m p_{nt}^m - \frac{\sigma^2}{\sigma-1} p_{nt} + \frac{1}{\sigma-1} q_{nt}\Big), \\
\kappa^2 &= \frac{(\sigma-1)}{\sigma-\alpha_m(\sigma-1)}, \\
\psi_{jt} &= \omega_{jt} + \xi_{jt}.
\end{aligned}$$

Given that the function $h(l_{jt}, k_{jt}; \alpha)$ is linear in α, we can rewrite the revenue function as:

$$y_{jt} = \kappa_{nt}^{1} + h(l_{jt}, k_{jt}; \beta) + \kappa^{2}\psi_{jt},$$

where $\beta = \alpha\kappa^{2}(1 - \alpha_m)$.

Value added is defined as

$$VA_{jt} = Y_{jt} - P_{nt}^{m} M_{jt}^{*}.$$

From the first order condition for materials,

$$P_{nt}^{m} M_{jt}^{*} = \Big(\frac{\alpha_m(\sigma - 1)}{\sigma}\Big) Y_{jt}$$

and, therefore,

$$VA_{jt} = \Big(1 - \frac{\alpha_m(\sigma - 1)}{\sigma}\Big) Y_{jt},$$

or, equivalently,

$$va_{jt} = \kappa_{nt}^{3} + h(l_{jt}, k_{jt}; \beta) + \kappa^{2}\psi_{jt},$$

where

$$\kappa_{nt}^{3} = \ln\Big(1 - \frac{\alpha_m(\sigma - 1)}{\sigma}\Big) + \kappa_{nt}^{1}.$$

Given observed values for VA_{jt} and Y_{jt}, we can rewrite κ_2 as

$$\kappa_2 = \frac{\frac{\sigma-1}{\sigma}}{1 - \frac{\alpha_m(\sigma-1)}{\sigma}} = \frac{\frac{\sigma-1}{\sigma}}{\mathbb{E}\Big[\frac{VA}{Y}\Big]} = \frac{\sigma - 1}{\sigma}\Big\{\mathbb{E}\Big[\frac{VA}{Y}\Big]\Big\}^{-1},$$

where the expectation is taken over all affiliates and time periods whose values of α_m and σ are assumed to be the same.

A.2 Estimation: Details

A.2.1 First Step

Given the production function in equation (1) and the assumption that labor is a flexible input, the first order condition with respect to labor is

$$\beta_l + \beta_{ll} 2 l_{jt} + \beta_{lk} k_{jt} = \frac{W^l_{jt} L_{jt}}{VA_{jt}} \exp(-\varepsilon_{jt}),$$

where W^l_{jt} is an observed measure of total payments to labor, $P^l_{nt} L_{jt}$. Given the assumption that $\mathbb{E}[\varepsilon_{jt} | S_{js}, L_{js}] = 0$, we can identify $(\beta_l, \beta_{ll}, \beta_{lk})$ from the moment condition

$$\mathbb{E}[w^l_{jt} - va_{jt} - \log(\beta_l + \beta_{ll} 2 l_{jt} + \beta_{lk} k_{jt}) | l_{jt}, k_{jt}] = 0.$$

Given this orthogonality condition, we estimate $(\beta_l, \beta_{ll}, \beta_{lk})$ using NLS. Using the estimates $(\hat{\beta}_l, \hat{\beta}_{ll}, \hat{\beta}_{lk})$, we can recover an estimate of ε_{jt} for every firm j and period t as

$$\hat{\varepsilon}_{jt} = \log(\hat{\beta}_l + \hat{\beta}_{ll} 2 l_{jt} + \hat{\beta}_{lk} k_{jt}) + va_{jt} - w^l_{nt} \tag{17}$$

A.2.2 Second Step

Defining $\widehat{va}_{jt} = va_{jt} - \hat{\beta}_l l_{jt} - \hat{\beta}_{ll} l^2_{jt} - \hat{\beta}_{lk} l_{jt} k_{jt} - \hat{\varepsilon}_{jt}$ and $h(k_{jt}; \beta_k, \beta_{kk}) = \beta_k k_{jt} + \beta_{kk} k^2_{jt}$, we can rewrite equation (13) as

$$\begin{gathered} \widehat{va}_{jt} = \\ h(k_{jt}; \beta_k, \beta_{kk}) + (1 - d_{jt-1})(\gamma_{1nt} + \rho_1(\widehat{va}_{jt-1} - h(k_{jt-1}; \beta_k, \beta_{kk}))) + \\ d_{jt-1}(\gamma_{2nt} + \rho_2(\widehat{va}_{jt-1} - h(k_{jt-1}; \beta_k, \beta_{kk}))) + \gamma_a r_{jt-1} + \gamma_p r_{0t-1} + \kappa^2 \eta_{jt}. \end{gathered} \tag{18}$$

In order to estimate the parameters $(\beta_k, \beta_{kk}, \rho_1, \rho_2, \gamma_a, \gamma_p)$ from equation (18), we follow two different approaches.

In a first approach, we apply the Frisch-Waugh-Lovell theorem and project $\widehat{va}_{jt}$, k_{jt}, k^2_{jt}, $(1-d_{jt-1})\widehat{va}_{jt-1}$, $d_{jt-1}\widehat{va}_{jt-1}$, $(1-d_{jt-1})k_{jt-1}$, $(1-d_{jt-1})k^2_{jt-1}$, $d_{jt-1}k_{jt-1}$, $d_{jt-1}k^2_{jt-1}$, r_{jt-1} and r_{0t-1} on the vector of fixed effects $((1 - d_{jt-1})\gamma_{1nt}, d_{jt-1}\gamma_{2nt})$. Denoting the residuals from this regression with a prime, we estimate $(\beta_k, \beta_{kk}, \rho_1, \rho_2, \gamma_a, \gamma_p)$ using NLS on the following estimating equation

$$\begin{aligned}\widehat{va}'_{jt} &= \beta_k k'_{jt} + \beta_{kk}(k^2_{jt})' \\ &\quad + \rho_1\big(((1-d_{jt-1})\widehat{va}_{jt-1})' - \beta_k((1-d_{jt-1})k_{jt-1})' - \beta_{kk}((1-d_{jt-1})k^2_{jt-1})'\big) \\ &\quad + \rho_2\big((d_{jt-1}\widehat{va}_{jt-1})' - \beta_k(d_{jt-1}k_{jt-1})' - \beta_{kk}(d_{jt-1}k^2_{jt-1})'\big) \\ &\quad + \gamma_a r'_{jt-1} + \gamma_p r'_{0t-1} + \kappa^2 \eta'_{jt}.\end{aligned}$$

In a second approach, we simplify the set of fixed effects included in equation (18) and assume that $\gamma_{1nt} = \gamma_1$ and $\gamma_{2nt} = \gamma_2$. Once we impose this restriction, we use NLS to estimate $(\gamma_1, \gamma_2, \beta_k, \beta_{kk}, \rho_1, \rho_2, \gamma_a, \gamma_p)$ directly from equation (18).

A.3 Nonlinear Autoregressive Process for Productivity: Details

A.3.1 Estimation

From equations (12) and (15), we can derive the following estimating equation:

$$\begin{aligned}va_{jt} &= \kappa^3_{nt} + h(l_{jt}, k_{jt}; \beta) + \varepsilon_{jt} \\ &\quad + (1-d_{jt-1})(\kappa_2\mu_{1nt} + \rho_1(va_{jt-1} - \kappa^3_{nt-1} - h(l_{jt-1}, k_{jt-1}; \beta) - \varepsilon_{jt-1})) \\ &\quad + d_{jt-1}(\kappa_2\mu_{2nt} + \rho_2(va_{jt-1} - \kappa^3_{nt-1} - h(l_{jt-1}, k_{jt-1}; \beta) - \varepsilon_{jt-1}) \\ &\quad + \rho_3(va_{jt-1} - \kappa^3_{nt-1} - h(l_{jt-1}, k_{jt-1}; \beta) - \varepsilon_{jt-1})r_{jt-1} \\ &\quad + (\rho_4/\kappa_2)(va_{jt-1} - \kappa^3_{nt-1} - h(l_{jt-1}, k_{jt-1}; \beta) - \varepsilon_{jt-1})^2 \\ &\quad + \kappa_2\mu_a r_{jt-1} + \kappa_2\mu_p r_{0t-1} + \kappa_2\eta_{jt}.\end{aligned}$$

Estimating $(\beta_l, \beta_{ll}, \beta_{lk})$ and ε_{jt} following the procedure in Appendix A.2.1, we are left with the estimating equation

$$\begin{aligned}\widehat{va}_{jt} &= \kappa^3_{nt} + h(k_{jt}; \beta_k, \beta_{kk}) \\ &\quad + (1-d_{jt-1})(\kappa_2\mu_{1nt} + \rho_1(\widehat{va}_{jt-1} - \kappa^3_{nt-1} - h(k_{jt-1}; \beta_k, \beta_{kk}))) \\ &\quad + d_{jt-1}(\kappa_2\mu_{2nt} + \rho_2(\widehat{va}_{jt-1} - \kappa^3_{nt-1} - h(k_{jt-1}; \beta_k, \beta_{kk})) \\ &\quad + \rho_3(\widehat{va}_{jt-1} - \kappa^3_{nt-1} - h(k_{jt-1}; \beta_k, \beta_{kk}))r_{jt-1} \\ &\quad + (\rho_4/\kappa_2)(\widehat{va}_{jt-1} - \kappa^3_{nt-1} - h(k_{jt-1}; \beta_k, \beta_{kk}))^2 \\ &\quad + \kappa_2\mu_a r_{jt-1} + \kappa_2\mu_p r_{0t-1} + \kappa_2\eta_{jt}. \qquad (19)\end{aligned}$$

or, equivalently,

$$
\begin{aligned}
\widehat{va}_{jt} = {} & h(k_{jt};\beta_k,\beta_{kk}) \\
& + (1-d_{jt-1})(\gamma_{1nt} + \rho_1(\widehat{va}_{jt-1} - h(k_{jt-1};\beta_k,\beta_{kk}))) \\
& + d_{jt-1}(\gamma_{2nt} + \rho_2(\widehat{va}_{jt-1} - h(k_{jt-1};\beta_k,\beta_{kk})) \\
& + \rho_3(\widehat{va}_{jt-1} - h(k_{jt-1};\beta_k,\beta_{kk}))r_{jt-1} \\
& + \gamma_4\big((\widehat{va}_{jt-1})^2 + (h(k_{jt-1};\beta_k,\beta_{kk}))^2 - 2\widehat{va}_{jt-1}h(k_{jt-1};\beta_k,\beta_{kk})\big) \\
& + \gamma_{3nt}(\widehat{va}_{jt-1} - h(k_{jt-1};\beta_k,\beta_{kk})) \\
& + \gamma_a r_{jt-1} + \gamma_p r_{0t-1} + \kappa_2\eta_{jt},
\end{aligned}
$$

where $\gamma_{1nt} = \kappa_2\mu_{1nt} + \kappa^3_{nt} - \rho_1\kappa^3_{nt-1} + (\rho_4/\kappa_2)(\kappa^3_{nt-1})^2$, $\gamma_{2nt} = \kappa_2\mu_{2nt} + \kappa^3_{nt} - \rho_2\kappa^3_{nt-1} + (\rho_4/\kappa_2)(\kappa^3_{nt-1})^2$, $\gamma_{3nt} = -(\rho_4/\kappa_2)2\kappa^3_{nt-1}$, $\gamma_4 = \rho_4/\kappa_2$, $\gamma_a = \kappa_2\mu_a$, and $\gamma_p = \kappa_2\mu_p$. It is computationally infeasible to estimate the vectors of fixed effects γ_{1nt}, γ_{2nt}, and γ_{3nt} jointly with the structural parameter vector $(\beta_k,\beta_{kk},\rho_1,\rho_2,\gamma_a,\gamma_p,\gamma_4)$. There are two approaches we might follow to estimate the parameter vector $(\beta_k,\beta_{kk},\rho_1,\rho_2,\gamma_a,\gamma_p,\gamma_4)$.

First, we apply the Frisch-Waugh-Lovell theorem and project $\widehat{va}_{jt}$, k_{jt}, k^2_{jt}, $\widehat{va}^2_{jt-1}$, k^3_{jt-1}, k^4_{jt-1}, $\widehat{va}_{jt-1}k_{jt-1}$, $\widehat{va}_{jt-1}k^2_{jt-1}$, r_{jt-1} and r_{0t-1} on the set of covariates $((1-d_{jt-1})\gamma_{1nt}, d_{jt-1}\gamma_{2nt}, \widehat{va}_{jt-1}\gamma_{3nt}, k_{jt-1}\gamma_{3nt}, k^2_{jt-1}\gamma_{3nt})$. Denoting the residuals from this regression with a prime, we estimate $(\beta_k,\beta_{kk},\rho_1,\rho_2,\rho_3,\gamma_4,\gamma_a,\gamma_p)$ using NLS on the following estimating equation

$$
\begin{aligned}
\widehat{va}'_{jt} = {} & \beta_k k'_{jt} + \beta_{kk}(k^2_{jt})' \\
& + \rho_1\big(((1-d_{jt-1})\widehat{va}_{jt-1})' - \beta_k((1-d_{jt-1})k_{jt-1})' - \beta_{kk}((1-d_{jt-1})k^2_{jt-1})'\big) \\
& + \rho_2\big((d_{jt-1}\widehat{va}_{jt-1})' - \beta_k(d_{jt-1}k_{jt-1})' - \beta_{kk}(d_{jt-1}k^2_{jt-1})'\big) \\
& + \rho_3\big((r_{jt-1}\widehat{va}_{jt-1})' - \beta_k(r_{jt-1}k_{jt-1})' - \beta_{kk}(r_{jt-1}k^2_{jt-1})'\big) \\
& + \gamma_4\big((\widehat{va}^2_{jt-1})' + \beta^2_k(k^2_{jt-1})' + \beta^2_{kk}(k^4_{jt-1})' + 2\beta_k\beta_{kk}(k^3_{jt-1})' - 2\beta_k(\widehat{va}_{jt-1}k_{jt-1})' \\
& - 2\beta_{kk}(\widehat{va}_{jt-1}k^2_{jt-1})'\big) + \gamma_a r'_{jt-1} + \gamma_p r'_{0t-1} + \kappa_2\eta'_{jt}. \qquad (20)
\end{aligned}
$$

Given that we have previously regressed on $(\widehat{va}_{jt-1}\gamma_{3nt}, k_{jt-1}\gamma_{3nt}, k^2_{jt-1}\gamma_{3nt})$, this regression does not allow to separately identify ρ_1 and ρ_2 (we can only identify the difference between both of them). However, this approach will allow us to test whether ρ_3 and γ_4 are statistically different from zero.

A second approach relies on the assumption that $\gamma_{3nt} = \gamma_3$. This implies assuming that $\kappa^3_{nt} = \kappa^3$ (i.e. price and quantity indices are assumed constant across markets). Given this assumption, we may apply the Frisch-Waugh-Lovell theorem and project $\widehat{va}_{jt}$, $\widehat{va}_{jt-1}$, k_{jt}, k_{jt-1}, k^2_{jt}, k^2_{jt-1}, $\widehat{va}^2_{jt-1}$, k^3_{jt-1}, k^4_{jt-1}, $\widehat{va}_{jt-1}k_{jt-1}$, $\widehat{va}_{jt-1}k^2_{jt-1}$, r_{jt-1} and r_{0t-1} on the set of covariates $((1-d_{jt-1})\gamma_{1nt}, d_{jt-1}\gamma_{2nt})$. Denoting the residuals from this regression with a prime, we estimate $(\beta_k, \beta_{kk}, \rho_1, \rho_2, \rho_3, \gamma_4, \gamma_a, \gamma_p)$ using NLS on the following estimating equation

$$\begin{aligned}
\widehat{va}'_{jt} &= \beta_k k'_{jt} + \beta_{kk}(k^2_{jt})' \\
&+ \rho_1\big(((1-d_{jt-1})\widehat{va}_{jt-1})' - \beta_k((1-d_{jt-1})k_{jt-1})' - \beta_{kk}((1-d_{jt-1})k^2_{jt-1})'\big) \\
&+ \rho_2\big((d_{jt-1}\widehat{va}_{jt-1})' - \beta_k(d_{jt-1}k_{jt-1})' - \beta_{kk}(d_{jt-1}k^2_{jt-1})'\big) \\
&+ \rho_3\big((r_{jt-1}\widehat{va}_{jt-1})' - \beta_k(r_{jt-1}k_{jt-1})' - \beta_{kk}(r_{jt-1}k^2_{jt-1})'\big) \\
&+ \gamma_4\big((\widehat{va}^2_{jt-1})' + \beta_k^2(k^2_{jt-1})' + \beta_{kk}^2(k^4_{jt-1})' + 2\beta_k\beta_{kk}(k^3_{jt-1})' - 2\beta_k(\widehat{va}_{jt-1}k_{jt-1})' \\
&- 2\beta_{kk}(\widehat{va}_{jt-1}k^2_{jt-1})'\big) + \gamma_a r'_{jt-1} + \gamma_p r'_{0t-1} + \kappa_2\eta'_{jt}.
\end{aligned}$$

Note that this equation is identical to equation (20). The only difference is that its covariates are residuals of a projection that does not include $(\widehat{va}_{jt-1}\gamma_{3nt}, k_{jt-1}\gamma_{3nt}, k^2_{jt-1}\gamma_{3nt})$. Therefore, both ρ_1 and ρ_2 are separately identified.

Finally, a third approach relies on assuming that $\mu_{1nt} = \mu_1$, $\mu_{2nt} = \mu_2$, and $\kappa^3_{nt} = \kappa^3_{nt-1} = \kappa^3$. Once we impose this restriction, we use NLS to estimate $(\gamma_1, \gamma_2, \kappa_3, \beta_k, \beta_{kk}, \rho_1, \rho_2, \rho_3, \gamma_4, \gamma_a, \gamma_p)$ directly from equation (18), where $\gamma_1 = \kappa_2\mu_1$, $\gamma_2 = \kappa_2\mu_2$, and $\gamma_4 = \rho_4/\kappa_2$.

A.3.2 Returns to R&D

Impact of R&D Investment on Revenue Productivity The effect of a marginal increase in r_{0t-1} on both $\tilde{\psi}_{jt}$, for $j = 1, \ldots, J_{it}$ and $\tilde{\psi}_{0t}$ is identical to that in the baseline specification and equal to μ_p and μ_{0p}, respectively. However, the propagation of the change in productivity at period t to subsequent periods is affected by the non-linearities introduced in equation (15). Specifically, this propagation depends on the value of the parameters ρ_1 and ρ_2. Therefore, in order to compute the impact of R&D investment on revenue productivity we use the estimates obtained either by the second or the third approach described in Section A.3.1

$$\frac{\partial\tilde{\psi}_{jt+s}}{\partial\tilde{\psi}_{jt+s-1}} = (1-d_{jt+s-1})\rho_1 + d_{jt+s-1}(\rho_2 + \rho_3 r_{jt-1}) + 2\rho_4\psi_{jt+s-1},$$

or, equivalently,

$$\frac{\partial\tilde{\psi}_{jt+s}}{\partial\tilde{\psi}_{jt+s-1}} = (1-d_{jt+s-1})\rho_1 + d_{jt+s-1}(\rho_2 + \rho_3 r_{jt+s-1}) + 2\gamma_4\tilde{\psi}_{jt+s-1},$$

with $\tilde{\psi}_{jt+s-1} = va_{jt+s-1} - \kappa^3 - h(l_{jt+s-1}, k_{jt+s-1}; \beta) = \widehat{va}_{jt+s-1} - \kappa^3 - h(k_{jt+s-1}; \beta_k, \beta_{kk})$. Therefore, if $s > 0$,

$$\begin{aligned}\frac{\partial \mathbb{E}[\tilde{\psi}_{jt+s}|S_{it}]}{\partial r_{0t-1}} &= \mathbb{E}\Big[\frac{\partial \tilde{\psi}_{jt+s}}{\partial r_{0t-1}}\Big|S_{it}\Big] = \mathbb{E}\Big[\frac{\partial \tilde{\psi}_{jt+s}}{\tilde{\psi}_{jt+s-1}}\frac{\partial \tilde{\psi}_{jt+s-1}}{\partial \tilde{\psi}_{jt+s-2}}\cdots\frac{\partial \tilde{\psi}_{jt}}{\partial r_{0t-1}}\Big|S_{it}\Big] \\ &= \mu_p \mathbb{E}\Big[\prod_{s'=0}^{s-1}\big((1-d_{jt+s'})\rho_1 + d_{jt+s'}(\rho_2 + \rho_3 r_{jt+s'}) + 2\gamma_4 \tilde{\psi}_{jt+s'}\big)\Big|S_{it-1}\Big],\end{aligned}$$

and the cumulative effect over infinite periods ahead is

$$\sum_{s=0}^{\infty}\frac{\partial \mathbb{E}[\tilde{\psi}_{jt+s}|S_{it}]}{\partial r_{0t-1}} = \mu_p \mathbb{E}\Big[\sum_{s=1}^{\infty}\prod_{s'=1}^{s}\big((1-d_{jt+s'-1})\rho_1 + d_{jt+s'-1}(\rho_2 + \rho_3 r_{jt+s'-1}) + 2\gamma_4 \tilde{\psi}_{jt+s'-1}\big)\Big|S_{it-1}\Big],$$

Taking the observed data in year 1994 as steady-state, we can simplify this expression as

$$\begin{aligned}&\sum_{s=0}^{\infty}\frac{\partial \mathbb{E}[\tilde{\psi}_{jt+s}|S_{it}]}{\partial r_{0t-1}} \\ &= \mu_p \mathbb{E}\Big[\sum_{s=1}^{\infty}\prod_{s'=1}^{s}\big((1-d_{j1994})\rho_1 + d_{j1994}(\rho_2 + \rho_3 r_{j1994}) + 2\gamma_4 \tilde{\psi}_{j1994}\big)\Big|S_{i1994}\Big] \\ &= \mu_p \sum_{s=1}^{\infty}\prod_{s'=1}^{s}\big((1-d_{j1994})\rho_1 + d_{j1994}(\rho_2 + \rho_3 r_{j1994}) + 2\gamma_4 \tilde{\psi}_{j1994}\big) \\ &= \mu_p \sum_{s=1}^{\infty}\prod_{s'=1}^{s}\big((1-d_{j1994})(\rho_1 + 2\gamma_4 \tilde{\psi}_{j1994}) + d_{j1994}(\rho_2 + \rho_3 r_{j1994} + 2\gamma_4 \tilde{\psi}_{j1994})\big) \\ &= \mu_p \sum_{s=1}^{\infty}\Big\{\big((1-d_{j1994})(\rho_1 + 2\gamma_4 \tilde{\psi}_{j1994})\big)^{s-1} + d_{j1994}\big((\rho_2 + \rho_3 r_{j1994} + 2\gamma_4 \tilde{\psi}_{j1994})\big)^{s-1}\Big\} \\ &= \mu_p \Big(\frac{1-d_{j1994}}{1-\rho_1 + 2\gamma_4 \tilde{\psi}_{j1994}} + \frac{d_{j1994}}{1-\rho_2 + \rho_3 r_{j1994} + 2\gamma_4 \tilde{\psi}_{j1994}}\Big),\end{aligned}$$

where $\tilde{\psi}_{j1994} = \widehat{va}_{j1994} - \kappa^3 - h(k_{j1994}; \beta_k, \beta_{kk})$. Aggregating across all affiliates, the relevant expression becomes

$$\sum_{j=1}^{J_{1994}} \mu_p \Big(\frac{1-d_{j1994}}{1-\rho_1 - 2\gamma_4 \tilde{\psi}_{j1994}} + \frac{d_{j1994}}{1-\rho_2 - \rho_3 r_{j1994} - 2\gamma_4 \tilde{\psi}_{j1994}}\Big),$$

where J_{1994} denotes the total number of affiliates in 1994.

For the case of the parent firm, the cumulative effect over infinite periods of an infinitesimal change in r_{01994} is

$$\frac{\mu_{0p}}{1-\rho_{02}-\rho_{03}r_{01994}-2\gamma_{04}\tilde{\psi}_{01994}},$$

where $\tilde{\psi}_{01994}=\widehat{va}_{01994}-\kappa^3-h(k_{01994};\beta_{0k},\beta_{0kk})$.

Impact of R&D Investment on Firm Value Using the expressions derived above and following the same steps as in Section 6, the relevant equation equivalent is

$$\begin{aligned}&\frac{Y_{01994}}{R_{01994}}\frac{\mu_{0p}}{1-\rho_{02}-\rho_{03}r_{01994}-2\gamma_{04}\tilde{\psi}_{01994}}+\\ \mu_p\frac{Y_{j1994}}{R_{j1994}}\sum_{j=1}^{J_{1994}}&\Big(\frac{1-d_{j1994}}{1-\rho_1-2\gamma_4\tilde{\psi}_{j1994}}+\frac{d_{j1994}}{1-\rho_2-\rho_3 r_{j1994}-2\gamma_4\tilde{\psi}_{j1994}}\Big),\end{aligned}$$

where the first line captures the impact on the parent and the second line the total impact on all affiliates.

A.3.3 Returns to R&D

Impact of R&D Investment on Revenue Productivity Given the specification of parents' and affiliates' productivities in section 3, a marginal increase in parent R&D at period $t-1$ will affect the revenue productivity of any affiliate j at any period t, exclusively through its impact on parent productivity:

$$\frac{\partial\tilde{\psi}_{jt}}{\partial r_{0t-1}}=\frac{\partial\tilde{\psi}_{jt}}{\partial r_{0t-1}}=\frac{\partial\tilde{\psi}_{jt}}{\partial\tilde{\psi}_{0t}}\frac{\partial\tilde{\psi}_{0t}}{\partial r_{0t-1}}=\gamma_{pp}\gamma_{0p}.$$

The effect on revenue productivity in year $t+1$ will happen through two different channels: through $\tilde{\psi}_{jt}$ and through $\tilde{\psi}_{0t+1}$.

$$\begin{aligned}\frac{\partial\tilde{\psi}_{jt+1}}{\partial r_{0t-1}}&=\Big(\frac{\partial\tilde{\psi}_{jt+1}}{\partial\tilde{\psi}_{jt}}\frac{\partial\tilde{\psi}_{jt}}{\partial\tilde{\psi}_{0t}}+\frac{\partial\tilde{\psi}_{jt+1}}{\partial\tilde{\psi}_{0t+1}}\frac{\partial\tilde{\psi}_{0t+1}}{\partial\tilde{\psi}_{0t}}\Big)\frac{\partial\tilde{\psi}_{0t}}{\partial r_{0t-1}}\\&=\big(((1-d_{jt})\rho_1+d_{jt}\rho_2)\gamma_{pp}+\gamma_{pp}\rho_{02}\big)\gamma_{0p}\\&=\big((1-d_{jt})\rho_1+d_{jt}\rho_2+\rho_{02}\big)\gamma_{pp}\gamma_{0p}.\end{aligned}$$

The key fact that allows to simplify this expression is that

$$\frac{\partial\tilde{\psi}_{jt+1}}{\partial\tilde{\psi}_{0t+1}}=\frac{\partial\tilde{\psi}_{jt}}{\partial\tilde{\psi}_{0t}}=\gamma_{pp}.$$

The effect on revenue productivity in year $t+2$ is:

$$
\begin{aligned}
&\frac{\partial \tilde{\psi}_{jt+2}}{\partial r_{0t-1}} \\
&= \frac{\partial \tilde{\psi}_{jt+2}}{\partial \tilde{\psi}_{jt+1}} \frac{\partial \tilde{\psi}_{jt+1}}{\partial r_{0t-1}} + \frac{\partial \tilde{\psi}_{jt+2}}{\partial \tilde{\psi}_{0t+2}} \frac{\partial \tilde{\psi}_{0t+2}}{\partial \tilde{\psi}_{0t+1}} \frac{\partial \tilde{\psi}_{0t+1}}{\partial \tilde{\psi}_{0t}} \frac{\partial \tilde{\psi}_{0t}}{\partial r_{0t-1}} \\
&= \big((1-d_{jt+1})\rho_1 + d_{jt+1}\rho_2\big)\big((1-d_{jt})\rho_1 + d_{jt}\rho_2 + \rho_{02}\big)\gamma_{pp}\gamma_{0p} + \rho_{02}^2 \gamma_{pp}\gamma_{0p} \\
&= \Big(\big((1-d_{jt+1})\rho_1 + d_{jt+1}\rho_2\big)\big((1-d_{jt})\rho_1 + d_{jt}\rho_2\big) + \big((1-d_{jt+1})\rho_1 + d_{jt+1}\rho_2\big)\rho_{02} + \rho_{02}^2\Big)\gamma_{pp}\gamma_{0p}.
\end{aligned}
$$

Generalizing this expression for a general $\tilde{\psi}_{jt+s}$ and assuming that the values of all variables are kept constant at their observed 1994 values, we obtain that, for an affiliate performing R&D in year 1994,

$$
\begin{aligned}
\frac{\partial \tilde{\psi}_{jt+s}}{\partial r_{0t-1}} &= \gamma_{pp}\gamma_{0p}\Big(\sum_{s'=0}^{s} \rho_2^{s-s'} \rho_{02}^{s'}\Big) = \gamma_{pp}\gamma_{0p}\rho_2^s \Big(\sum_{s'=0}^{s} (\rho_{02}/\rho_2)^{s'}\Big) = \gamma_{pp}\gamma_{0p}\rho_2^s \times \frac{1-(\rho_{02}/\rho_2)^s}{1-(\rho_{02}/\rho_2)} \\
&= \frac{\gamma_{pp}\gamma_{0p}\rho_2^s}{1-(\rho_{02}/\rho_2)} - \frac{\gamma_{pp}\gamma_{0p}\rho_{02}^s}{1-(\rho_{02}/\rho_2)} = \frac{\gamma_{pp}\gamma_{0p}}{1-(\rho_{02}/\rho_2)}(\rho_2^s - \rho_{02}^s) = \frac{\gamma_{pp}\gamma_{0p}\rho_2}{\rho_2 - \rho_{02}}(\rho_2^s - \rho_{02}^s),
\end{aligned}
$$

and, for an affiliate not performing R&D in steady state,

$$
\begin{aligned}
\frac{\partial \tilde{\psi}_{jt+s}}{\partial r_{0t-1}} &= \gamma_{pp}\gamma_{0p}\Big(\sum_{s'=0}^{s} \rho_1^{s-s'} \rho_{02}^{s'}\Big) = \gamma_{pp}\gamma_{0p}\rho_1^s \Big(\sum_{s'=0}^{s} (\rho_{02}/\rho_1)^{s'}\Big) = \gamma_{pp}\gamma_{0p}\rho_1^s \times \frac{1-(\rho_{02}/\rho_1)^s}{1-(\rho_{02}/\rho_1)} \\
&= \frac{\gamma_{pp}\gamma_{0p}\rho_1^s}{1-(\rho_{02}/\rho_1)} - \frac{\gamma_{pp}\gamma_{0p}\rho_{02}^s}{1-(\rho_{02}/\rho_1)} = \frac{\gamma_{pp}\gamma_{0p}}{1-(\rho_{02}/\rho_1)}(\rho_1^s - \rho_{02}^s) = \frac{\gamma_{pp}\gamma_{0p}\rho_1}{\rho_1 - \rho_{02}}(\rho_1^s - \rho_{02}^s).
\end{aligned}
$$

Therefore, the cumulative effect of an infinitesimal change in r_{0t-1} on the sum of value added productivity for all affiliates over any subsequent period (assuming that the number of affiliates stays constant at their 1994 level) is

$$
\gamma_{pp}\gamma_{0p}\Big(J_{i1994,d=0}\frac{\rho_1}{\rho_1-\rho_{02}}\big(\frac{1}{1-\rho_1} - \frac{1}{1-\rho_{02}}\big) + J_{i1994,d=1}\frac{\rho_2}{\rho_2-\rho_{02}}\big(\frac{1}{1-\rho_2} - \frac{1}{1-\rho_{02}}\big)\Big),
$$

or, equivalently,

$$
\gamma_{pp}\gamma_{0p}\Big(J_{i1994,d=0}\frac{\rho_1}{(1-\rho_1)(1-\rho_{02})} + J_{i1994,d=1}\frac{\rho_2}{(1-\rho_2)(1-\rho_{02})}\Big),
$$

For the parent firm, the elasticity of the cumulative effect on parent productivity with respect to parent R&D is identical to that in the baseline case.

Impact of R&D Investment on Firm Value Using the expressions derived above and following the same steps as in Section 6, the equation equivalent to that described in section 5 is

$$\frac{\partial V(S_{it})}{\partial R_{0t-1}} = \frac{Y_{01994}}{R_{01994}} \frac{\gamma_{0p}}{1-\delta\rho_{02}} +$$

$$\gamma_{pp}\gamma_{0p}\Big(J_{i1994,d=0}\frac{\delta\rho_1}{(1-\delta\rho_1)(1-\delta\rho_{02})}\frac{\bar{Y}_{1994,d=0}}{R_{01994}} + J_{i1994,d=1}\frac{\delta\rho_2}{(1-\delta\rho_2)(1-\delta\rho_{02})}\frac{\bar{Y}_{1994,d=1}}{R_{01994}}\Big).$$

A.4 Data and Measurement

Multinational activity and data sample: Confidential firm-level data on the activity abroad of U.S. multinational firms is provided by the Bureau of Economic Analysis through a sworn-status research arrangement. The data include detailed financial and operating information for each foreign affiliate owned (at least a 10% share) by a U.S. entity. The data variables used for this project were extracted from the BEA's comprehensive data files for each year during 1989–2008, and then merged by parent and affiliate identification numbers to form a complete panel.

The estimation described in sections 4 and 5 proceeds at the industry level for each of five major manufacturing sectors: industrial machinery (SIC 35), electronics (SIC 36), instruments and devices (SIC 38), chemicals (SIC 28), and transportation equipment (SIC 37). We build separate datasets by industry that are each subject to a uniform cleaning procedure. Observations are excluded if a) values are carried over or imputed based on previous survey responses; b) the affiliate is minority-owned or small and therefore exempt from reporting R&D expenditures; or c) the observation is neither preceded nor succeeded by another observation corresponding to the same affiliate. Below, we evaluate the extent to which the final dataset and the raw data capture overlapping information regarding the link between R&D and productivity.

The data-cleaning procedure impacts sample sizes across all tables. We therefore provide a detailed, step-by-step description of this procedure for the chemical industry (SIC 28) as a representative example. The complete dataset spanning all industries and 1989–2008 includes 612,196 affiliate-year level observations. Based on the primary industry reported for each affiliate, approximately one-third of these observations correspond to manufacturing affiliates in SIC 20–39 (36.84%), one-sixth correspond to retail affiliates in SIC 50–59 (18.92%), and the remaining half of affiliate observations correspond to other industries. The raw dataset for the chemical industry includes each parent firm reporting SIC 28 as its primary industry, and each of its foreign affiliates; this includes 226,076 observations.

The BEA requires only majority-owned and relatively large foreign affiliates of U.S. parent firms to report R&D expenditures, and we therefore restrict our analysis to these affiliates. The size threshold for affiliate participation in R&D reporting varies across years during the sample period; the highest such threshold in 1999 indicates an affiliate must report R&D only if its sales, assets, or net income exceed \$50 million. To maintain a consistent sample, this cut-off is imposed uniformly across years in our baseline analysis; 80,191 affiliate-year observations remain in the sample after this cleaning step. While most affiliates are not continuously present in the data, the estimation in sections 4 and 5 requires only a minimum of two consecutive observations per affiliate; 3,718 observations are dropped to satisfy this restriction. An additional 10,543 imputed values are dropped, bringing the total number of observations to 65,930. These observations are collected to form three separate datasets: 1) 17,369 affiliate-year observations in the chemical industry (SIC 28); 2) 31,250 affiliate-year observations in manufacturing (SIC 20 through 39); 3) 39,945 affiliate-year observations in manufacturing and retail both (SIC 20 through 39, SIC 50 through 59). Finally, observations with missing or negative values for value added, lagged value added, capital, lagged capital, labor, lagged labor, or R&D expenditures are dropped to arrive at the following number of observations in each of the three datasets above: 1) 5,730; 2) 7,439 observations; and 3) 11,016 observations. An identical data cleaning process is applied to SIC 35, 36, 37, and 38.

Although all specifications in section 5 include country-year fixed effects so that our results are not sensitive to the following step, reported values in each year are nevertheless adjusted for inflation to U.S. dollars in 2004 using the the following consumer price index-based correction factors from the U.S. Bureau of Labor Statistics: 1989, 1.52; 1990, 1.45; 1991, 1.39; 1992, 1.35; 1993, 1.31; 1994, 1.27; 1995, 1.24; 1996, 1.20; 1997, 1.18; 1998, 1.16; 1999, 1.13; 2000, 1.10; 2001, 1.07; 2002, 1.05; 2003, 1.03; 2004, 1; 2005, 0.967; 2006, 0.937; 2007, 0.911; 2008, 0.877. In addition, during the sample period, the BEA switches from SIC to NAICS-based parent-firm and foreign-affiliate industry classifications. The U.S. Census Bureau concordance is applied to match NAICS-based observations to each of the five industries.

Variable definitions in the dataset: We define the main variables used in our analysis and document information regarding their construction. This information may be found in the instruction booklet for benchmark and annual surveys of U.S. direct investment abroad, Bureau of Economic Analysis, U.S. Department of Commerce. We provide condensed versions of the variable definitions here for clarity.

U.S. parent: The BEA requires a survey response from any U.S. person that had a foreign affiliate – that is, that had direct or indirect ownership or control of at least 10 percent of the voting stock of an incorporated foreign business enterprise, or an equivalent interest in an unincorporated foreign business enterprise – at any time during the U.S. persons fiscal year corresponding to the survey year.

Affiliate: An affiliate is defined as a business enterprise located in one country which is directly or indirectly owned or controlled by a person of another country to the extent of 10 percent or more of its voting securities for an incorporated business enterprise or an equivalent interest for an unincorporated business enterprise, including a branch.

Output: The surveys collect both parent and affiliate-level sales revenues, which may be used as a measure of output. The BEA also constructs a parent and affiliate-level measure of value added using the following definition from Mataloni and Goldberg (1994). Specifically, the BEA measures value added for the U.S. parent or for a foreign affiliate from the factor-cost side as employee compensation (wages and salaries plus employee benefits), plus profit-type return (net income plus income taxes plus depreciation, less capital gains and losses, less income from equity investments), plus net interest paid (monetary interest paid plus imputed interest paid, less monetary interest received, less imputed interest received), plus indirect business taxes (taxes other than income and payroll taxes plus production royalty payments to governments, less subsidies received), plus capital consumption allowances (depreciation). Our analysis focuses on value added as the primary measure of output.

R&D expenditure: The BEA Survey of U.S. Direct Investment Abroad collects information on firms' innovation expenditures at each production location, subject to reporting requirements documented above. Research and development expenditures includes basic and applied research in science and engineering, and the design and development of prototypes and processes, if the purpose of such activity is to: 1) Pursue a planned search for new knowledge whether or not the search has reference to a specific application; 2) Apply existing knowledge to the creation of a new product or process, including evaluation of use; or 3) Apply existing knowledge to the employment of a present product or process. R&D includes the activities described above, whether assigned to separate R&D organizational units of the company or conducted by company laboratories and technical groups that are not a part of a separate R&D organization. This variable includes all costs incurred to support R&D, including R&D depreciation and overhead. The variable excludes capital expenditures, routine product testing and quality control conducted during commercial production, geological and geophysical exploration, market research and surveys, and legal work pertaining to patents.

Labor: Labor is defined as number of employees of the U.S. parent or a foreign affiliate. Employees must be on the payroll at the end of the survey fiscal year, and include part-time employees, but exclude temporary and contract employees not included on your payroll records. The BEA allows this variable to be based on a count taken at some other date during the reporting period may be given provided it is a reasonable estimate of employees on the payroll at the end of the fiscal year of the survey. If the number of employees at the end of the survey fiscal year (or when the count was taken) was unusually high or low due to temporary factors (e.g., a strike), parent and affiliates are to enter the number of employees that reflects normal operations. If the number of employees fluctuates widely during the year due to seasonal business variations, firms are to report the average number of employees on the payroll during the fiscal year. They are to base such an average on the number of employees on the payroll at the end of each pay period, month or quarter.

Capital: Capital is defined as the net (of depreciation) plant, property, and equipment of the U.S. parent or a foreign affiliate. Unlike assets, this measure thus captures physical capital and not inventories, other current assets, accumulated depreciation and depletion, equity investments in other foreign affiliates of which the reporter is a parent, or other noncurrent assets.

Ownership: Parent ownership of a foreign affiliate is determined based on the U.S. reporter's direct and indirect ownership interest based on voting stock in an incorporated foreign affiliate, or an equivalent interest in the case of an unincorporated foreign affiliate.

Industry: The BEA surveys collect sales or gross operating revenues for both the U.S. parent and each foreign affiliate. These sales revenues are reported for five or more industries, ranked from largest sales to fifth-largest sales. The industry of an affiliate or U.S. parent is defined based on the industry for which it reports the highest sales revenues. In building the industry-level datasets, we define a parent firm to be in an industry based on whether it has reported top sales revenues in that industry in at least one period.

Affiliate country: The country of location for a foreign affiliate is the country in which the affiliate's physical assets are located or where its primary activity is carried out.

Table A.1: Parent and Affiliate R&D Investment and Productivity Change, Computer Industry, Nonlinearity

	(1)	(2)	(3)	(4)	(5)	(6)
	Parent firms		Foreign affiliates			
Productivity (t-1), ρ_{02}	1.3732	1.3653				
	0.0956***	0.0940***				
Productivity (t-1), R&D > 0, ρ_2			0.7153	0.7619	0.6937	0.7540
			0.1007***	0.0929***	0.1031***	0.0943***
Productivity (t-1), R&D = 0, ρ_1			0.7223	0.7692	0.7005	0.7609
			0.1007***	0.0929***	0.1031***	0.0943***
Productivity squared (t-1), ρ_4	-0.0405	-0.0399	0.0141	0.0033	0.0155	0.0037
	0.0094***	0.0093***	0.0070**	0.0074	0.0017**	0.0075
Parent R&D x Productivity (t-1), ρ_{03}, ρ_3	0.0075	0.0076		0.0086		0.0088
	0.0028***	0.0030***		0.0293**		0.0038**
Parent R&D (t-1), γ_{0p}, γ_p	-0.0383	-0.0388		-0.0616		-0.0617
	0.0169**	0.0179**		0.0039**		0.0293**
Total affiliate R&D (t-1), γ_{0a}		-0.0002				
		0.0015**				
Affiliate R&D x Productivity (t-1), ρ_5			0.0021	0.0013	0.0019	0.0013
			0.0017	0.0016	0.0017	0.0016
Affiliate R&D (t-1), γ_a			-0.0082	-0.0022	-0.0066	-0.0014
			0.0142	0.0136	0.0144	0.0136
Labor elasticity, mean	0.8157	0.8157	0.4509	0.4509	0.4509	0.4509
Capital elasticity, mean	0.0976	0.0976	0.1333	0.1210	0.1325	0.1207
Market, Year FE	Y	Y	Y	Y	Y	Y
Other affiliate R&D (t-1)	N	N	N	N	Y	Y
N	536	536	3,290	3,290	3,290	3,290

Notes: ** $p < 0.05$, *** $p < 0.01$. This table provides GMM estimates of the parameters in equation (12) modified by (14) for foreign affiliates, and estimates of an analogous equation for U.S. parents in the computer industry, SIC 357, during 1989−2008. All specifications measure the impact of R&D investment on value added and productivity change. Columns 1 and 2 evaluate the full sample of U.S. parents; columns 3 through 6 evaluate corresponding majority-owned, manufacturing affiliates located abroad. Labor (number of employees), capital (plant, property and equipment), value added, and R&D expenditure for parents and each foreign affiliate are from the Bureau of Economic Analysis Survey of U.S. Direct Investment Abroad, and pertain to U.S. outward foreign direct investment reported annually during this sample period. The estimated mean elasticities of value added with respect to labor and capital are reported above. Standard errors clustered by firm-year appear below each point estimate.

Table A.2: Parent and Affiliate R&D Investment and Productivity Change, Industrial Machinery, Nonlinearity

	(1)	(2)	(3)	(4)	(5)	(6)
	Parent firms		Foreign affiliates			
Productivity (t-1), ρ_{02}	0.9069	0.9588				
	0.1667***	0.1692***				
Productivity (t-1), R&D > 0, ρ_2			0.7269	0.9155	0.7533	0.9174
			0.1045***	0.1014***	0.1042***	0.1013***
Productivity (t-1), R&D = 0, ρ_1			0.7358	0.9235	0.7622	0.9253
			0.1048***	0.1017***	0.1044***	0.1016***
Productivity squared (t-1), ρ_4	0.0038	-0.0015	0.0130	-0.0098	0.0111	-0.0100
	0.0196	0.0196	0.0077	0.0080	0.0077	0.0081
Parent R&D x Productivity (t-1), ρ_{03}, ρ_3	-0.0011	-0.0016		0.0092		0.0092
	0.0049	0.0049		0.0033***		0.0032***
Parent R&D (t-1), γ_{0p}, γ_p	0.0140	0.0166		-0.0602		-0.0606
	0.0253	0.0254		0.0232***		0.0234***
Total affiliate R&D (t-1), γ_{0a}		0.0022				
		0.0011**				
Affiliate R&D x Productivity (t-1), ρ_5			0.0011	0.0018	0.0011	0.0013
			0.0018	0.0018	0.0018	0.0016
Affiliate R&D (t-1), γ_a			0.0013	-0.0041	0.0010	-0.0014
			0.0138	0.0140	0.0139	0.0136
Labor elasticity, mean	0.7271	0.7271	0.5442	0.5442	0.5442	0.5442
Capital elasticity, mean	0.0922	0.0930	0.0914	0.0965	0.0920	0.0966
Market, Year FE	Y	Y	Y	Y	Y	Y
Other affiliate R&D (t-1)	N	N	N	N	Y	Y
N	2,609	2,609	5,016	5,016	5,016	5,016

Notes: ** $p < 0.05$, *** $p < 0.01$. This table provides GMM estimates of the parameters in equation (12) modified by (14) for foreign affiliates, and estimates of an analogous equation for U.S. parents in the industrial machinery sector, SIC 35, during 1989−2008. All specifications measure the impact of R&D investment on value added and productivity change. Columns 1 and 2 evaluate the full sample of U.S. parents; columns 3 through 6 evaluate corresponding majority-owned, manufacturing affiliates located abroad. Labor (number of employees), capital (plant, property and equipment), value added, and R&D expenditure for parents and each foreign affiliate are from the Bureau of Economic Analysis Survey of U.S. Direct Investment Abroad, and pertain to U.S. outward foreign direct investment reported annually during this sample period. The estimated mean elasticities of value added with respect to labor and capital are reported above. Standard errors clustered by firm-year appear below each point estimate.