R&D Productivity And The Nexus Between Product Substitutability And Innovation: Theory And Experimental Evidence

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This draft: March 6, 2021

Abstract

The present study proposes a theoretical model that investigates how R&D productivity influences the relationship between product substitutability and R&D investment in a duopolistic market. We argue that the effects on R&D investment are more complex than the previous literature suggests. We show theoretically that, in unlevelled industries, the laggard's R&D investment decreases with product substitutability regardless of the R&D productivity level. In sharp contrast, in levelled industries, whether R&D investment increases or decreases with product substitutability depends crucially on the level of the R&D productivity. We choose parameters and formulate testable predictions that we take to the laboratory. We find that subjects' behavior is largely consistent with the model's predictions.

JEL: C12, C72, C91, L13

Keywords: Duopoly, R&D Productivity, Product Substitutability, Experiments

*The paper has benefited greatly from the comments of Michele Boldrin, Holger Herz, David Levine, Nikolaos Tsakas, and Daniel Zizzo. We are also indebted to the editor, Friederike Mengel, the associate editor and two anonymous referees for their insightful comments, which significantly improved the paper. The usual disclaimer applies.

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1 Introduction

The present work studies how the effect of a change in the degree of product substitutability on the R&D investments of competing firms varies with *R&D productivity* (i.e. the efficiency in generating product and process improvements). The interaction we highlight in this paper between the R&D productivity in the industry and product substitutability (competition more generally) in determining the R&D investment has not been recognized in the received literature, both the theoretical and the applied one.

Our contribution evolves into more than one dimensions. First, on the theoretical dimension, we show that whether an increase in product substitutability leads to an increase or a decrease in R&D investment depends, among others, in a non-trivial manner on the level of firms' R&D productivity. Arguably, such an exercise would have been redundant from a more applied point of view had there been no variations in firms' R&D productivity in the data. The relevance of our investigation on the impact of variations in R&D productivity on the relationship between product substitutability and R&D investment is indeed emphasized by the evidence provided by Agarwal and Gort (2002) and Bloom, Jones, Reenen, and Webb (2017). The former work shows that opportunities for innovation are often higher for industries at the early stages of their development, while the latter shows that R&D productivity is rising in some industries and declining in others. Second, by showing that variations in R&D productivity can largely affect the relationship between product substitutability and R&D investments, our theoretical analysis emphasizes the importance of controlling for such variations to ensure the robustness of any empirical relationship found in the data. The last contribution of our work lies in making a first attempt towards establishing the quantitative importance of the novel interaction between R&D productivity and product substitutability in influencing R&D investment by taking our theoretical model's testable predictions to the laboratory.

There are two advantages in employing controlled laboratory experiments to analyze the effect of the interaction of R&D productivity with product substitutability on firms' R&D investments. First, in an experimental investigation, the experimenter has full power over which variables to control to eliminate a simultaneity bias. For instance, numerous empirical studies on competition and innovation suffer from endogeneity issues as the degree of competition influences the rate of innovation and vice versa. Here, the degrees of product substitutability and R&D productivity are exogenously chosen, which circumvents the endogeneity problem and, thus, enables us to identify clearly causality. Second, a controlled experiment mitigates the measurement errors of field studies. For one, several empirical studies measure competition with the price-cost margin (PCM) or with concentration measures, such as the

Herfindahl index (HI). However, these measures are, not only, inherently endogenous, but their theoretical foundations are also not robust.[1] In our experimental setup, the degrees of product substitutability and R&D productivity match the foundations of our theoretical model thus eliminating such concerns. For another, how R&D productivity influences the relationship between product substitutability and R&D investment is moderated by several factors that are not directly observed in the field, such as the technological gap between the firms at specific time periods. This implies that field studies cannot always fully disentangle the interplay between R&D productivity and the relationship between product substitutability and innovation. On the contrary, our controlled laboratory experiments accommodate for the technological gap across the firms.

To investigate the aforementioned interaction, we put forward a stylized model where, given the level of R&D productivity, firms can, first, invest in R&D in order to improve their *technology*, which consists of improvements in the quality of their products and/or a reduction in their manufacturing costs, and, subsequently, decide on their production levels. In making their choices, they take their rivals' current decisions as given while anticipating the best responses at future interactions. Each firm's R&D investment will stochastically influence its technology, which, in turn, will affect the share of the economic rents that the competing firms will capture at the production stage. We pay particular attention to the level of firms' R&D productivity, the firms' technology gaps, and the role these play in shaping the appropriation of the economic rents at the manufacturing stage as well as the incentives for R&D investments at the R&D stage.

Even though differences in R&D productivity could emerge within a sector, we restrict attention to an environment where firms face the same R&D productivity. Apart from its analytical convenience, this assumption attempts to capture an R&D environment where every firm in a given industry can rely on the *same pool of knowledge and research capabilities* when they invest in R&D.[2] Note that our model does not assume that the two firms need to have the same technology and hence market profitability. In fact, in our setup, differences

[1] Boone (2008) (see also references therein) notes that "sometimes more intense competition (in the theoretical sense) leads to higher PCM and/or higher HI" (p. 588).

[2] A state where firms within an industry face similar R&D productivities could arise under many plausible scenarios. For one, consider firms with inferior knowledge that end up making losses at the manufacturing stage and thereby exit the industry. Surviving firms, despite having possible different technologies for the production of their imperfectly substitutable products, would thus tend to have similar and high research capabilities. Klepper (2002) provides a compelling analysis of the process and evidence on the survival of firms with such higher R&D productivities. Similarities in the R&D productivities of firms within an industry may also arise over time because of industry-wide learning-by-doing spillovers (Irwin and Klenow (1994)), knowledge spillovers through worker mobility (Stoyanov and Zubanov (2014) and Mostafa and Klepper (2018)), and technology-sharing agreements between competitors (Petrakis and Tsakas (2018)), including cross-licensing arrangements (Choi and Gerlach (2019)). Our model can thus be considered as one that tries to capture the R&D environment faced by firms at the end of such processes.

in technology can arise as a result of differences in the rate of innovation under the common R&D productivity. Taking explicitly into account the dependence of firms' investment decisions on the R&D productivity, our model is parsimonious enough to capture industries with high R&D productivity as well as industries with low R&D productivity. It is also suitable to capture the *same* industry in different phases of its lifetime (i.e. going from high R&D productivity to low or vice versa).

We focus on markets with two competitors. The analytical simplicity of duopoly will also be very useful when we take the predictions of our theory to the laboratory. Focusing on duopolies is also motivated by the fact that there are important duopolistic markets that resemble our modelling environment. Two prime examples of such duopolistic markets are Boeing 737 vs. Airbus A320 and Google's Android vs. Apple's iOS.[3]

In the proposed model, we assume that an increase in product substitutability (or, more generally, an increase in competition) increases the incremental benefit (in terms of appropriated economic rents) from innovating to become a leader (what is generally known as the 'escape-competition' effect), but leads to a reduction of the incremental benefit to the laggard from innovating to catch up with the competitor (what is generally known as the 'Schumepterian' effect). In line with existing literature, our model predicts that an increase in product substitutability leads to a decrease in the laggard's R&D investment regardless of the level of R&D productivity.[4] However, in a levelled industry, we find that R&D investment does depend on the level of R&D productivity. The reason is that R&D productivity affects the likelihood that the opponent innovates (for any given investment) and, thereby,

[3] Since the 1990s, the competition in the aircraft manufacturing industry between Airbus and Boeing has been fierce as evidenced by the similarity in the number of orders and deliveries. Furthermore, the two manufacturers, share similar R&D productivities as evidenced by the striking similarities in the number of patents granted from equally close R&D expenditures.The two most popular aircrafts of the two aerospace behemoths, Boeing 737 and Airbus A320, cannot be considered perfect substitutes due to the use of different operating systems. Nevertheless, the two firms spend a significant amount of resources to reduce costs of production and improve the quality of the aircrafts through wireless controls, larger cargo areas, more comfortable seating arrangements, and increased fuel efficiency. Fierce competition and similar R&D productivity is also present in the mobile technology industry, and in particular, between Google's Android and Apple's iOS. Along similar lines to the aforementioned aircrafts, Google's Android and Apple's iOS cannot be considered perfect substitutes as the two platforms inspire unparalleled loyalty culminating in high switching costs for users to move from one operating system to the other. At the same time, Google and Apple continuously improve the speed, stability, security, call and messaging features of their operating systems.

[4] The fact that an increase in product substitutability increases the incremental benefit from innovating to become a leader raises the incentive of the leader to invest. However, an increase in product substitutability leads also to a decrease in the laggard's R&D investment. When the laggard's R&D investment is lower, the threat from the laggard catching up with the leader is smaller and therefore the leader's incentive to invest is weaker, all other things equal. As a result, the net effect on the leader's R&D investment of an increase in product substitutability could, in general, go towards either direction depending on the primitives of the environment.

whether a firm by innovating faces a higher likelihood to become a leader or higher likelihood to maintain its relative technological position at the manufacturing stage. In particular, our model predicts that when R&D productivity is low enough (in which case the opponent's likelihood of innovating is low), an increase in product substitutability leads to an increase in R&D investment in a levelled industry, whereas when R&D productivity is high enough (in which case the opponent's likelihood of innovating is high), R&D investment decreases with product substitutability (see Subsection 2.1.2 for details). The latter is a novel result, which sheds new insights into the interplay of R&D productivity with product substitutability in determining R&D investment in an industry.

In our experiment, subjects are randomly matched in pairs to form duopolies, and are asked to decide on the level of investment to be undertaken in *each* of three scenarios: (a) both firms are in a levelled industry, (b) their own firm is lagging behind the other one, and (c) their own firm is leading the other firm. An innovation may improve the relative position of the firm, if the other firm's investment was unsuccessful. R&D investments are costly. The investment cost depends not only on the investment level chosen, but also on the R&D productivity, where, ceteris paribus, the higher the R&D productivity the lower the cost of the firm's investment. Rents are, then, distributed to the two subjects according to their final relative position. On one hand, if subjects end up to be levelled, the rents of the two firms are equal. On the other hand, if one subject is ahead of the other, then, the leader always receives a higher rent than the laggard. The laboratory results are largely in line with the proposed model's predictions. Thus, R&D productivity *does* matter for the relationship between product substitutability and R&D investment in a duopolistic market.

Related Literature In their 1975 seminal survey on market structure and innovation, Kamien and Schwartz (1975) emphasize the importance of *technological opportunities* (what we call R&D productivity) in influencing the R&D investments of firms. However, after discussing some basic empirical findings available in the literature,[5] they did not explore the matter further. Since then, and in particular after the publication of the influential work by Aghion, Bloom, Blundell, Griffith, and Howitt (2005) on the inverted-U relationship between competition and innovation, the focus of scholars has concentrated on the effect of market structure and competition on R&D investments[6] (see Gilbert (2006) and De Bondt and Van-

[5] The authors refer to the early empirical works by Scherer (1965), who finds that the bulk of interindustry variation in patenting activities was explained by differences in the underlying technological opportunities of the various industries, and by Kelly (1970), who finds that technological opportunities had a significant role on the innovative activity of the chemical and petroleum industries relative to the other industries studied.

[6] On one hand, Aghion, Bloom, Blundell, Griffith, and Howitt (2005) define competition in their theoretical model by the inverse of the degree to which firms in a duopoly model can collude. On the other hand, in their empirical investigation, the authors measure competition by the average price-cost margins (i.e. the

dekerckhove (2012) for a survey on this literature). Specifically, the studies of Vives (2008) and Schmutzler (2013), among others, have shown that the relationship between competition and R&D investment can be positive or negative depending on, amongst other things, how competition in the product market is modelled,[7] the extent of efficiency differences among rivals, and the existence of externalities. The distinction between incremental and discrete innovation is another key element that may play a role in the relationship. For instance, the paper by Ghosh, Kato, and Morita (2017) shows that competition can decrease firms' incentives to invest in incremental innovation in the presence of discrete innovation.

Though some aspects and ideas in the aforementioned studies do find common ground with our theoretical model, what we propose here is different in that we model investment with a stochastic outcome, and study how R&D productivity influences the impact of changes in product substitutability on the incentives to invest. We also draw similarities to the models by Sacco and Schmutzler (2011) and Aghion, Bechtold, Cassar, and Herz (2018). However, the former model differs from ours in two substantial ways. First, the authors assume that the probability of successful R&D investment is independent of the investment level. Second, economic rents depend on the level of R&D investment conditional on innovation having taken place. In contrast, we assume that the success probability is increasing in the level of investment, while rents depend on the technology gaps at the production stage, but not on the actual levels of investment (see also Subsection 2.2 for a discussion on our modelling assumptions). In this respect, the model proposed in this study is closer to the theoretical framework by Aghion, Bechtold, Cassar, and Herz (2018).

As mentioned earlier, one of the main challenges faced by empirical works has been to construct a reasonable measure of competition and, then, find credible sources of exogenous variation of this variable. A number of studies have used laboratory experiments to circumvent these problems. In particular, Darai, Sacco, and Schmutzler (2010) and Aghion, Bechtold, Cassar, and Herz (2018) have studied experimentally the relationship between competition and R&D investment decisions. In the Darai, Sacco, and Schmutzler (2010) study, the authors use two-stage static investment games to derive and test predictions about the effects of increasing competition on cost-reducing investments. In Aghion, Bechtold, Cassar, and Herz (2018), the authors analyze experimentally the effects of competition on a step-by-step innovation model. However, to re-emphasize, our contribution to the existing literature is combining theory and experiments to investigate *explicitly* the interaction of R&D productivity with product substitutability (i.e. competition) on the determination

Lerner Index) across firms in a given industry.

[7] Vives (2008) models competition as an increase in product substitutability or an increase in the number of firms in an oligopolistic model á la Cournot or á la Bertrand. Schmutzler (2013) models competition as an increase in product substitutability or as a change from Cournot to Bertrand.

of R&D investment.

The layout of this paper adheres to the following plan. In Section 2, we describe and discuss the novel theoretical model, while in Section 3, we present the experimental design and formulate the testable predictions based on our parameter choices. In Section 4, we provide the main experimental results. Finally, in Section 5, we offer concluding remarks and directions for future research.

2 The Model

In what follows, we present and analyze a reduced-form model that describes the firms' expected payoffs for any given profile of R&D investment. The reduced-form model captures the essential ingredients that are needed to derive our predictions. In Appendix A, we provide a microfoundation for this reduced-form model, which is based on a two-stage strategic interaction between two firms. In the first stage, firms engage in R&D investment with the aim of reducing the production costs and/or enhancing the quality of their product. In the second stage, the two firms choose their production in a setup of Cournot competition under product differentiation.[8] We emphasize here that our main results are robust to any extension of the second-stage output market as long as the duopolists' "economic rents" and "product substitutability" satisfy assumptions (1)-(3) below.

We restrict attention to a duopoly where firms face the same R&D productivity. Specifically, in our reduced-form model there are two firms $i = 1, 2$ and two stages. In the first stage, firms set their R&D investment non-cooperatively. In the second stage, the outcome of R&D investments (profile of technologies) is realised and firms attain the associated (economic) rents. In more detail, given the realised technologies, if the industry turns out to be "levelled" in the second stage (henceforth, duopoly and industry are used interchangeably), then, each firm earns the same rents. Denote the second-stage rents in such a duopoly by π_s (where s is a mnemonic for symmetric). In an industry which turns out to be "unlevelled" in the second stage, one firm obtains higher rents than the other. We refer to the firm with

[8] Our choice of a two-stage game is driven by our focus to study both theoretically and experimentally the interaction of the degree of product substitutability and R&D productivity in determining R&D investment. A fully-dynamic model where the relative technological advantage of firms would change stochastically over time as a result of past investment decisions would give rise to complicated stochastic dynamics. Therefore, it would be possible to attain explicit solutions (to be taken to the laboratory) only through simulations. Moreover, the kind of complicated decision environment that would be needed to test experimentally the numerical predictions of such a dynamic model would make the experimental setup too contrived and, as a result, could skew the results and compromise the conclusions. We thus opted for the simpler and still insightful two-stage setup.

the high rents as the *leader*, and to the firm with the lower rents as the *laggard*. We also denote second-stage high rents in such an industry by π_h, and the corresponding lower rents by π_l. We postulate that

$$\pi_h > \pi_s > \pi_l, \tag{1}$$

where π_h is finite.

We also parametrize second-stage rents by a variable θ, which captures the degree of *product substitutability* in the industry: the higher the θ, the easier for consumers to substitute the products. We assume that

$$\frac{\partial[\pi_h - \pi_s]}{\partial\theta} > 0 \tag{2}$$

and

$$\frac{\partial[\pi_s - \pi_l]}{\partial\theta} < 0. \tag{3}$$

that is, the higher the θ, the higher the gain from being the leader, and the lower the loss from being the laggard, compared to the situation where firms operate in a levelled industry and earn π_s. The first assumption introduces a stronger incentive, all other things equal, on the part of firms to become the leader as the level of the product's substitutability increases. The second assumption introduces a weaker incentive, all other things equal, on the part of firms to avoid being the laggard as the level of the product's substitutability increases.

A successful R&D investment gives rise to an innovation in the form of a technology improvement that reduces the production costs and/or enhances the quality of the product in the second stage. We assume that an obsolete technology becomes freely and immediately available to the laggard firm. Therefore, if the current leader successfully innovates while the laggard does not, the technology that was previously giving the advantage to the leader becomes immediately and, at no cost, available to the laggard.[9] As a result, the difference in rents between the leader and the laggard continues to be equal to $\pi_h - \pi_l$.

R&D investment is described in terms of the implied probability of success in innovating $p_i \in [0,1], i = 1,2$. We refer to this probability as *research capacity* or *R&D investment*, interchangeably. The cost of research capacity p_i for either firm i is given by

$$C(p_i, K_i) = \frac{c(p_i)}{K}, \tag{4}$$

where $c(p_i)$ is an increasing and convex function with $c(0) = 0$, and $\lim_{p_i \to 1} c'(p_i) = \infty$, while $K \geq 1$ captures the (industry-specific) efficiency in terms of R&D investment. The focus of

[9] This assumption is without loss of generality. In Appendix B, we show theoretically that the results of our model are robust to allowing for a wider technology gap between the leader and the laggard in the second stage compared to their initial one-step gap.

our paper is to study the impact of changes in the R&D productivity K on how firms' R&D investment p_i responds to variations in product substitutability θ.

We finally assume that

$$\min_{p_i} c''(p_i) > K[(\pi_s - \pi_l) - (\pi_h - \pi_s)]; \tag{5}$$

that is, the gain in rents from not being the laggard relative to the gain from being the leader (with both gains be calculated with reference to the situation where firms are identical) is not very high. Condition (5) is a regularity condition, which ensures that there is a symmetric equilibrium with positive investment in the levelled industry (see Subsection 2.1.2).

2.1 The Investment Problem

In this subsection, we discuss the Nash equilibrium (simply referred to as equilibrium hereafter) investment choices of the firms. At equilibrium, the investment problem of a firm is to maximize its expected payoff with respect to its research capacity, taking as given the research capacity of its rival. Optimal choices are denoted with an asterisk. The investment decision depends on whether a firm is the leader or the laggard or in a levelled industry at the time of choosing the investment (i.e. at the first stage). Given our assumptions so far, we have that $p_i < 1$ for any $i = 1, 2$. We first characterize the equilibria when the industry is unlevelled, and, subsequently, the symmetric equilibrium when the industry is levelled.[10]

2.1.1 The First-Stage Unlevelled Industry

To fix ideas, suppose that firm $i = 2$ is the laggard and that firm $i = 1$ is the leader at the time of R&D investment. The investment problem of the laggard is to maximize with respect to p_2:

$$(1 - p_2)\pi_l + p_2 [p_1^* \pi_l + (1 - p_1^*)\pi_s] - C(p_2, K) =$$
$$\pi_l + p_2(1 - p_1^*)(\pi_s - \pi_l) - \frac{c(p_2)}{K}.$$

Based on the aforementioned assumptions, this problem is well-defined. To understand this problem note that increasing marginally the research capacity of firm $i = 2$ leads to a higher cost by $c'(p_2)/K$ units, and to an increase in expected rents by $(1 - p_1^*)(\pi_s - \pi_l)$ units. The

[10] In the levelled industry, there are also asymmetric equilibria when $1 \geq c'^{-1}(K(\pi_h - \pi_s)) \geq \frac{\pi_h - \pi_s - \frac{\bar{c}}{K}}{\pi_h - \pi_s + \pi_l - \pi_s} > 0$. However, for the set of parameters used in our experiments, the symmetric equilibrium is the unique equilibrium, and so here, to simplify our discussion, we abstain from discussing asymmetric equilibria.

latter increase is the gain from being in a levelled industry in the second stage, which occurs when firm $i = 2$ innovates and the rival does not succeed in innovating.

Taking the first-order condition with respect to p_2, we have at an interior solution (i.e. when $p_2^* > 0$) that

$$K(1 - p_1^*)(\pi_s - \pi_l) = c'(p_2^*). \tag{6}$$

The optimal research capacity of the laggard p_2^* is increasing in its relative marginal benefit $K(1 - p_1^*)(\pi_s - \pi_l)$. Clearly, if $K(1 - p_1^*)(\pi_s - \pi_l) \leq c'(0)$ then $p_2^* = 0$.

The problem of the leader, in turn, is to maximize with respect to p_1:

$$(1 - p_1)[p_2^*\pi_s + (1 - p_2^*)\pi_h] + p_1\pi_h - C(p_1, K) =$$

$$\pi_h - (1 - p_1)p_2^*(\pi_h - \pi_s) - \frac{c(p_1)}{K}.$$

This problem is well-defined as well. As with the laggard's problem, increasing marginally the research capacity of firm $i = 1$ leads to a higher cost by $c'(p_1)/K$ units, and to an increase in expected rents by $p_2^*(\pi_h - \pi_s)$ units. The latter increase is the gain from avoiding being in a levelled industry in the second stage, which will occur when firm $i = 1$ fails to innovate and the rival succeeds in innovating. Taking the first-order condition with respect to p_1, we have at an interior solution (i.e. when $p_1^* > 0$) that

$$Kp_2^*(\pi_h - \pi_s) = c'(p_1^*). \tag{7}$$

The optimal research capacity of the leader p_1^* is increasing in its relative marginal benefit $Kp_2^*(\pi_h - \pi_s)$. If $Kp_2^*(\pi_h - \pi_s) \leq c'(0)$, we, then, have that $p_1^* = 0$.

We restrict attention to the (more interesting) case where there is strictly positive investment from the laggard in the equilibrium.[11] To start with, we observe that if $p_1^* = 0$, then, the laggard's R&D investment decreases with product substitutability: in this case $p_2^* = c'^{-1}(K(\pi_s - \pi_l))$, where, by the convexity of the cost function and assumption (3), $c'^{-1}(K(\pi_s - \pi_l))$ is decreasing in θ.

Turning to the case where both firms invest, to find the effect of θ on the equilibrium research capacities, we need to use the Implicit Function Theorem. So, dropping the asterisks for notational simplicity, and using (6) and (7), we have that

$$\partial p_2/\partial\theta = \frac{c''(p_1)K(1 - p_1)\frac{\partial[\pi_s - \pi_l]}{\partial\theta} - K(\pi_s - \pi_l)Kp_2\frac{\partial[\pi_h - \pi_s]}{\partial\theta}}{c''(p_1)c''(p_2) + K(\pi_h - \pi_s)K(\pi_s - \pi_l)}.$$

[11] In Appendix E, we characterize all Nash equilibria and provide more details on the use of the Implicit Function Theorem.

Note that the denominator is positive by the convexity of the cost function and assumption (1). In addition, the numerator is negative by the convexity of the cost function and assumptions (2) and (3). Therefore, the laggard's R&D investment decreases with product substitutability in this case as well. Crucially, the effect of higher θ on the leader's R&D investment (i.e. $\partial p_1/\partial\theta$) cannot be signed without further assumptions on the primitives of the model. These findings are formalized in our first theoretical prediction below.

Theoretical Prediction *In an unlevelled industry, when R&D productivity is low enough, the leader's R&D investment is zero regardless of the level of product substitutability, whereas the laggard's R&D investment decreases with product substitutability regardless of the level of R&D productivity.*

2.1.2 The First-Stage Levelled Industry

We turn our focus to the investment of firms in a levelled industry in the first stage. The problem of any firm i is to maximize with respect to p_i:

$$(1-p_i)\left[p^*_{-i}\pi_l + (1-p^*_{-i})\pi_s\right] + p_i\left[p^*_{-i}\pi_s + (1-p^*_{-i})\pi_h\right] - C(p_i, K) =$$

$$p^*_{-i}\pi_l + (1-p^*_{-i})\pi_s +$$

$$p_i\left[p^*_{-i}(\pi_s-\pi_l) + (1-p^*_{-i})(\pi_h-\pi_s)\right] - \frac{c(p_i)}{K}.$$

This problem is also well-behaved. Under this problem, increasing marginally the research capacity leads to a higher cost by $c'(p_i)/K$ units, and to an increase in expected rents by $p^*_{-i}(\pi_s-\pi_l) + (1-p^*_{-i})(\pi_h-\pi_s)$ units. The latter increase is the gain from being the leader in the second stage, compared to a situation where either firm i fails to innovate and the rival succeeds in innovating, or when both firm i and its rival fail to innovate.

Taking the first-order condition with respect to p_i, we have at an interior solution (i.e. when $p^*_i > 0$ for all i) that

$$K\left[p^*_{-i}(\pi_s-\pi_l) + (1-p^*_{-i})(\pi_h-\pi_s)\right] = c'(p^*_i). \quad (8)$$

Note that the optimal research capacity p^*_i is increasing in the relative marginal benefit $K\left[p^*_{-i}(\pi_s-\pi_l) + (1-p^*_{-i})(\pi_h-\pi_s)\right]$. We restrict attention to (symmetric) equilibria with strictly positive investment by both firms. This is ensured by condition

$$K\left[\pi_h - \pi_s\right] > c'(0), \tag{9}$$

which we assume to hold hereafter. Let $p^* = p_i^* = p_{-i}^*$ denote the symmetric equilibrium research capacity. We can then rewrite (8) as

$$K\left[p^*(\pi_s - \pi_l) + (1-p^*)(\pi_h - \pi_s)\right] = c'(p^*). \tag{10}$$

Assumption (5) and condition (9) imply directly that there is a unique solution $p^* > 0$ to the above condition. This solution is increasing in R&D productivity, captured by K.

We now turn to the analysis of the effect of θ on R&D investment p^*. Note from the above equilibrium condition (after dropping the asterisks) that

$$\frac{\partial p}{\partial \theta} = -\frac{K\left\{p\frac{\partial[\pi_s - \pi_l]}{\partial \theta} + (1-p)\frac{\partial[\pi_h - \pi_s]}{\partial \theta}\right\}}{K\left[2\pi_s - \pi_h - \pi_l\right] - c''(p)}, \tag{11}$$

and observe that (5) implies that the denominator is negative. Therefore, R&D investment increases with θ if the numerator is positive. The numerator, however, cannot be signed without further assumptions on the primitives of the environment. Given that $\frac{\partial[\pi_h - \pi_s]}{\partial \theta} > 0$ by (2) and $\frac{\partial[\pi_s - \pi_l]}{\partial \theta} < 0$ by (3), the numerator will be positive (negative) for lower (higher) values of p. In other words, if in equilibrium, the probability of success of the opponent is low enough, the gain of firm i moving from a levelled duopoly to becoming the leader (what is generally known as the 'escape-competition' effect) dominates, and, as a result, θ has a positive effect on the R&D investment p^*. On the contrary, if in equilibrium, the probability of success of the opponent is high enough, it will discourage R&D investments as the gain of moving to a levelled duopoly from being a laggard is low at high levels of product substitutability (what is generally known as the 'Schumpeterian' effect); that is, θ has a negative effect on the R&D investment p^*.

Consider now the threshold level of equilibrium research capacity defined by

$$\widehat{p}\frac{\partial[\pi_s - \pi_l]}{\partial \theta} + (1-\widehat{p})\frac{\partial[\pi_h - \pi_s]}{\partial \theta} = 0;$$

that is,

$$\widehat{p} \equiv \frac{\frac{\partial[\pi_h - \pi_s]}{\partial \theta}}{\frac{\partial[\pi_h - \pi_s]}{\partial \theta} - \frac{\partial[\pi_s - \pi_l]}{\partial \theta}} \in (0,1). \tag{12}$$

This threshold level depends on the degree of θ through the impact of the latter on the profile of rents π_h, π_s, π_l. In particular, the effect of θ on $\widehat{p}$ depends on the relative concavity of $\pi_h - \pi_s$ and $\pi_s - \pi_l$ with respect to θ, something for which our model is agnostic. Moreover, we note that $\widehat{p}$ does not depend on the R&D productivity K.

Recall from (10) that p^* is increasing in R&D productivity K. Accordingly, R&D productivity will influence the equilibrium value of p^* and thereby whether, for the given $\widehat{p}$, we have $p^* < \widehat{p}$ or not. Concretely, we have two cases. If R&D productivity is low enough, then $p^* < \widehat{p}$ and R&D investment increases with θ, whereas if R&D productivity is high enough, then $p^* > \widehat{p}$ and higher product substitutability leads to lower R&D investment in the symmetric equilibrium of a levelled industry. The equilibrium condition (10) implies directly that the threshold level of R&D productivity that defines these two cases, $\widehat{K}$, is given by

$$\widehat{K} \equiv \frac{c'(\widehat{p})}{\widehat{p}(\pi_s - \pi_l) + (1 - \widehat{p})(\pi_h - \pi_s)}. \tag{13}$$

Note that this threshold level *does* depend on the degree of product substitutability θ (both directly, through the impact of θ on the rents, and via $\widehat{p}$). The equilibrium for the case where $\pi_h - \pi_s > \pi_s - \pi_l$ is described in detail in Figure 1.

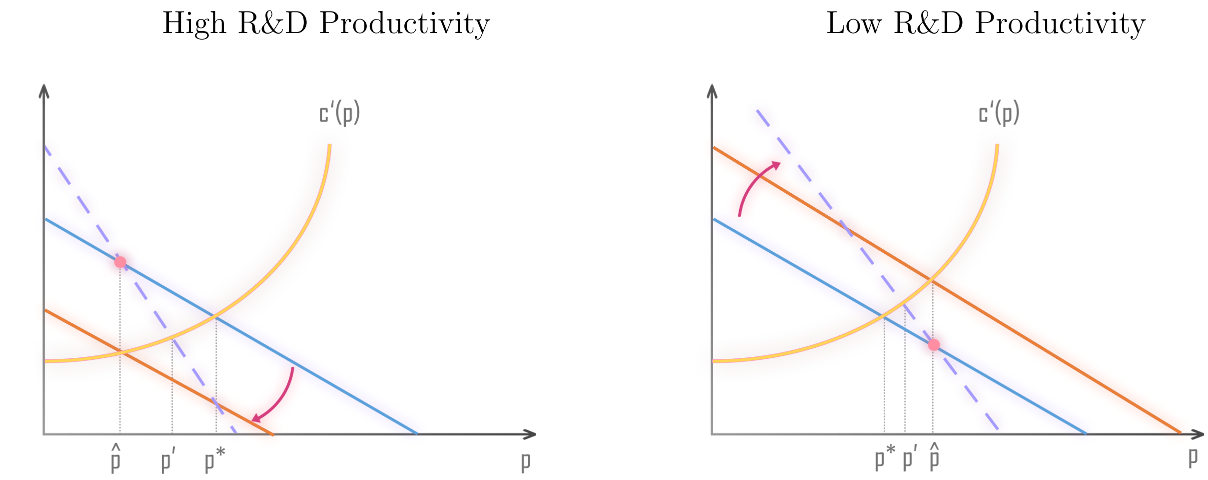
Therefore, our second theoretical prediction is formalized as follows.

Theoretical Prediction *In a levelled industry, when R&D productivity is low enough so that $K < \widehat{K}$ for any θ, R&D investment increases with product substitutability, whereas when R&D productivity is high enough so that $K > \widehat{K}$ for any θ, R&D investment decreases with product substitutability.*

The above discussion highlights that R&D productivity *together* with product substitutability interact to determine the impact of the latter on optimal R&D investment in the levelled industry: both influence the optimal investment p^*, while the extent of product substitutability determines the threshold values $\widehat{p}$ and $\widehat{K}$. The optimal investment p^* together with the threshold values $\widehat{p}$ and $\widehat{K}$ determine, in turn, whether an increase in product substitutability will lead to an increase or decrease in investment.

Before we conclude this section, we note that we cannot say more about the monotonicity properties of p^* with respect to the degree of product substitutability θ, unless we impose more assumptions on the dependence of the industry's rents profile on θ. One possible scenario, for instance, could be that the rents profile is such that $\widehat{p}$ is increasing in θ. In this case, we can think of an increase in the degree of product substitutability as an increase in $\widehat{p}$. In such an environment, the left panel of Figure 1 would depict a situation where product substitutability (and $\widehat{p}$) is low, whereas the right panel would depict a situation

Figure 1: Equilibrium Research Capacity



Notes: Recall (10) after dropping the asterisk: $K\left[p(\pi_s-\pi_l)+(1-p)(\pi_h-\pi_s)\right]=c'(p)$. The upward yellow line is the right-hand side. The solid blue line corresponds to the left-hand side for some initial θ, whereas the dashed line corresponds to the left-hand side for some higher θ. Their intersection with $c'(p)$ gives the equilibrium research capacity under these two alternative θs, denoted with p^* and p' respectively. The orange line corresponds to the left-hand side when $K=\widehat{K}$; its intersection with $c'(p)$ provides $\widehat{p}$ for the given initial θ. The left-hand side is decreasing in p as we are assuming $\pi_h-\pi_s>\pi_s-\pi_l$. Furthermore, for any given θ, the left-hand side increases (and so the solid blue line that represents it, shifts upwards) when R&D productivity K increases. The threshold level of research capacity $\widehat{p}$ thus defines two cases. If R&D productivity is high enough (i.e. $K>\widehat{K}$) then $p^*>\widehat{p}$. This case is depicted at the left panel. If R&D productivity is low enough (i.e. $K<\widehat{K}$) then $p^*<\widehat{p}$. This case is shown at the right panel. The left-hand side is increasing in θ when $p<\widehat{p}$, whereas it is decreasing in θ when $p>\widehat{p}$. Thus, when θ increases, we must have that the dashed line is below the solid blue line for $p>\widehat{p}$ and above the solid blue line for $p<\widehat{p}$. Therefore, at both panels, an increase in θ, for given R&D productivity K, results in a clockwise movement around the pivotal point of the line representing the left-hand side of (10). As a result, at the left panel, we observe a decrease in the equilibrium research capacity, and at the right panel, we observe an increase in the equilibrium capacity.

where product substitutability (and $\widehat{p}$) is high. Recall that in Figure 1, we have also assumed that $\pi_h-\pi_s>\pi_s-\pi_l$, and observe that when $\pi_h-\pi_s>\pi_s-\pi_l$, condition (13) implies that $\widehat{K}$ is increasing in $\widehat{p}$ and (by using the definition of $\widehat{p}$) increasing in θ. After recalling that $p^*\in(0,1)$ (under condition (9)) and that $\widehat{p}\in(0,1)$, it follows, then, immediately that, for a low level of K (i.e. $K<\widehat{K}$ for any θ), R&D investment is increasing in θ, while for high levels of K (i.e. $K>\widehat{K}$ for any θ), R&D investment is decreasing in θ. Finally, for an intermediate level of K (i.e. $K>\widehat{K}$ for low $\theta's$ and $K<\widehat{K}$ for high $\theta's$), the relationship between R&D investment and θ is U-shaped (locally).[12] However, if $\widehat{p}$ is decreasing in θ, then, analogous

[12]To see this, simply, start from the level of product substitutability at the left panel of Figure 1 and increase θ for any given K. By doing so, the orange line shifts upwards and the solid blue line pivots

reasoning implies the converse relationship (locally) between R&D investment and product substitutability.[13]

2.2 Remarks on Modelling Choices

Before proceeding to the experimental design, we provide three remarks on our modelling choices. The first remark deals with the robustness of assumptions (1)-(3). In the microfoundation of assumptions (1)-(3), provided in Appendix A, we assume a linear inverse demand system of the form used in Shubik and Levitan (1980) and Singh and Vives (1984) with the additional assumption that the goods are substitutes.[14] Within this class of models, the Cournot and Bertrand problems are dual to each other; in particular, Cournot competition with substitute products is the dual of Bertrand competition with complements (see Singh and Vives (1984) for the details). Therefore, our results carry through to the dual Bertrand problems insofar assumptions (1)-(3) are satisfied. To ensure these assumptions, we need additional structure, which is explained in the microfoundation provided in Appendix A.[15]

The second remark sheds light on whether our results would have been affected had we assumed instead that innovation is deterministic (i.e. $p_i \in \{0, 1\}$). In Appendix C, we analyze this version of our model. In such a discrete-choice model, equilibrium research capacities are de facto flat or (non-trivial) step functions of the degree of substitutability, whereas in our model with stochastic innovation, equilibrium research capacities are smooth functions of the degree of substitutability. Bearing in mind this difference, the results in the case of deterministic innovation echo our results here. Namely, the laggard's research capacity is one for low degrees of substitutability and zero for high degrees of substitutability, while when a unique symmetric equilibrium exists, R&D investment is the same for all degrees of

clockwise. At some level of product substitutability, the environment will be represented by the right panel of Figure 1 and so on. Therefore, by continuity, for low θ or $\widehat{p}$, we have that $\widehat{p} < p^*$, while for high θ or $\widehat{p}$, we have that $\widehat{p} > p^*$. In the former case, investment is decreasing in θ, and in the latter case, it is increasing in θ.

[13]Of course, in principle, $\widehat{p}$ may not be monotonically related to θ, in which case the relationship between R&D investment and product substitutability becomes more complicated to describe. However, our discussion in the main text is still useful to understand this relationship locally.

[14]Models with substitutes that have as a special case linear inverse demand systems have also been used in Dixit (1979) and Vives (1985).

[15]Given that the direct demand system is not invertible, the Hoteling model cannot lead to a linear inverse demand system. As such there is no direct comparison with our setup. Even in the case we did derive the equilibrium profit functions of the Hoteling duopoly directly, we would still not be able to discuss the robustness of our results in a comparable way. The reason is that in the Hoteling model, product substitutability is captured by the transportation costs, with changes in it affecting the cross-price responsiveness of demand as well as the own-price responsiveness of demand and autonomous (i.e. when prices are zero) demand, whereas in our model, a variation in product substitutability neither has an impact on the own-price responsiveness of demand nor on autonomous demand.

product substitutability in the levelled industry.

The final remark clarifies the impact of continuous versus discrete innovations on our results. In particular, a feature of the model is that the duopolists rents do not depend on the actual levels of R&D investment, but depend instead, only, on the outcome of investments where the latter determines the realized level of the technology gap between the firms along a predetermined technology ladder. One might wonder whether our results are specific to this feature. In other words, whether our main result is robust to allowing for the actual levels of R&D investment to affect rents directly through the (stochastic or non-stochastic) impact of firms' R&D investments on their technology gap. To address this, in Appendix D, we build a model where the technology gap is allowed to change incrementally (i.e. in a continuous manner) as a direct consequence of a marginal change in investment/innovation. It turns out that in such a model, our main message can survive under certain conditions that echo assumptions (2) and (3) above. To understand this, note that when firms' investments have a direct effect on rents, the laggard's (leader's) marginal benefit from a small increase in innovation is equal to the marginal increase in rents due to the small decrease (increase) in the technology gap between the two firms for a given innovation by the opponent. This marginal benefit will also depend on the degree of product substitutability, where the exact relationship is determined by the primitives of the duopoly. If the impact on this marginal benefit of a small increase in the degree of product substitutability is negative (positive), then, our main results will remain valid qualitatively. Namely, the laggard's investment is decreasing in the degree of product substitutability, whereas the investment of the leader can be non-monotone with the exact relationship being dependent on R&D productivity.[16]

3 Experimental Design

In the experimental design, we focused on two dimensions. The first dimension is the degree of product substitutability. We allowed for four levels of product substitutability measured by θ, where the higher the θ the easier for consumers to substitute the products. The four levels were $\theta \in \{0.1, 0.2, 0.5, 0.6\}$. The second dimension is the level of R&D productivity. We allowed for two levels of R&D productivity: $K = 2.63$ and $K = 13.16$. Henceforth, we refer to the treatments of $K = 2.63$ as the treatments with "low" R&D productivity, and

[16]Analyzing the latter relationship in detail is out of the scope of the current study and is thus deferred for future work. Moreover, the implementation of such a model in an experimental setup would be very complicated. However, for completeness, we provide some of the details of such a model in Appendix D. Importantly, in that model, the qualitative robustness of our main insights can be true under certain conditions regardless of whether the outcome of R&D investments is stochastic or not, while allowing also for an arbitrary initial technology gap.

to the treatments with $K = 13.16$ as the treatments with "high" R&D productivity. We should emphasize, however, that these terms (low and high) characterize only the relative size of the two levels of K we use in our treatments, and do not refer to the size of each level of K in relation to all possible levels of R&D productivity. In summary, we applied a 4×2 experimental design to examine the impact of product substitutability and R&D productivity on firms' investments.

3.1 Treatments

In the game play, subjects were recruited to play the role of firms. Initially, subjects were randomly matched in pairs to form duopolies. After reading the game instructions, subjects had to complete a quiz to ensure their understanding of the game. Subjects were, then, asked to decide on the level of investment to be undertaken under three scenarios that differed in the relative standing of the two firms on a fictional point score. The game was single shot; that is, the three decisions were the only decisions subjects were asked to make in the game play. Specifically, subjects were asked to choose an investment level α, where α corresponds to a value from 0 to 80 all inclusive[17] in *each* of the following three scenarios: (a) assuming that both firms had the same number of points in the point score, (b) assuming that the other firm was one point ahead in the point score from their firm, and (c) assuming that their firm was one point ahead in the point score from the other firm. The order the subjects were presented with the three scenarios was randomized to eliminate any order effects. Moreover, no feedback on the game play was provided until subjects had responded to all three scenarios. This information was common knowledge.

The probability of success or research capacity, as defined in the previous section, was given by $p = \alpha/100$. Furthermore, for each investment level α, there was an associated cost. We deployed the cost function

$$c(p_i) = \frac{1}{K}\frac{p_i}{1 - p_i}. \qquad (14)$$

The investment levels and the corresponding probabilities of success and costs were displayed in an easy-to-read table. The table was identical in all three scenarios. In fact, the only change in the table across treatments was the cost schedule to reflect the level of R&D productivity. Specifically, in the four treatments for the low level of R&D productivity, K was set to 2.63, whereas in the four treatments for the high level of R&D productivity, K was set to 13.16. Therefore, the cost schedule in the treatments for the low level of R&D

[17] We chose to place an upper bound to the probability of success to maintain realism.

productivity was five-fold the one in the treatments with the high level of R&D productivity.[18]

To determine subjects' payoffs in the game, one scenario was selected at random for *each* pair. In addition, a separate draw of an integer from 1 to 100 for each subject took place to determine whether the investment of that subject in the selected scenario was successful or not. Recall that a subject's investment choice reflects the probability of success; if the subject's investment in the selected scenario was below the computer-drawn integer then, that subject's investment was considered unsuccessful, otherwise it was considered successful. This information was common knowledge. A subject's successful investment would increase the point score of that subject by one point, and lead to an improvement in the relative standing if the subjects were levelled in the initial standing and the other subject's investment was unsuccessful. In each duopoly, the final payoffs of the two subjects were determined based on the selected scenario, their investment choices and corresponding costs, the outcomes of their investments and the final relative standing. In the experimental sessions, we used the following payoff function

$$u_i = \begin{cases} \pi_h - C(p_i, K_i) & \text{if } i \text{ was the leader in the final relative standing,} \\ \pi_s - C(p_i, K_i) & \text{if } i \text{ and } j \text{ were levelled in the final relative standing,} \\ \pi_l - C(p_i, K_i) & \text{if } i \text{ was the laggard in the final relative standing,} \end{cases} \tag{15}$$

where, recall, π_h is the economic rent of the leader, π_s denotes the economic rents of the two firms in a levelled industry, and π_l is the economic rent of the laggard. The numerical values of the economic rents for each level of product substitutability θ are shown in Table 1. To safeguard against potential losses, subjects were endowed with £5 in lieu of a show-up fee.

The experimental sessions were conducted in the Social Sciences Experimental Laboratory (SSEL) of the University of Southampton in May and October of 2016. We conducted two sessions per treatment, where each session had 16 subjects and 8 duopolies. The 256 subjects were recruited from the undergraduate and graduate population of the University of Southampton using ORSEE (Greiner (2015)). Participants were allowed to participate in only *one* session. Each session lasted around 30 minutes. Average payoffs per participant were £5.78. Subjects were paid in cash privately at the end of the session. The experiments were programmed and conducted with the use of the experimental software z-Tree (Fischbacher (2007)). The detailed instructions are reported in Appendix H.

[18]The numerical value of K was not included in the experimental instructions. Based on our theoretical framework, the only relevant factors for subjects' decisions were the starting relative standing of the two firms on the fictional point score, the cost schedule and the respective payoffs for all possible final standings. We thus chose not to provide any redundant information to the subjects to simplify their cognitive environment as such information could potentially compromise the clarity of the instructions and lead to confounding effects.

Table 1: Economic Rents

θ	π_h	π_s	π_l
0.1	2.19	0.91	0.18
0.2	2.15	0.83	0.12
0.5	2.15	0.64	0.02
0.6	2.20	0.59	0.00

Notes: θ is the level of product substitutability, π_h is the economic rent of the leader, π_s denotes the economic rents of the two firms in a levelled industry, and π_l is the economic rent of the laggard.

3.2 Testable Predictions

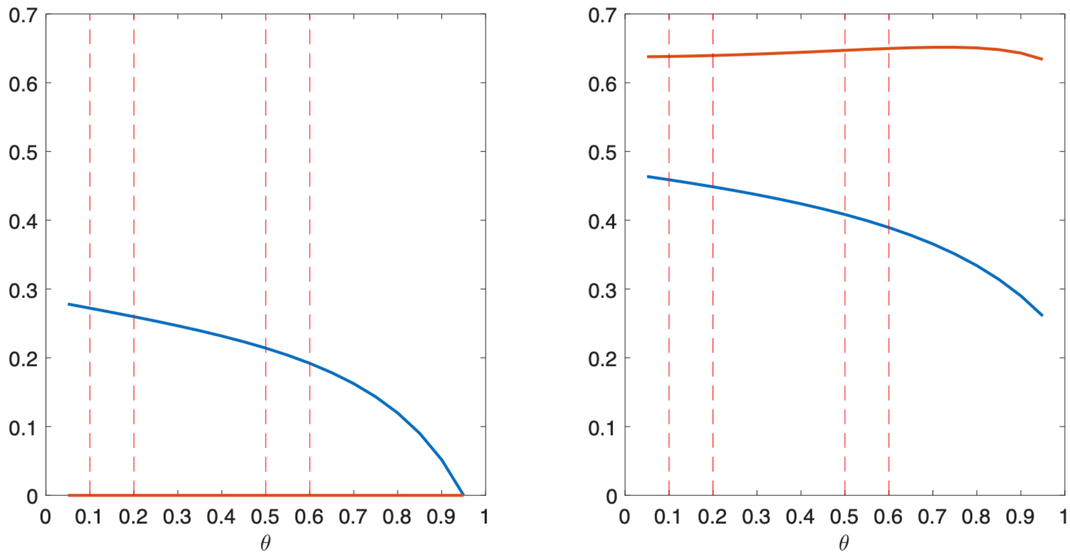
We formulate next our testable predictions based on the proposed theoretical model and the parameter choices in the experiments. First, we hypothesize on the equilibrium research capacity of the laggards and leaders in an unlevelled duopoly for low and high levels of R&D productivity. Second, we hypothesize on the equilibrium research capacity of firms in a levelled industry, again, for low and high levels of R&D productivity.

We look at the unlevelled industry in Figure 2. When R&D productivity is low (i.e. $K = 2.63$), the model, based on our parameter choices, predicts that the leader should invest 0. However, the laggard should invest a strictly positive value. On the left panel of Figure 2, we plot a laggard's equilibrium research capacity against θ for $K = 2.63$. Clearly, as θ increases, the equilibrium research capacity goes down. We also display the equilibrium research capacity of the leader. On the right panel of Figure 2, we display the equilibrium research capacity of the leader and laggard, respectively, when R&D productivity is high (i.e. $K = 13.16$). In this case, the model predicts that both the leader and the laggard should invest a strictly positive value. Specifically, in the case of the leader, the equilibrium research capacity is rather flat as θ increases, whereas, in the case of the laggard, the equilibrium research capacity goes down with θ. The two panels highlight that regardless of the level of R&D productivity, R&D investment decreases with θ for the laggard in an unlevelled duopoly. Our first prediction is formalized as follows.

Prediction 1 Research capacity by a laggard in an unlevelled duopoly should decrease with product substitutability regardless of the level of R&D productivity.

Next, we look at the levelled duopoly. Based on the industry's rents profile chosen in the experiments, the dependence of $\widehat{p}$ on θ is non-monotone (see Appendix F). However, for the θs chosen in the experiments, $\widehat{p}$ is increasing in θ. As we have argued in the last paragraph

Figure 2: Equilibrium Research Capacity in an Unlevelled Duopoly



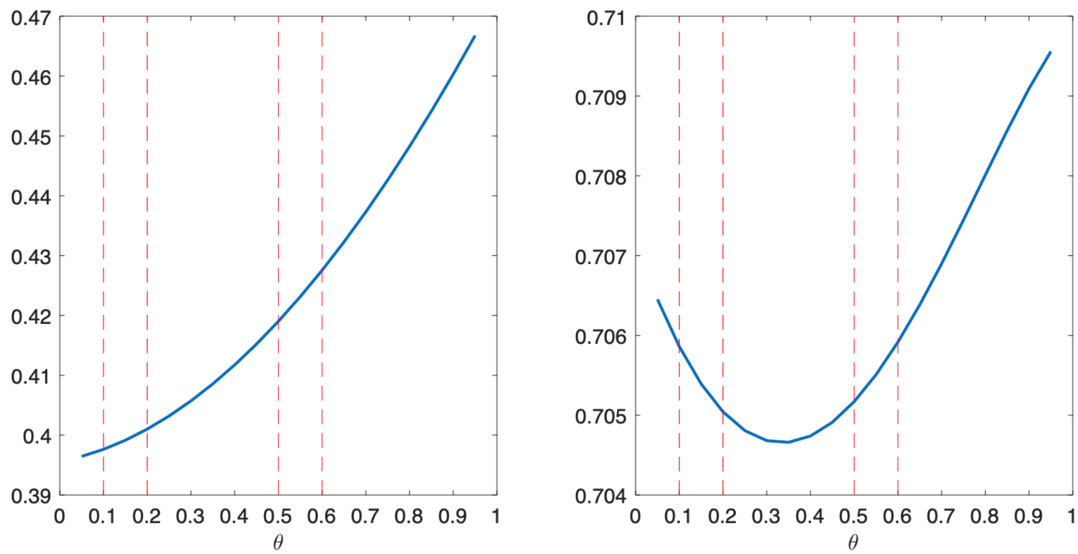
Notes: We display the equilibrium research capacity in an unlevelled industry for the leader (in red) and laggard (in blue), respectively. On the left, we display the equilibrium research capacity for $K = 2.63$ (i.e. low R&D productivity). On the right, we display the equilibrium research capacity for $K = 13.16$ (i.e. high R&D productivity). To map equilibrium research capacity to the subjects' choices in the actual experiments, simply, multiply the values on the vertical axis by 100. The vertical dotted lines indicate the four levels of product substitutability chosen in the experiments.

of Subsection 2.1.2, for such a range of θs, the relationship between research capacity and product substitutability is positive for low enough R&D productivity, while it is U-shaped for intermediate levels of R&D productivity. In fact, in our experiments, when the level of R&D productivity is $K = 2.63$, equilibrium research capacity should increase with θ, whereas, when the level of R&D productivity is $K = 13.16$, the relation between equilibrium research capacity and product substitutability should be U-shaped. This is shown in Figure 3. However, given that the actual differences in research capacity across the various levels of θ are very small, we expect subjects' choices in levelled firms to be practically invariant to changes in product substitutability. Based on these conclusions, we formulate the following two predictions.

Prediction 2 Based on the parameters chosen, research capacity by levelled firms increases with product substitutability when the level of R&D productivity is low.

Prediction 3 Based on the parameters chosen, research capacity by levelled firms is essentially flat with product substitutability when the level of R&D productivity is high.

Figure 3: Equilibrium Research Capacity in a Levelled Duopoly



Notes: We display the equilibrium research capacity in a levelled industry. On the left, we display the equilibrium research capacity for $K = 2.63$ (i.e. low R&D productivity). On the right, we display the equilibrium research capacity for $K = 13.16$ (i.e. high R&D productivity). To map equilibrium research capacity to the subjects' choices in the actual experiments, simply, multiply the values on the vertical axis by 100. The vertical dotted lines indicate the four levels of product substitutability chosen in the experiments.

3.3 Parameter Choices

We justify next our parameter choices. Our novel result in this study is the interplay of R&D productivity with product substitutability in determining R&D investment in an industry. Recall that depending on whether $\hat{p}$ is increasing or decreasing in the degree of product substitutability, R&D investment expressed as a function of θ can have a U-shape, inverted U-shape or it can be weakly or strictly monotonic (see Subsection 2.1.2). In the linear duopoly model of product substitutability (outlined in Appendix A) that we utilized to calculate the economic rents of Table 1, the chosen values for θs, $\{0.1, 0.2, 0.5, 0.6\}$, ensure that (a) $\widehat{p}$ is increasing (see Figure on the dependence of $\widehat{p}$ on θ in Appendix F) and hence that there are levels of K for which the equilibrium research capacity in a levelled industry with high R&D productivity is U-shaped, and (b) there are two pairs of θs so that, when K is such that the equilibrium research capacity is U-shaped, one pair of θs is at the decreasing part, while the other pair is at the increasing part (i.e. see the right panel of Figure 3).[19]

[19] A byproduct of our aforementioned desiderata is that there would be very small variation in equilibrium research capacity expressed as a function of product substitutability in the specific levelled duopoly with high

Given the chosen values for θs and the linear duopoly model of product substitutability we used for the construction of Table 1, the definition of $\widehat{K}$ in (13) implies that for the treatments of "low" K, we should choose a K in the interval of $(0, 4.9786)$, while for the treatments of "high" K, we should choose a K in the interval of $(4.9786, 18.706)$. Our choices of low and high K are roughly in the upper halves of the corresponding intervals, with the particular choices striking a balance between (a) the cost-effectiveness of our experiments (pushing for low initial endowments and thereby for low investment costs and hence high K), and (b) theoretically predicted investment levels distinctively away from the maximum investment level of 80 (pushing for high investment costs and thereby low K).

We also note here that we did not consider treatments with $K > 18.706$ as the theoretical prediction for such levels of K would be that the equilibrium research capacity in a levelled industry is decreasing in θ, but also very close to the maximum research capacity of 0.80 (due to the implied very low investment costs). Given that subjects would tend to choose the maximum investment when faced with very low investment costs, it would be very difficult to derive any useful insights about the interaction of R&D productivity and product substitutability in determining subjects' investment choices when $K > 18.706$. We therefore opted for not including such treatments in our experimental design.

Finally, considering the duration of the experiment (approximately 30 minutes) and the minimum wage in UK ($\approx$ £7 per hour), we stipulated that no subject should get a compensation below £3.50. Therefore, the difference between the highest investment cost (i.e. £1.52) and the lowest economic rent (i.e. £0.00) was added to £3.50, which led us to provide subjects with an initial endowment of £5.

4 Results

This section is divided into three subsections. Subsection 4.1 discusses the research capacity choices of subjects in the different scenarios (i.e. as laggards or leaders or levelled duopolies). Subsection 4.2 tests the formulated predictions about the decisions of laggards and levelled competitors for low and high levels of R&D productivity. Each prediction is matched with the corresponding result; that is, result i is a report on the test of prediction i. These results

R&D productivity. In conjunction with the other treatments, cost-effectiveness, and the need to maintain consistency in the parameters across treatments, we did not have any degrees of freedom to amplify the variation in equilibrium research capacity in the specific environment. Ultimately, for the chosen θs, the function is flat. Having said this, we do not see the small variation in equilibrium research capacity in this environment as necessarily a weakness of the experimental design. Instead, we look at it as a tight test of the theory that can highlight its limitations.

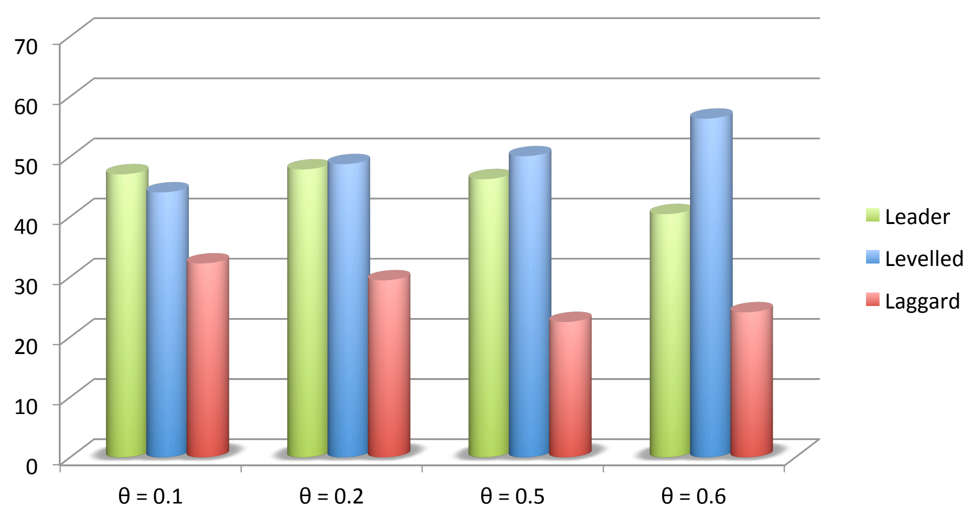
are the main focus of our study. Finally, in Subsection 4.3, we present for completeness the results of the leaders in unlevelled duopolies.

4.1 Preliminary Analysis

4.1.1 Descriptive Statistics

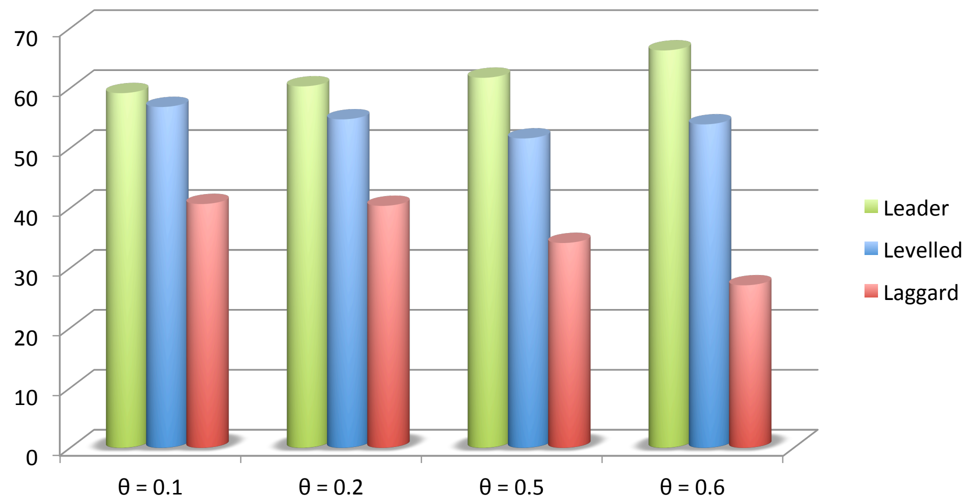
Figures 4 and 5 show the average research capacity of laggards, leaders and levelled duopolies for the four levels of product substitutability investigated for low and high levels of R&D productivity, respectively. For the low level of R&D productivity, the average research capacity of laggards goes down from 29.44 at $\theta = 0.20$ to 22.5 at $\theta = 0.50$, but increases slightly to 24.13 at $\theta = 0.60$. For the high level of R&D productivity, the average research capacity of laggards goes down monotonically with product substitutability. In levelled industries, the average research capacity increases with product substitutability for the low level of R&D productivity, while for the high level of R&D productivity, average research capacity decreases and, then, increases slightly at $\theta = 0.60$. Finally, average research capacity of leaders, for the low level of R&D productivity, goes up and, then, goes down with product substitutability, whereas, for the high level of R&D productivity, average research capacity of leaders increases monotonically with product substitutability.

Figure 4: Low R&D Productivity



Notes: We provide the average research capacity of laggards, leaders and levelled duopolies for the four levels of product substitutability investigated when the level of R&D productivity is low.

Figure 5: High R&D Productivity



Notes: We provide the average research capacity of laggards, leaders and levelled duopolies for the four levels of product substitutability investigated when the level of R&D productivity is high.

4.1.2 Tests of Difference on Research Capacity

Clearly, when the level of R&D productivity is high, the cost of research capacity decreases, hence firms, when controlling for the scenario (i.e. laggard or levelled or leader) and the degree of product substitutability, should increase their research capacity. To test whether research capacity choices with high R&D productivity are higher, we regress research capacity of laggards, levelled firms, and leaders on a dummy variable taking the value of 1 when $K = 13.16$ (i.e. when R&D productivity is high). Table 2 reports the estimated coefficients on the R&D productivity dummy in each of the three scenarios. In the first row, we regress research capacity on the R&D productivity dummy and on the level of product substitutability θ in all experimental sessions (i.e. we have 256 observations) and for each of the three scenarios. In the next four rows, we regress research capacity on the R&D productivity dummy when fixing the level of product substitutability θ (i.e. we have 64 observations) in each of the three scenarios.

Results in Table 2 show that research capacity choices by laggards and leaders are higher when R&D productivity is high (with the exception of the coefficient for the laggard at $\theta = 0.6$). The findings for levelled firms are not as clear. Research capacity choices when the R&D productivity level is high are significantly higher for levelled firms at $\theta = 0.1$, but are not significantly different for higher levels of product substitutability when compared to research capacity choices when the level of R&D productivity is low. Overall, results in Table 2, confirm the theoretical prediction that subjects tend to invest more with high R&D productivity.

Table 2: Tests of Difference on Research Capacity Choices

Variables	Laggard	Levelled	Leader
θ	8.52***	4.52*	16.48***
	(2.44)	(2.46)	(2.39)
$\theta = 0.1$	8.44*	12.81**	12.13**
	(4.88)	(4.86)	(5.21)
$\theta = 0.2$	10.94**	6.06	12.44**
	(5.46)	(5.11)	(4.92)
$\theta = 0.5$	11.69**	1.56	15.50***
	(4.89)	(4.52)	(4.99)
$\theta = 0.6$	3.00	-2.38	25.88***
	(4.38)	(5.16)	(3.87)

Notes: We regress research capacity choices of laggards, levelled firms, and leaders on a dummy variable taking the value of 1 when R&D productivity is high. Results reported show the estimated coefficients on the R&D productivity dummy in each of the three scenarios. In the first row, we regress research capacity on the R&D productivity dummy and on the level of product substitutability θ in all experimental sessions (i.e. we have 256 observations) and for each of the three scenarios. In the next four rows, we regress research capacity on the R&D productivity dummy when fixing the level of product substitutability θ (i.e. we have 64 observations) in each of the three scenarios. All standard errors are reported in parentheses. * Significant at the 10% level ** Significant at the 5% level *** Significant at the 1% level

4.2 Analysis of Laggards and Levelled Firms

The purpose of our empirical framework is to investigate the impact of product substitutability on the research capacity decisions of firms for low and high levels of R&D productivity. To test the predictions of the proposed model, we use the following linear form

$$\tilde{\alpha}_i = \beta \cdot \theta + \gamma \cdot X_i + \varepsilon_i, \qquad (16)$$

where the investment $\tilde{\alpha}$ of firm i depends on the degree of product substitutability θ in the industry, the vector of control variables X_i, which consists of the characteristics of player i (i.e. age, gender, race, university degree),[20] and the error term ε_i, which captures

[20] 50% of the participants were self-reported as "White," 40% were self-reported as "Asian," and 10% were self-reported as "Other" in the racial background question. Specifications include dummy variables for each

individual unobservable factors affecting the level of investment that are assumed to be uncorrelated with the degree of product substitutability θ. We used two different measures of product substitutability in (16). In the first specification, we included θ as a discrete variable taking increasing values from 0.1 to 0.6. In the second specification, we created three dummy variables for each of the values $\theta = \{0.2, 0.5, 0.6\}$ with $\theta = 0.1$ set as the base group. The second specification allowed us to assess how investments change in response to marginal increases of θ. However, this comes at a cost of reduced precision as three different parameters need to be estimated.

The β parameters in (16) were estimated using the OLS regression. Results are displayed in Table 3.[21] In Panel A, we regress investment of laggards on product substitutability. In Panel B, we regress investment of levelled firms on product substitutability. Given that none of the coefficients on dummy variables for gender, racial background and university degree were found to be statistically significant in the specifications, we chose to omit them from the table.[22]

The first prediction was formulated to test whether research capacity decreases with product substitutability for the laggards in unlevelled duopolies. The results of Panel A in Table 3 show a significant negative effect of product substitutability on investment choices of laggards both when the level of R&D productivity is low and when it is high (see columns (i), (ii), (iv) and (v)). The results in columns (iii) and (vi) of Panel A in Table 3, pick out a significant marginal decrease in average investment at $\theta = 0.5$ and $\theta = 0.6$. We formalize next our first result.

Result 1 Investment by laggards in unlevelled duopolies decreases with product substitutability regardless of the level of R&D productivity.

Our second testable prediction investigates the impact of product substitutability on firms' investment in levelled duopolies when the level of R&D productivity is low. The specification in column (iii) of Panel B in Table 3 identifies a significant marginal increase in investment at $\theta = 0.6$, while investments for intermediate levels of product substitutability are higher, but not statistically different from the reference group $\theta = 0.1$. These findings

of the three racial groups. In addition, given that the largest major was economics (around 23% of the sample), we felt compelled to include a dummy taking the value of 1 for economics students and 0 otherwise. Finally, for the gender, we assigned a value of 1 to the participants who were self-reported as "Female" and 0 otherwise in vector X.

[21]Table 3 and Table 4 (Panel A) show (heteroskedasticity) robust standard errors. Similar results are obtained when bootstrapping standard errors by re-sampling the observations (with replacement) in our dataset.

[22]The detailed regressions are available upon request. Furthermore, to complement our regression analysis, in Appendix G, we provide and disucss the Mann-Whitney-Wilcoxon tests to determine any difference in the distributions of investment choices across the selected levels of product substitutability.

Table 3: Regressions on Investment

Panel A: Laggard						
	Low R&D Productivity			High R&D Productivity		
Variables	(i)	(ii)	(iii)	(iv)	(v)	(vi)
θ	-18.07**	-17.67**		-25.40***	-27.68***	
	(7.33)	(7.58)		(8.94)	(9.20)	
$\theta = 0.2$			-3.19			-3.06
			(4.38)			(6.06)
$\theta = 0.5$			-9.68**			-9.99*
			(4.73)			(5.68)
$\theta = 0.6$			-8.13*			-14.64***
			(4.37)			(5.27)
Intercept	33.40***	32.28***	31.65***	44.49***	44.95***	42.02***
	(2.95)	(3.48)	(3.78)	(3.95)	(5.15)	(5.44)
Controls	No	Yes	Yes	No	Yes	Yes

Panel B: Levelled						
	Low R&D Productivity			High R&D Productivity		
Variables	(i)	(ii)	(iii)	(iv)	(v)	(vi)
θ	19.17**	20.10***		-7.13	-6.38	
	(7.53)	(7.40)		(9.30)	(9.80)	
$\theta = 0.2$			3.39			-3.28
			(5.06)			(5.16)
$\theta = 0.5$			4.44			-5.78
			(4.09)			(5.52)
$\theta = 0.6$			12.97***			-2.83
			(4.23)			(5.82)
Intercept	43.09***	42.97***	45.06***	56.81***	50.32***	51.51***
	(3.13)	(4.12)	(4.54)	(3.71)	(5.68)	(5.87)
Controls	No	Yes	Yes	No	Yes	Yes

Notes: In Panel A, we regress investment of laggards on product substitutability. In Panel B, we regress investment of levelled firms on product substitutability. Models (i), (ii) and (iii) provide the coefficients when the level of R&D productivity is low, whereas models (iv), (v) and (vi) provide the coefficients when the level of R&D productivity is high. As a base in models (iii) and (vi), we used $\theta = 0.1$. All regressions utilized 128 observations. Controls include variables collected in the questionnaire. Note that the intercept in column (i) and (iv) shows the average investment of all players, while the values in column (ii), (iii), (v) and (vi) show the average investment of the reference group, which is represented by white female players studying a degree other than economics with age less than 21 years. All standard errors are reported in parentheses. * Significant at the 10% level ** Significant at the 5% level *** Significant at the 1% level confirm the causal relation between product substitutability and investment when the level of R&D productivity is low. They are formalized in our second result.

Result 2 Investment by levelled firms increases with product substitutability when the level of R&D productivity is low.

The third prediction aims to examine the U-shaped but practically 'flat' relation between investment and product substitutability identified by the proposed model when the level of R&D productivity is high. Panel B of Table 3 shows that in levelled duopolies, investment is not affected by product substitutability (see columns (iv) and (v)). Our third result formalizes our findings.

Result 3 Investment by levelled firms is invariant to changes in product substitutability when the level of R&D productivity is high.

4.3 Analysis of Leaders

In the previous subsection, we provided results on the behavior of laggards and levelled firms for low and high levels of R&D productivity. The aforementioned findings are the main focus of the study. However, for completeness, we also discuss next the behavior of leaders in unlevelled industries for low and high levels of R&D productivity.

Recall that when R&D productivity is low, the leader should invest zero. Conversely, as depicted in Figure 2, the equilibrium research capacity of the leader is predicted to be strictly positive but rather flat when R&D productivity is high. We observe that the investment of the leader when R&D productivity is low in Figure 4 is not zero. However, the levels of investment chosen in the laboratory when R&D productivity is high follow a similar pattern to the one predicted by the model. In the Table 4, we regress investment of leaders on product substitutability (in an analogous fashion to Table 3). Point estimates suggest that investments tend to slightly decrease (increase) when R&D productivity is low (high), but none of the estimated coefficients on the product substitutability variable θ is statistically different from zero at the conventional levels of significance. Overall, the results presented in Table 4, give strong support to the theoretical prediction that the investments of leaders are not affected by the environment.

Table 4: Tests on Investment of Leaders

	Low R&D Productivity			High R&D Productivity		
Variables	(i)	(ii)	(iii)	(iv)	(v)	(vi)
θ	-11.18	-11.34		11.75	6.92	
	(7.92)	(8.00)		(8.08)	(8.14)	
$\theta = 0.2$			0.73			-0.62
			(5.05)			(5.28)
$\theta = 0.5$			-1.31			0.173
			(4.93)			(5.00)
$\theta = 0.6$			-6.48			4.12
			(4.51)			(4.79)
Intercept	49.32***	47.23***	44.64***	57.78***	55.09***	56.91***
	(3.21)	(3.83)	(4.39)	(3.73)	(4.72)	(4.85)
Controls	No	Yes	Yes	No	Yes	Yes

Notes: In the Table, we regress investment of leaders on product substitutability. Models (i), (ii) and (iii) provide the coefficients when the level of R&D productivity is low, whereas models (iv), (v) and (vi) provide the coefficients when the level of R&D productivity is high. As a base in models (iii) and (vi), we used $\theta = 0.1$. All regressions utilized 128 observations. Controls include variables collected in the questionnaire. All standard errors are reported in parentheses. * Significant at the 10% level ** Significant at the 5% level *** Significant at the 1% level

5 Concluding Remarks

In this study, we propose a novel model that investigates how the interaction of R&D productivity and product substitutability affects R&D investment in a duopoly setup. It turns out that the aforementioned interaction affects innovation in a non-trivial way. We conduct experiments where subjects playing the role of duopolists are asked to decide on their investment level. In the treatments, we vary the level of R&D productivity and product substitutability. The laboratory results are largely in line with the proposed model's predictions. Our first set of results shows that investment by the laggards in unlevelled duopolies decreases with product substitutability regardless of the level of R&D productivity. Our second set of results finds that investment by levelled firms increases with product substitutability when the level of R&D productivity is low, whereas, when the level of R&D productivity is high, investment is practically invariant to product substitutability. Our final set of results finds that leaders in the laboratory invest a strictly positive amount regardless of the level of R&D productivity. Overall, our experimental results indicate that

R&D productivity influences significantly the relationship between product substitutability and R&D investment in a duopolistic market.

Regarding future research, our theoretical framework could be extended in, at least, two fruitful directions. First, our model could be enriched to study situations where there are more than two firms in the market and there is free entry and exit. This would allow us to understand better how the interaction between R&D productivity and product substitutability (competition more generally) can affect innovative activities, and its implications for competition policy. For instance, our model seems to hint at the fact that, in an established market characterized by low R&D productivity, R&D investment may increase as a result of more stringent merger-control enforcements. On the contrary, a more lenient approach could be applied in industries at the early stages of development when R&D productivity is high.

Second, our model could be tweaked to allow for some heterogeneity in the R&D productivity between competing firms within an industry, possibly driven by differences in knowledge spillovers. This extension would be valuable to understand the role of patents on the incentives to innovate. In fact, patents can be thought of as a legal tool that introduces asymmetries in the flow of knowledge spillovers; thus, a patent owner can still benefit from the knowledge capital of competitors but can now successfully retain part of their knowledge capital within the walls of the organisation. This line of investigation would shed light on the impact of property rights on R&D investments in an industry by comparing the effects of patents when they are assigned early on at the stage of the industry's development (i.e. when R&D productivity is high) versus when they are assigned later on in the life-cycle (i.e. when R&D productivity is low).

Finally, our paper also urges future empirical works to incorporate a measure of R&D productivity in their analysis. Alternatively, the analysis should differentiate between industries at different stages of development as a way to control for R&D productivity.

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