The Role of Research Equipment for Firm Innovation

Lindbjerg, Louise; Simeth, Markus; Grimpe, Christoph

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Introduction

The innovation literature has paid substantial attention to human capital as a determinant of firms' innovation performance (Song, Almeida and Wu, 2003; 2011; Kaiser et al., 2018). There is no doubt that creating new solutions and taking them to market is a knowledge intensive process requiring highly skilled human capital (Grant, 1996; Kogut & Zander, 1992). For firms to capitalize on their scientific human capital, they must provide R&D workers which research equipment such as high-throughput screening machines, gene sequencers, and specialized instruments to perform tasks (Stephan & Levin, 1992). With this study, we try to understand the role of such physical capital for innovation.

As opposed to human capital which has free will and take their knowledge with them if they leave to competing firms (Agarwal et al., 2016; Coff, 1997), physical capital can be fully appropriated and controlled by the possessing firm. Following this logic, physical capital should be relatively more attractive to human capital as a means to improve sustained competitive advantage especially in settings where obtaining highly skilled human capital is challenging. However, when it comes to research and development for firm innovation, human capital in the form of R&D workers and physical capital in the form of research equipment has no value if not both are present. Therefore, the source of competitive advantage may lie in the balance between human and physical capital.

Internal R&D is often viewed as a determinant of firms' innovation potential (Berchicci, 2013; Hagedoorn & Wang, 2012) and absorptive capacity (Fabrizio, 2009) but with little notion of how R&D resources are spend. A key decision for corporate R&D managers is how to allocate the R&D budget, for instance, across internal and external R&D (Berchicci, 2013; Cassiman & Veugelers, 2006; Grimpe & Kaiser, 2010; Hagedoorn & Wang, 2012) as well as basic and applied research (Mansfield, 1980; Czarnitzki and Thorwarth, 2012). To the best of our knowledge, this study is the first to investigate the balance between human capital and physical capital for internal R&D as well as the first large scale empirical evidence of the role of research equipment for firms' innnovation performance.

Investments into research equptment may increase productivity of firms' scientific human capital through optimization and redirection of attention (Baruffaldi & Gaessler, 2021; Dasgupta & David, 1994; Furman & Teodoridis, 2020; Stephan, 1996, 2012), but also, we argue, improve firms' ability to attract and retain scientific human capital with the prospect of working with cutting-edge research tools.

We explore these ideas in the empirical setting of Denmark using Community Innovation Survey (CIS) and employer-employee linked labor market data (IDA) to obtain a panel of R&D active firms. We find an inverted u-shaped relationship between research equipment and innovation, but the majority of firms invest far below the infliction point. Results indicate that investment into equipment is associated with more PhD intensive R&D teams in line with our argument the research equipment improves firms' ability to attract and retain highly skilled human capital. We find that increased spending on equipment only matters for small firms and industry laggards, which speak to diminishing returns of additional research equipment, but may also indicate that investing in research equipment is a viable strategy for industry laggards and smaller firms who may be challenged in attracting highly skilled human capital. In further support for the argument that research equipment improves innovation performance through attraction and retention of highly skilled human capital and, thus, is more attractive in settings where employees are prone to leave and take their knowledge with them, we show that increased equipment spending intensity matters only in industries with high employee turnover.

Theory

Human and physical capital

While the role of human capital for innovation has been emphasized (Azoulay et al., 2010; 2018; Kaiser et al., 2018; Kehoe & Tzabbar, 2015; Song et al., 2003), physical capital also plays an important and potentially overlooked role. New knowledge is a result of a highly (physical) capital-intensive process (Stephan, 2012). R&D scientists and technicians need instruments and tools for tasks such as experimenting and testing. Corporate researchers often reside in highly specialized laboratories with a diverse range of equipment at their disposal (Latour & Woolgar, 2013). As such, human capital and physical capital are complements as both types of inputs are needed in the innovation process. Labor-capital substation effects might occur as routine tasks performed by R&D workers are performed or optimized by machines (Furman & Teodoridis, 2020).

R&D managers are faced with fixed budgets to be allocated across R&D salaries and R&D equipment which are main cost drivers of R&D. From a strategic perspective the two capital inputs hold distinct properties. Human capital can be adjusted through the hiring and firing of individuals who independently affect the rate and direction of technological discovery (Campbell et al., 2012; Coff, 1997). Physical capital is less flexible such that overinvestment in physical capital may lead to path dependencies (Dosi, 1982; Teece, 1986) and myopia (Levinthal & March, 1993; Maskell & Malmberg, 2007). But, physical capital enjoys the advantage over human capital, which has free will and can move to rival firms, (Agarwal et al., 2016; Coff, 1997), that it is fully appropriable and controllable by the firm. In settings with high labor mobility, increasing equipment spending intensity may be an attractive avenue for firms in order to appropriate a larger share of the value generated from its internal R&D activities. Individuals join or leave firms based on the attractiveness of the firm as an employer. Since R&D activities are a capital-intensive process often requiring and array of tools and machinery, it is likely that the decision of researchers to join a firm is influenced by the availability of high-quality research equipment.

Research equipment and innovation

While the innovation literature is silent about the role of research equipment for innovation, the economics of science literature lends insights on the relationship between equipment and scientific knowledge production. Furman and Teodoridis (2020) explore the effect of a suddenly available motion-sensing technology and find that automation increased number of ideas and lead to ideas distinct from scientists' existing trajectories. These findings suggest that research equipment may not only enable more innovation but also change direction towards more radical innovation as researchers are tied away from routine tasks.

R&D in firms resemble research in academic science in which scientists and engineers require tools and instruments to conduct experiments, create designs, and assemble prototypes (Dasgupta and David, 1994) Yet, the relationship between research equipment and firm innovation is distinct from scientific knowledge production when it comes to the degree of researcher-equipment specialization. Equipment for scientific knowledge production tends to be highly specialized and its value is to a large extent tied to individual researchers or research teams (Baruffaldi & Gaessler, 2021). In the setting of industrial R&D, we assume less specialized equipment as industrial research is driven to a greater extent by applied and developmental research compared with academic research (Mansfield, 1980; Czarnitzki and Thorwarth, 2012). Higher levels of financial resources available to firms compared to universities may create a market for specialized equipment for industrial application. Yet, if research equipment is readily available on the market may not be a source of competitive advantage (Wernerfelt, 1984). We argue that the procurement of research equipment is an immediate enabler of industrial innovation, while sustained competitive advantage may arise from some degree of co-specialization of firms' human capital and physical capital. As R&D budgets are constrained, the ability of firms to strike the optimal balance between equipment spending and other R&D spending may be a source of competitive advantage.

Non-linear relationship between research equipment and firm innovation

Research equipment may enable firm innovation by increasing efficiency of R&D tasks redirecting R&D employees' attention to other more value-creating tasks. Together with increased ability to attract and retain scientific human capital, we theorize a positive yet non-linear relationship between research equipment and innovation. An inverted u-shaped relationship with increasing returns to equipment investment followed by diminishing and negative returns may arise for three reasons: 1) At high levels, increased spending on research equipment diminish returns to adding an additional unit of equipment, 2) R&D budgets tend to be constrained implying that overinvestment in physical capital compromises spending on human capital with adverse effects for innovation performance, 3) overinvestment in R&D equipment may lead to path dependency and myopia further arguing for a negative effect at high spending levels.

Empirical Context and Methodology

Dataset and sample

Our empirical setting, Denmark, has two key advantages for the purpose of this study. First, the Danish economy is largely driven by export of R&D intensive products such as pharmaceuticals, green tech, and chemicals. A setting with many globally innovative firms grants a large and representative sample of R&D intensive firms. Second, the ability to link firm-level and individual-level data from multiple sources through the national statistics bureau, Statistics Denmark, provides a rich dataset to tackle heterogeneity and endogeneity concerns related to R&D equipment and innovation.

Key variables in this study comes from the Community Innovation Survey (CIS), which is the main source of innovation information for European firms. The Danish version of the survey covers ~4,500 firms per year. The sample is randomly stratified across industries and likelihood of being in the sample increases with firm size and R&D intensity such that the largest and most R&D active firms (~500 firms) participate every year with most firms participating multiple times in our panel. The CIS data is linked to a general firm register containing financial and legal information on all firms in Denmark providing measures such as firm sales, size, age, ownership, and assets. The dataset is linked to the Integrated Database for Labor Market Research (IDA) and with other registers containing International Standard Classification of Occupations (ISCO) codes and educational codes. This individual-level information is used to identify R&D employees before aggregating to firm-level.

Our analysis sample is restricted to firms participating in the Community Innovation Survey (approximately 4,500 per year). The main dependent variable, innovation sales, can be tracked consistently from 2007 and onwards and we have access to the CIS data until and including year 2016. Our sample is further restricted to firms with R&D expenditures because the main independent variable, share of R&D spend on equipment, can only be computed for firms with R&D expenditures. For main specifications, we are left with 6,534 firm-year observations and 1,416 unique firm observations from 2007-2016.

Dependent variables

We measure firm innovation as the natural logarithm of *sales from innovation.* The variable is generated by multiplying share of sales from innovation reported in CIS with firm sales from the general firm register. To access whether research equipment has a differentiated effect on incremental and radical innovation, we disaggregate the variable into sales from innovation *new to the firm* and sales from innovation *new to the market* representing incremental and radical innovation respectively (Laursen & Salter, 2006). To assess our theoretical prediction that research equipment improves efficiency of firms' human capital, a measure of *R&D labor productivity* is computed which is given by sales from innovation over number of R&D workers. Using the approach by Kaiser et al., (2015), R&D workers are identified based on individuals' educational background and position in the organizational hierarchy of the focal firm. we compute *share of R&D workers w. PhD degree* to empirically test our theoretical idea that research equipment increases ability to attract and retain scientific human capital.

Independent variables of interest

The main independent variable is the share of R&D spending devoted to *research equipment* and it come from the CIS where managers are asked to report total R&D spending across 1) salary and other expenses related to R&D employees, 2) other operational expenses, 3) R&D buildings, and 4) R&D equipment. Spendings on salary and other expenditures related to human capital is by far the largest cost driver of corporate internal R&D while equipment is the second largest. Though expenditures for buildings is a form of physical capital, we do not include these because buildings are not expected to directly affect productivity as R&D workers do not interact with buildings like they interact with research equipment. To investigate a potential non-linear relationship between research equipment and innovation, the *squared term* of share of R&D spend on equipment is included. In robustness checks, three-year averages of the independent variables are used instead of yearly spending as firms may make large equipment investments in one year and no investments in other.

Controls

Multiple variables which may co-determine equipment spending and firm innovation are included. These are *firm size* measured by number of employees, *firm age*, *physical capital* given by the logged book value of firms' fixed assets, logged number of *R&D workers* and *university graduates*, and R&D expenditure normalized by revenue is included as measure of *R&D intensity*. Dummies for whether the firm is *publicly traded* and located in the *Capital* region are included as well. Finally, we control for two lags of sales growth and investment intensity as measures of investment opportunity and actual investments (Bloom et al., 2007; Michaely & Roberts, 2012).

Econometric estimations

We regress logged sales from innovation on share of R&D spend on research equipment and its squared term along with control variables specified above. All specifications include year, industry (NACE 2-digit), and firm fixed effects and standard errors are clustered at firm-level. As current output is a function of past input and to alleviate concerns of reverse causality, all input variables are lagged by one year. A key challenge is endogeneity, due to unobserved factors co-determining investments in R&D equipment and innovation outcomes. The inclusion of firm fixed effects is alleviating concerns that fundamentally better firms make better investment decisions. A second concern is that firms who are already on an upward trend in terms of innovation invest more in research equipment given expectations of increasing innovation output. The endogenous choice of managers to invest in equipment may correlate with other strategic decisions which enable innovation such as devoting more resources to innovation in general. In an initial attempt to address this, we rerun models with three-year averages of innovation output and inputs in years prior to R&D investment to account for past innovation input and output. [1]

Result

Main results

We report main results from firm fixed estimations in Table 1. Model 1 shows that research equipment is positively and significantly associated with sales from innovation with a negative and significant squared term in support of a u-shaped relationship between equipment and innovation. The positive association between research equipment and innovation is stronger for innovation of higher novelty as per model 2 and model 3. These results support the notion that research equipment unties researchers' attention from routine tasks in redirect them to more knowledge intensive tasks. Model 4 displays the result of regressing

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[1] We plan to implement an instrumental variable approach in the form of exogenous variation which affect the decision to invest in research equipment but not innovation outcomes. Specifically, we will look into wage shocks which would make human capital inputs relatively more expensive to physical capital inputs for some firms but not others as well as constraints on monetary capital for investment.

innovation sales per R&D employee as a measure of innovation productivity on equipment spending. Similar to model 1, share of research equipment is associated with innovation productivity first in an increasing then descending relationship, supporting the idea that research equipment increases efficiency of routine R&D tasks. Marginal effects predict a positive return to increasing investment intensity in equipment up until 30 percent of R&D budget spend on equipment. Though keeping in mind that this effect cannot be treated as causal, it is interesting that 95 percent of our sample appear to invest below optimum. In sum, we find strong support for our prediction that the association between research equipment and innovation follows and inverted u-shape.

Additional analyses

Model 5 displays a positive non-linear relationship between equipment investment intensity and the share of R&D workers with a PhD degree implying that firms that spend relatively more on research equipment move towards more PhD intensive research teams in support of the argument that cutting-edge research equipment helps firm attract and retain scientific human capital. We explore potential capital-labor substitution effects. If research equipment automates routine R&D tasks, we would expect to see substitution mainly at the technician-level rather scientists-level. We find no evidence of such substitution. The increased intensity of PhD-scientists in firms' R&D labor force stems from more researchers with PhD degrees compared to researchers without PhD degrees. In models 6 and 7, the sample is split by firms in industries with lower and higher employee turnover than sample average, respectively. Results suggest that increasing equipment spending intensity only matters for firm innovation in settings with high employee turnover. Though these results are preliminary, it lends support to the theoretical idea that investment in research equipment may be an attractive strategy when it is difficult to retain human capital. Splitting the sample first by firms who are industry laggards and leaders in terms of innovation and by larger (more than 250 employees as per OECDs definition) and smaller firms, results from models 8, 9, 10, and 11 show that increasing the share of spending on equipment only seem to matter for firms who are industry laggards and for smaller firms. These boundary conditions may indicate that increased equipment intensity is a viable strategy for firms which are not at the frontier, and thus less prestigious for potential employees, to attract highly skilled scientific human capital with the prospect of accessing cutting edge research equipment.

Conclusion

This paper analyses how increasing R&D investment intensity in research equipment relates to innovation performance. Results suggest that the relationship between increasing relative spending on R&D equipment and sales from innovation follows and inverted u-shape, but with majority of firms investing below the infliction point. Equipment appears to shift focus towards more radical innovation and more PhD-intensive R&D teams. We contribute to innovation literature by theorizing and providing empirical evidence for the role of physical capital for innovation productivity and ability to attract scientific human capital. The result that investing in research equipment is associated with PhD-intensive research teams is interesting as previous research has found that inflow of academic scientists positively influence innovation (Kaiser et al., 2018). Universities are faced with funding pressures which may open an opportunity for firms to attract academic human capital with the prospect of working with cutting edge research equipment. The findings of this study call for a more nuanced investigation of the strategic implications of internal R&D spending.

Table 1: **Main regresssions**

	A. Full sample				
	(1)	(2)	(3)	(4)	(5)
	Sales from innovation	Sales from innov. new to firm	Sales from innov. new to market	Innovation productivity	R&D workers w. PhD degree
	Coeff (SE)	Coeff (SE)	Coeff (SE)	Coeff (SE)	Coeff (SE)
Share R&D equipment	3.261**	3.335*	4.521***	2.621**	0.284***
	(1.560)	(1.737)	(1.652)	(1.328)	(0.094)
Share R&D equipment sq.	-5.606**	-5.869**	-7.427***	-4.608*	-0.394***
	(2.632)	(2.783)	(2.639)	(2.384)	(0.133)
Controls	Yes	Yes	Yes	Yes	Yes
Number of observations/firm	6,534/1,416	6,534/1,416	6,534/1,416	6,095/1,288	6,974/2,167
Pseudo/Adjusted R^2	0.381	0.312	0.367	0.358	0.639

	B. Split samples					
	(6)	(7)	(8)	(9)	(10)	(11)
	Sales from innovation	Sales from innovation	Sales from innovation	Sales from innovation	Sales from innovation	Sales from innovation
Sample	*Low employee turnover*	*High employee turnover*	*Industry laggard*	*Industry leader*	*Smaller Firm*	*Larger Firm*
	Coeff (SE)	Coeff (SE)	Coeff (SE)	Coeff (SE)	Coeff (SE)	Coeff (SE)
Share R&D equipment	-1.474	6.616***	4.270**	-0.640	4.227**	1.538
	(2.457)	(2.524)	(1.825)	(0.975)	(1.847)	(3.106)
Share R&D equipment sq.	1.233	-10.074**	-8.505***	2.710	-8.237***	-0.942
	(4.329)	(4.029)	(2.649)	(2.843)	(2.892)	(5.464)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Number of observations/firm	3,278/826	2,551/844	4,123/1,059	1,768/555	4,874/1,181	1,611/272
Number of firms	826	844	1,059	555	1,181	272
Adjusted R^2	0.388	0.372	0.474	0.910	0.343	0.368

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