

Two Regimes, One Threshold: Absorptive Capacity and the Structural Divergence of EU Innovation Systems

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Why do European Union member states that invest nearly as much in public research as the innovation leaders produce a fraction of their innovation output? This paper argues that the answer is structural rather than parametric. The EU innovation space is not a continuum of greater or lesser efficiency operating on a common production function - it contains two qualitatively distinct regimes separated by a threshold in private absorptive capacity, below which the standard conversion mechanisms between knowledge inputs and innovation outputs break down simultaneously. Where private capacity to absorb and commercialise knowledge falls short of this threshold, the symptoms compound rather than offset one another: public research generates knowledge that has nowhere to go; doctoral graduates emigrate to systems capable of deploying their skills; and internationally mobile researchers use peripheral academic environments as waypoints rather than destinations. The conventional policy reflex - to raise public research investment in the expectation that outputs will follow - therefore misdiagnoses the constraint, treating a structural discontinuity as a matter of degree. Drawing on a decade of European Innovation Scoreboard data, the paper identifies the private R&D threshold that separates these regimes and documents the sign reversal in the innovation returns to researcher mobility across them. The central policy implication follows directly: capacity building must precede - not merely accompany - investment in public knowledge production, since absent a private sector able to absorb it, additional public research deepens the very leakage it is intended to remedy.

Keywords: Absorptive Capacity; Innovation Divergence; Panel Threshold Regression; Brain Drain; Public R&D; European Innovation Scoreboard; Two-Regime Model.

Introduction

Between 2014 and 2024, the EU's innovation Leaders - Denmark, Finland, Sweden, and the Netherlands - consistently outperformed the group of Emerging innovators comprising Bulgaria, Croatia, Latvia, Romania, and Slovakia by a factor of approximately five on the Summary Innovation Index. The gap is not narrowing. What makes this persistence theoretically puzzling is not its magnitude but its asymmetry: public R&D expenditure across these same member states differs by a factor of less than three. The lagging economies are spending nearly as much on public research as the leaders. They are producing far less innovation.

The standard explanation appeals to institutional heterogeneity - weaker governance, shallower financial markets, lower educational attainment — and these factors are real and their effects well-documented. But institutional quality describes a level difference in efficiency, not a mechanism. It does not explain why, within a given country and holding institutions constant, increases in public R&D is not associated with measurable improvements in innovation performance. If the problem were simply efficiency, marginal increases in public investment should still produce positive marginal returns, however modest.

The evidence assembled in this paper suggests something more fundamental is at work: in a substantial subset of EU member states, the conversion mechanism from public knowledge to commercial innovation is not merely inefficient. It is structurally absent.

This paper argues that the EU innovation space contains two qualitatively distinct regimes, separated by a threshold in private absorptive capacity. Above a critical level of business R&D intensity, public knowledge investment and private conversion capacity are complementary: public research expands the knowledge frontier that private firms can exploit, doctoral graduates find productive employment in knowledge-intensive sectors, and internationally mobile researchers are attracted to and retained by systems capable of deploying their skills. Below that threshold, these mechanisms are simultaneously undetectable in the data. Doctoral graduates, lacking a private sector capable of absorbing them at the level their training demands, emigrate to higher-capacity systems. Foreign doctoral students use peripheral academic environments as temporary waypoints rather than permanent destinations. The same inputs that drive innovation in high-capacity systems become, in low-capacity systems, either ineffective or actively harmful.

The core of this argument is not new in its components. Cohen and Levinthal's (1990) absorptive capacity framework

establishes that R&D investment serves a dual function: generating knowledge and building the organisational capacity to recognise and exploit knowledge generated elsewhere. Zahra and George (2002) extend this to a distinction between potential and realised absorptive capacity that captures precisely the EU paradox - countries may possess a well-developed university system while lacking the private-sector infrastructure to convert academic knowledge into commercial application. Docquier and Rapoport (2012) identify the conditions under which skilled emigration shifts from drain to gain, conditions that are systematically violated in economies operating below the absorptive capacity floor. What is new is the integration of these arguments into a single framework with a specific, empirically testable structural prediction: the returns to public R&D, doctoral human capital, and international researcher mobility are not fixed parameters but state-dependent functions of the private absorptive capacity of the host system - and their sign can reverse across the threshold.

We test this framework using a panel of all 27 EU member states over 2014–2024, combining European Innovation Scoreboard data with Eurostat R&D statistics. The empirical strategy proceeds in three stages: a two-way fixed effects baseline that establishes the aggregate patterns, a sample-split analysis that tests whether coefficients differ systematically between high- and low-capacity systems, and a panel threshold regression following Hansen (1999) that estimates the numerical value of the private absorptive capacity floor endogenously from the data. The threshold analysis is the methodological core of the paper: it allows us to identify not only that the two regimes exist but at what level of business R&D intensity the structural break between them occurs.

Three findings emerge from this analysis that would be difficult to reconcile outside the two-regime structure: Public R&D expenditure has no statistically significant direct effect on innovation performance in pooled estimation - but this null is not evidence of uniform ineffectiveness; it is the expected artefact of averaging across two structurally different regimes. Doctoral human capital has a large and significant effect below the threshold, where it functions as the innovation system's residual mechanism in the absence of private conversion capacity, and a much smaller effect above it, where private R&D displaces it as the dominant driver. Most strikingly, the coefficient on international doctoral mobility reverses sign across regimes: positive among Leaders and Strong innovators - consistent with talent attraction - and negative among Moderate and Emerging innovators - consistent with transit dynamics in which peripheral systems cannot retain the researchers they temporarily host. This sign reversal is the distinctive empirical signature of the two-regime framework and cannot be generated by any single-mechanism theory of human capital and innovation.

The paper contributes to three intersecting literatures. To the literature on European innovation divergence, it provides the first estimate of the private absorptive capacity threshold that structurally separates the EU innovation space and documents its policy implications for cohesion investment. To the absorptive capacity literature, it extends the Cohen and Levinthal framework from the firm to the national level and operationalises the lockout condition in a

setting where the policy relevance is immediate. To the brain drain literature, it shows that the same mobility indicator can proxy for diametrically opposite processes - talent attraction or transit drain - depending on the innovation regime, with direct implications for how international researcher mobility is interpreted in peripheral economies.

Three research questions follow from this framework. RQ1: Is the contribution of doctoral human capital to innovation performance conditioned by the level of private absorptive capacity - specifically, does the marginal effect of new doctorate graduates on the Summary Innovation Index differ significantly between high- and low-capacity regimes, and at what level of business R&D intensity does the structural break between them occur? RQ2: Does public R&D expenditure have a statistically significant direct effect on innovation performance across the EU as a whole, or does the pooled null result reflect structural heterogeneity between two regimes that operate through different mechanisms? RQ3: Is the relationship between international doctoral mobility and innovation performance positive in high-capacity economies and negative in low-capacity economies - consistent with talent-attraction dynamics above the absorptive capacity threshold and transit-flow dynamics below it?

These questions map directly to hypotheses H1–H3 developed in Section 2.7, which formalise the regime-dependent predictions of the two-regime framework. The empirical answer to all three is affirmative, as the evidence in Section 4 shows.

The paper is structured as follows. Section 2 develops the theoretical framework. Section 3 describes data and econometric strategy. Section 4 presents descriptive statistics, empirical results and limitations. Section 5 discusses implications for European innovation policy. Section 6 concludes.

Theoretical Framework and Hypotheses

The Puzzle: Same Inputs, Different Outcomes

The standard diagnoses are familiar. Institutional quality differs across member states. Educational systems vary in depth and orientation. Historical trajectories create path dependencies that cannot be reversed through short-term investment cycles. These explanations are not incorrect, but they share a common limitation: they describe the gap without explaining the mechanism through which the same policy instrument - public R&D expenditure - generates systematically different returns depending on where it is deployed. A country that invests 0.8 % of GDP in public research and produces minimal innovation output is not simply a country with bad institutions. It is a country where the conversion mechanism from public knowledge to commercial innovation has broken down.

This structural divergence is confirmed by comparative typologies of European innovation efficiency. Kontolaimou, Giotopoulos and Tsakanikas (2016), using a metafrontier framework that explicitly avoids the assumption that all countries deploy the same innovation technology, find that developing and transition countries in Europe exhibit on average twice the technology gap of developed economies. Crucially, they identify absorptive capacity and knowledge spillover effects as the key

variables explaining group membership - not input levels per se, but the capacity to convert inputs into outputs. The EU innovation space is not a continuum of greater or lesser efficiency. It contains structurally distinct groups separated by qualitative differences in conversion capacity.

Understanding why that conversion fails in some systems and succeeds in others requires a different analytical framework from the one that has dominated the literature on European innovation policy. This paper argues that the key variable is not the level of public R&D investment but the level of private absorptive capacity - the capacity of the private sector to identify, internalise, and deploy publicly generated knowledge. Below a critical threshold of private R&D intensity, the conversion mechanism is not detectable in the data: public investment generates knowledge that has nowhere to go. Above that threshold, public and private knowledge systems are complementary. Understanding why that mechanism differs is the question this framework sets out to answer.

The Dual Face of R&D, the Lockout Condition, and the Potential-Realised Distinction

The foundational insight is Cohen and Levinthal's (1990) demonstration that research and development investment serves two functions simultaneously. The first is the one normally modelled: R&D generates new knowledge that can be commercialised. The second, which Cohen and Levinthal identify as equally important but systematically neglected, is that R&D builds the organisational capacity to recognise, assimilate, and exploit knowledge generated elsewhere. In their formulation, "prior related knowledge confers an ability to recognize the value of new information, assimilate it, and apply it to commercial ends" - and that prior knowledge is itself the product of accumulated R&D investment. A firm that does not invest in R&D cannot passively absorb competitors' discoveries: it lacks the cognitive infrastructure to evaluate their relevance.

The threshold implications of this argument are severe. Cohen and Levinthal (1994) establish that as learning becomes more difficult, more prior knowledge must have been accumulated via R&D for effective learning to occur. In fast-moving fields, the failure to maintain sufficient private R&D investment does not merely reduce absorptive capacity - it eliminates it: the firm may never assimilate and exploit new information in that field, regardless of the value of that information. They call this condition lockout, and identify two reinforcing mechanisms that make it self-perpetuating. Without early investment, a firm's beliefs about technological opportunities do not update because it misses the signals that would revise expectations. And because prior knowledge facilitates subsequent learning, the absence of early investment makes later investment progressively more costly - and therefore progressively less likely.

Zahra and George (2002) extend the Cohen and Levinthal framework by introducing an analytically important distinction between potential absorptive capacity - the ability to acquire and assimilate external knowledge - and realised absorptive capacity - the ability to transform and exploit it commercially. At the national level, this distinction captures an asymmetry that is immediately

relevant to the EU context: a country with a well-developed university system and significant public research output may possess substantial potential absorptive capacity while simultaneously exhibiting low realised absorptive capacity if the private sector lacks the organisational and financial infrastructure to transform academic knowledge into commercial applications. The knowledge exists in the system but cannot be exploited. This is not a problem of information - it is a structural problem of conversion capacity, and it is the mechanism underlying the innovation paradox documented for peripheral European regions.

Griffith, Redding and Van Reenen (2004) carry this argument to the level of country-industries in a twelve-country OECD panel. Their central contribution is to demonstrate empirically that country-industries lagging behind the productivity frontier catch up particularly fast if they invest heavily in R&D - that R&D has a higher rate of return in non-frontier economies precisely because they have more to gain from technology transfer. But this higher potential return is conditional: it materialises only when R&D investment is sufficient to activate the absorptive capacity that enables catch-up. In economies below the threshold, the potential return exists but cannot be realised.

Taken together, Cohen and Levinthal, Zahra and George, and Griffith et al. establish a paradox directly relevant to the EU context: the economies that most need to absorb externally generated knowledge - those furthest from the frontier - are precisely the economies for which the investment required to activate absorptive capacity is most likely to be below the critical threshold.

From Firm to Nation: the Social Filter as Aggregate Absorptive Capacity

The translation from Cohen and Levinthal's firm-level argument to the national level requires an intermediate concept that captures the aggregate conditions under which knowledge conversion occurs. Rodríguez-Pose and Crescenzi (2008) and Crescenzi & Rodríguez-Pose (2011) provide this through their construct of the social filter - the unique combination of innovative and conservative elements that favour or deter the development of successful regional innovation systems. In their empirical operationalisation, the social filter aggregates educational attainment, productive employment of human resources, and demographic structure into a composite index capturing the external conditions in which externalised learning and innovation occur.

Their central empirical finding is more provocative than it may first appear: local socio-economic conditions are a better predictor of economic growth than investment in R&D, and the social filter is always positively associated with economic growth and statistically significant, while R&D investment is not always robust when controlling for social conditions. This is not an argument against R&D - it is a restatement of the absorptive capacity argument in regional terms. R&D investment generates returns only when embedded in a social environment capable of converting knowledge into productive activity. Where that environment is absent, investment in R&D may not yield the expected returns. Recent evidence confirms this conditionality at the regional level: Iammarino et al. (2019)

and Ma et al.(2026) document that the regional innovation paradox - whereby peripheral regions fail to convert R&D spending into innovation output despite significant public investment - is explained precisely by deficits in absorptive capacity rather than by input levels, a finding that directly operationalises at the sub-national scale the mechanism Rodríguez-Pose and Crescenzi identify at the regional level.

Migueluez and Moreno (2015) add direct evidence on the conditionality of knowledge flows through human mobility. In a panel of 274 European regions, they find that inflows of inventors are critical for wealthier regions, while effects in less developed regions are more nuanced - precisely because absorptive capacity determines whether regions can effectively benefit from incoming technology flows through networks and labour mobility. The mechanism is not simply that less developed regions receive fewer knowledge inflows. It is that even when those inflows occur, the absence of sufficient prior knowledge stock limits the conversion of inbound knowledge into innovation output. This finding directly operationalises at the regional level the lockout condition Cohen and Levinthal identify at the firm level.

The Complementarity Condition: Non-Linearities in the Public-Private R&D Relationship

If absorptive capacity is regime-dependent rather than uniformly present, the relationship between public R&D investment and innovation output should be non-linear: positive and significant above a threshold of private capacity, and close to zero or absent below it. The literature on public-private R&D interaction converges on exactly this structural implication, though largely without framing it in absorptive capacity terms.

The foundational cross-country evidence on public-private R&D interaction, established by Guellec and Van Pottelsberghe de la Potterie (2003) across 17 OECD economies, confirmed a positive average effect of public R&D expenditure on business R&D investment - a result that subsequent work has qualified rather than overturned. Becker (2015), in a systematic review of four decades of evidence, identifies non-linearity as one of the most important unresolved methodological issues in the field. The post-2000 literature has largely resolved the crowding-out versus complementarity debate in favour of complementarity, but with crucial qualifications. The positive effects are not unconditional: they depend on existing levels of private R&D engagement, and Becker's review identifies an inverted-U type relationship between subsidy intensity and additionality, with positive effects at lower rates and negative effects when subsidies exceed approximately 20% of total R&D expenditure. This non-linearity at the firm level has a direct parallel at the country level. Marino et al. (2016), extending this evidence to a large-scale multi-country evaluation, confirm net additionality at the aggregate level while documenting substantial heterogeneity across subsidy schemes and firm size categories - heterogeneity that the two-regime framework developed here attributes to variation in private absorptive capacity rather than to instrument design alone.

The mechanisms through which complementarity operates vary by regime. Lee (2011), in a multi-country, multi-industry analysis, identifies four channels through

which public R&D support affects private investment: a technological-competence-enhancing effect, a demand-creating effect, an R&D-cost-reducing effect, and a project-overlap effect. His empirical finding is that complementarity dominates for firms with low technological competence, while crowding-out appears for firms with high technological competence. Applied to the national level, this asymmetry predicts exactly the pattern we observe in the EIS data: public R&D should have stronger additionality in low-capacity systems - where it represents a rare source of frontier knowledge - but this additionality cannot translate into innovation output because the private absorptive infrastructure to exploit it is precisely what is absent. The instrument is not ineffective; the system that would use it is.

At the country level, Soete, Verspagen and Ziesemer (2022) provide macro-level evidence from 17 OECD countries for 1975–2014. Their key structural finding concerns what distinguishes high-complementarity from low-complementarity countries: countries where public and private R&D are strongly complementary tend to have a low share of foreign funding in business R&D combined with high business R&D intensity, and a higher share of basic R&D in the business sector combined with higher public R&D intensity. The implication is that complementarity is itself a structural condition - it requires a private sector already engaged in basic research and self-funded at scale, not merely present. Countries that depend heavily on foreign funding for business R&D, or that have low business R&D intensity, are structurally positioned in the low-complementarity regime regardless of their public R&D level.

Czarnitzki and Licht (2006) document precisely this asymmetry in eastern Germany during transition: public subsidies activated private R&D participation, but conversion into innovation output tracked the accumulated private capacity stock rather than the annual subsidy flow.

This asymmetry deepens in institutional environments where market failures compound absorptive capacity constraints. Bianchini, Llerena and Martino (2019), in a study of 13 European economies using CIS 2014 data, find that public R&D subsidies generate additionality even in regions with lower institutional quality - firms invest more than non-beneficiaries across all institutional environments, rejecting full crowding-out universally. The mechanism is constraint relief: public support leverages private resources when firms are constrained by lower quality public institutions, reducing uncertainty and favouring private risky investments. This finding is important for our framework because it means that the null effect of public R&D in low-capacity systems is not an institutional-quality artefact at the firm level. Firms respond to subsidies even in weak institutional environments. The bottleneck is not firm response but system conversion: the private R&D activated by subsidies cannot generate the aggregate threshold required for complementarity with public knowledge to operate.

Ziesemer's (2021) survey of the literature confirms these patterns at the broadest level: a majority of studies find complementarity, a minority finds incomplete crowding-out, and full crowding-out appears only for small parts of samples or sub-sectors. Heterogeneity is the primary empirical finding, and the heterogeneity is systematic: it relates to firm size, instrument interaction, and - most relevantly for our framework - the effectiveness of different

components of publicly performed R&D, which varies depending on whether the private sector has sufficient capacity to engage with the knowledge being produced.

The aggregate implication is unambiguous: pooled panel estimates that mix high- and low-capacity systems will systematically understate the effect of public R&D in the high-capacity regime and overstate it in the low-capacity regime. The null result for public R&D that emerges from many cross-national studies is not evidence that public R&D is ineffective. It is evidence that the literature has been averaging across two qualitatively different regimes without modelling the structural break between them.

Human Capital Under Capacity Constraints: When the Engine Becomes the Drain

The third pillar of the framework concerns the role of highly trained human capital in innovation systems operating below the absorptive capacity threshold. The standard view treats doctoral graduates and internationally mobile researchers as unambiguous inputs to the innovation system: they embody frontier knowledge, diffuse it through employment in productive sectors, and strengthen the international linkages through which external knowledge flows in. This view is empirically well-supported in high-capacity systems. It fails as a general claim because it ignores the conditions under which the same mechanism runs in reverse.

Docquier and Rapoport (2012), in their synthesis of four decades of brain drain research, identify the precise conditions under which skilled emigration shifts from a drain to a gain. The core mechanism is the incentive effect: migration prospects raise the expected return to education, inducing more people to invest in human capital formation before the emigration decision. If enough of the newly educated remain, the sending country ends up with more human capital than it would have had in the absence of emigration prospects. They formalise two necessary conditions for a beneficial brain drain: the skill-price differential must generate strong enough incentives without making liquidity constraints binding, and the emigration probability must remain sufficiently low - when p is close to one, a net brain gain can never obtain.

Mayr and Peri (2009) formalise the return mechanism that can rescue the sending economy even when gross outflows are large. In their model, the composition of returnees is decisive: a return premium that increases with education yields positive selection among returnees - only the most educated among emigrants return - which strengthens the human capital stock at home even after accounting for those who stay abroad permanently. Applied to Eastern Europe, they find that for plausible degrees of openness, the possibility of return migration combined with the education incentive channel can convert brain drain into brain gain. But this beneficial outcome is conditional on the return premium structure. When all returnees receive the same skill premium regardless of education, returnees will be negatively selected, and the net human-capital effect is negative. The conditions that produce brain gain are institutional - they require a labour market capable of offering education-selective returns, which is itself a function of the private absorptive capacity of the receiving economy.

The empirical magnitude of the challenge for EU Emerging economies is documented by Petersen and Puliga (2017), who track approximately 382,000 individuals across five high-skilled profession groups - medical, education, technical, science and engineering, and business and legal - over 1997–2014. They find a net directional loss of human capital from Eastern to Western EU enlargement countries of 29 % of total post-2004 mobility, against a counter-flow from West to East of only 7 %. This asymmetry is not random: it reflects the structural features of labour markets on both sides of the divide. High-capacity systems in western Europe attract talent because they offer superior research infrastructure, knowledge-intensive employment, and education-selective return premiums. Low-capacity systems in eastern Europe lose talent for exactly the opposite reasons.

Both conditions necessary for brain gain - mild emigration probability and education-selective returns - are systematically violated in the EU's low-capacity innovation systems. Countries operating below the absorptive capacity threshold combine high skilled emigration rates with labour markets that cannot offer the education-selective returns required to generate positive selection among returnees. Khan (2022) situates this structural failure in a broader comparative perspective: in national innovation systems where private absorptive capacity is insufficient, the standard R&D-based policy framework systematically misdiagnoses the problem - treating a structural conversion deficit as an input shortage - with the result that investment in human capital formation accelerates exit rather than retention. Ienciu and Ienciu (2015), using data from the World Economic Forum Global Competitiveness Report for Central and Eastern European economies, situate brain drain in a broader structural context where weak innovation systems, constrained labour markets, and limited public policy effectiveness combine to sustain outflows regardless of formal educational investment.

Applied to the EIS indicator of foreign doctorate students, this framework generates a specific and counterintuitive prediction. In high-capacity systems - Leaders and Strong innovators - an increase in the share of foreign doctoral students reflects genuine talent attraction: internationally mobile researchers choose these environments because they offer superior research infrastructure, career prospects, and private-sector absorption capacity. The knowledge these researchers bring flows into the system and is retained. In low-capacity systems, the same indicator captures a structurally different phenomenon. These systems function as transit nodes for doctoral candidates with high emigration probability p . The temporary presence of foreign doctoral students does not translate into knowledge retention because the productive system cannot absorb them upon graduation. The share of foreign doctoral students becomes, counterintuitively, a signal of outward knowledge flows rather than inward ones. This sign reversal - the same indicator operating through opposite mechanisms depending on the regime - is a distinctive prediction of the two-regime framework that cannot be derived from any single-mechanism theory.

Two Regimes, One Threshold: the Integrated Argument

The five strands reviewed above converge on a consistent implication that none has formally modelled in integrated form. The returns to public R&D, doctoral human capital, and international researcher mobility are not fixed parameters but state-dependent functions of the private absorptive capacity of the host system - a point implicit in Rodríguez-Pose and Crescenzi's finding that social filter conditions routinely outperform R&D investment as predictors of regional growth, in Männaasoo et al.'s demonstration that the marginal return to human capital and R&D is near zero for below-frontier CEE regions, and in Miguelez and Moreno's evidence that inventor inflows are critical for wealthier regions but have nuanced effects in less developed ones. Three empirical questions follow from this convergence that the existing literature leaves unresolved. First, what is the numerical value of the private absorptive capacity threshold that separates positive from negative spillover regimes - a question Ubada and Perez-Hernandez (2017) identify but do not answer at the national level? Second, how do dynamic time lags and instrument interactions condition the heterogeneous effects that Ziesemer's (2021) survey identifies but cannot attribute to specific structural features? Third, which observable country characteristics most reliably predict regime membership? This paper addresses the first of these questions directly, using a panel threshold model to estimate τ for the European innovation space.

This convergence suggests a unifying framework. The EU innovation space is not a continuum of greater or lesser efficiency - it is a binary structure with two qualitatively distinct regimes separated by a threshold τ of private absorptive capacity, operationalised here as business R&D expenditure as a share of GDP.

In the high-capacity regime, above τ , the innovation system operates through the complementarity that the literature describes as its normal mode. Public R&D expands the knowledge frontier; private R&D develops the absorptive capacity that converts public knowledge into commercial applications, consistent with Griffith et al.'s second face. Realised absorptive capacity, in Zahra and George's terms, matches potential absorptive capacity: knowledge does not only exist in the system but is converted into productive output. The social filter, in Rodríguez-Pose and Crescenzi's terms, is sufficiently strong to translate knowledge inputs into growth. Human capital is deployed productively in knowledge-intensive sectors. International academic mobility reflects genuine talent attraction because the system has the absorption capacity to retain what it attracts. The structural conditions for complementarity identified by Soete et al. - low foreign dependence in business R&D, high own-funded R&D intensity - are met.

In the low-capacity regime, below τ , these mechanisms are simultaneously undetectable in the data and for the same reason: the absence of sufficient private absorptive capacity means that knowledge - whether publicly generated, privately produced, or embodied in human capital - cannot be converted into innovation output. Public R&D investment accumulates knowledge in the academic system without generating spillovers into production. Only the most productive regions gain from additional human capital and

R&D investment, consistent with Männaasoo et al.'s finding for emerging Europe. System integration, in Fagerberg and Srholec's framework, is structurally incomplete. Human capital, lacking a private sector capable of absorbing it productively, exits the system - through emigration of domestic graduates or transit-flow dynamics among foreign doctoral students - leaving the knowledge conversion machinery starved of the inputs it would need to operate even if it were otherwise functional. The conditions for a beneficial brain drain identified by Docquier and Rapoport and Mayr and Peri - moderate emigration probability and education-selective return premiums - are systematically absent.

This framework has a precise empirical implication that distinguishes it from simpler single-mechanism explanations: the same innovation input - an increase in the share of internationally mobile doctoral researchers - should produce opposite effects in the two regimes. In the high-capacity regime it should accelerate innovation through talent attraction and knowledge retention. In the low-capacity regime it should be associated with reduced innovation performance through the transit-flow mechanism. This sign reversal is the distinctive prediction of the two-regime framework and the empirical signature through which it can be identified. The two-regime structure is represented schematically in Figure 1.

The contribution of this paper is distinct from prior applications of threshold regression to innovation research. Ubada and Perez-Hernandez (2017) identify a threshold in absorptive capacity conditioning FDI spillovers at the firm level in Spain; Huang et al. (2019) apply the Hansen (1999) estimator to total factor productivity across Chinese country-industries. These studies do not, however, model the national-level private absorptive capacity floor, derive the sign-reversal prediction for international researcher mobility as a discriminating empirical signature, or address the policy implication that capacity building should precede public knowledge investment. At the regional level, Ma et al. (2026) document that the regional innovation paradox is explained by absorptive capacity deficits rather than input levels - a finding at the NUTS-2 scale that is consistent with the national-level mechanism identified here. Building on this body of work, the present paper estimates τ^* for the EU innovation space as a whole, brings together the absorptive capacity, public-private R&D complementarity, and brain drain literatures within a single framework with a jointly testable threshold prediction, and provides evidence that the same mobility indicator may operate through opposing mechanisms above and below that threshold.

Hypotheses

Figure 1 maps the four dimensions through which threshold τ conditions the innovation system - R&D conversion, the social filter, human capital dynamics, and aggregate output. In the low-capacity regime each dimension is in a state of structural failure; in the high-capacity regime the same dimensions operate through complementarity. The hypothesis boxes at the base of the figure locate the three empirically testable predictions of this structure: each would, if falsified, require revision of the framework rather than merely adjustment of a parameter.

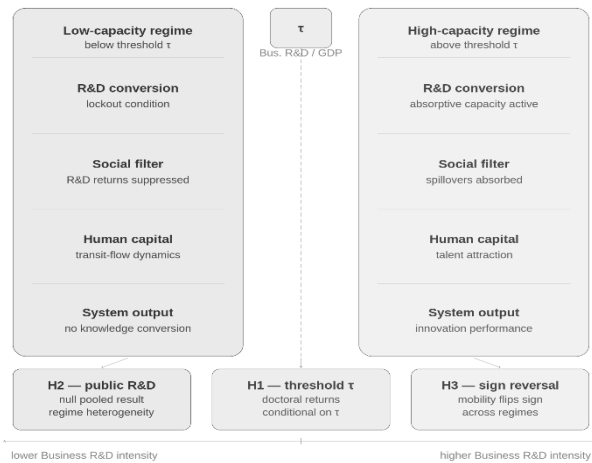


Figure 1. The two-regime innovation structure: mechanisms and hypotheses. Business R&D intensity (% GDP) determines regime membership relative to threshold τ . H1–H3 map to the theoretical predictions in Section 2.7.

H1 - Absorption threshold: The contribution of doctoral human capital to innovation performance is conditioned by the level of private absorptive capacity.

In economies where private R&D investment falls below a critical threshold, doctoral graduates constitute the primary innovation mechanism in the structural absence of a private conversion counterpart; in economies above that threshold, private R&D displaces doctoral human capital as the dominant driver of innovation, and the marginal effect of additional graduates diminishes substantially.

H2 - Regime-conditioned public R&D: Public R&D investment has no direct unconditional effect on innovation performance across the EU as a whole.

This absence does not reflect the uniform ineffectiveness of public research expenditure, but the structural heterogeneity of the systems in which it operates: the positive effect observable in high-capacity economies is offset in aggregate estimation by the absent effect in low-capacity economies, producing a null result that is an artefact of regime mixing rather than an indication of policy failure.

H3 - Asymmetric complementarity: The relationship between international doctoral mobility and innovation performance reverses sign across the absorptive capacity threshold.

In high-capacity economies, where the private sector can absorb and retain internationally mobile researchers, an increase in the share of foreign doctorate students is positively associated with innovation performance, consistent with a talent-attraction mechanism. In low-capacity economies, the same increase is negatively associated with innovation performance, consistent with a transit-flow mechanism in which the productive system cannot convert temporary academic presence into lasting knowledge accumulation.

Data and Methodology

Data Sources and Panel Construction

The empirical analysis draws on two complementary data sources. Innovation performance and the human capital indicators are taken from the European Innovation Scoreboard (EIS), published annually by the European Commission. The EIS provides a harmonised composite measure of national innovation performance — the Summary Innovation Index (SII) — alongside its constituent indicators for all EU member states, making it the natural choice for cross-national comparisons of innovation dynamics within the EU institutional context. R&D expenditure data are sourced from Eurostat's Research and Development Statistics database, which provides nationally reported figures on public and business R&D investment as shares of GDP with complete coverage across the panel period.

The estimation sample covers all 27 EU member states over 2014–2024, yielding an unbalanced panel of 297 country-year observations (one observation is excluded from the estimation sample due to a missing value, leaving 296 observations in all regression models). The starting year is determined by the availability of consistent EIS indicator definitions: the 2013 revision of the Scoreboard introduced the performance group classification and several indicator methodological changes that would compromise comparability with earlier waves. The terminal year is 2024; the 2025 edition of the Scoreboard introduced a revised weighting framework that is not backward-compatible with the 2014–2024 series and is therefore excluded from the panel. All variables are expressed as annual observations at the country level.

Variables

Dependent variable. The Summary Innovation Index (SII) is a composite indicator ranging from 0 to 1 that aggregates performance across four main categories - framework conditions, investments, innovation activities, and impacts - weighted equally across 32 individual indicators. Despite the limitations inherent in any composite, the SII is preferable to patent-based or output-only measures for this analysis because it captures the full innovation system rather than a single downstream output, and because it is the basis for the official EIS performance group classification used in the sample-split analysis. Year-to-year variation in the SII within countries reflects genuine changes in innovation system performance rather than measurement artefacts, as confirmed by the high within-country autocorrelation in the series.

Human capital variables. Three indicators capture different dimensions of the human capital stock. New doctorate graduates (*new_doc*) measures the number of new doctoral graduates per thousand population aged 25–34, capturing the flow of research-trained workers produced by the national academic system in each year. Tertiary education attainment (*tert_edu*) measures the share of the population aged 25–34 with a completed tertiary qualification, capturing the broader stock of educated workers

available to the labour market. Foreign doctorate students (foreign_doc) measures the share of all doctorate students enrolled in a country's universities who are nationals of another country, capturing the international composition of the academic pipeline and, as the framework developed in Section 2 argues, the dynamics of talent attraction versus transit-flow depending on the innovation regime.

R&D expenditure variables. Public R&D expenditure (rd_pub) and business R&D expenditure (rd_biz) are both expressed as shares of GDP. The distinction between public and private research investment is central to the theoretical argument: public R&D captures the knowledge frontier generated within the academic and governmental research system, while business R&D captures the private absorptive capacity through which that frontier knowledge can be converted into commercially relevant output. Both series are drawn from Eurostat to ensure consistency with national accounts definitions and cross-country comparability. Where EIS-reported values diverge marginally from

Eurostat due to rounding or revision cycles, the Eurostat figure is used as the primary source.

Performance group classification. The EIS classifies member states annually into four performance groups - Leaders, Strong innovators, Moderate innovators, and Emerging innovators - based on SII quintile boundaries relative to the EU average. This classification is used as the basis for the sample-split analysis in Section 4.3, with Leaders and Strong innovators pooled as High innovators (n=131 country-year observations) and Moderate and Emerging innovators pooled as Low innovators (n=166). Group membership is time-varying: a country's group assignment in each year reflects its relative performance in that year's Scoreboard. The threshold variable in the Hansen (1999) model is rd_biz rather than the group classification, allowing the data to determine the private capacity threshold endogenously rather than imposing the EIS categories as structural breaks.

Table 1

Descriptive Statistics by EIS Performance Group (2014–2024)

	N	SII	R&D Business (% GDP)	R&D Public (% GDP)	Foreign PhD (%)	Tertiary Edu (%)	New PhDs (norm.)
Leaders	44	0.678 (0.041)	1.930 (0.373)	0.932 (0.139)	32.0 (9.17)	46.1 (4.48)	1.084 (0.268)
Strong	88	0.575 (0.075)	1.310 (0.732)	0.658 (0.252)	33.4 (23.0)	47.4 (8.92)	0.836 (0.283)
Moderate	99	0.423 (0.058)	0.830 (0.373)	0.539 (0.158)	15.4 (12.0)	39.2 (8.65)	0.662 (0.417)
Emerging	66	0.274 (0.064)	0.469 (0.214)	0.399 (0.149)	6.77 (3.40)	35.6 (6.64)	0.433 (0.207)
Full panel	297	0.473 (0.151)	1.060 (0.679)	0.601 (0.250)	21.3 (18.4)	41.8 (9.14)	0.725 (0.380)

Notes: Mean values; standard deviations in parentheses. SII = Summary Innovation Index (0–1 scale). R&D variables sourced from Eurostat. Foreign PhD students = share of non-national doctoral students enrolled. New PhDs normalised per 1,000 population aged 25–34. Group classification based on EIS 2024 performance groups.

Table 1 reports descriptive statistics by performance group. Business R&D intensity declines monotonically from 1.93 % of GDP among Leaders to 0.47% among Emerging innovators - a fourfold gradient that contrasts with the less than threefold gradient in public R&D (0.93 % to 0.40 %), confirming that the gap between innovation leaders and laggards is substantially wider in private than in public research effort. The one non-monotonicity in the descriptives - the share of foreign doctorate students is higher among Strong innovators (33.4 %) than among Leaders (32.0 %) - foreshadows the heterogeneous effects documented in the regression analysis.

A methodological note is warranted on the relationship between the dependent variable and the regressors. The SII is a composite indicator that aggregates 32 individual EIS indicators; business R&D expenditure (rd_biz) enters the SII under the Investments category, and new doctorate graduates (new_doc) enters under the Human Resources category. This overlap implies that the regressors and the dependent variable share part of their underlying variation. Within-country correlations between the demeaned regressors and the demeaned SII are: rd_biz $r=+0.271$, new_doc $r=+0.162$, rd_pub $r=+0.107$, tert_edu $r=-0.124$, and foreign_doc $r=+0.035$. The two-way fixed effects estimator controls for the time-invariant component of this

overlap by absorbing country-level averages, but does not eliminate within-year simultaneity. Two considerations moderate this concern. First, the EIS weights rd_biz and new_doc as two of 32 indicators, so their contribution to SII variation is partial. Second, the lagged specifications reported in Appendix Table A1 show that new_doc remains positive and significant when lagged one and two years, while rd_biz is not significant at $t-1$ or $t-2$, providing some evidence that the direction of the findings does not depend on contemporaneous overlap.

Econometric Strategy

The analysis proceeds in three stages, each designed to test a distinct implication of the two-regime framework.

Stage 1: Baseline two-way fixed effects. The baseline specification is a two-way fixed effects model with country and year fixed effects:

$$SII_{it} = \alpha_i + \lambda_t + \beta_1 rd_biz_{it} + \beta_2 rd_pub_{it} + \beta_3 new_doc_{it} + \beta_4 tert_edu_{it} + \beta_5 foreign_doc_{it} + \varepsilon_{it} \quad (1)$$

where α_i captures time-invariant country heterogeneity — institutional quality, historical innovation trajectories, structural features of the national economy — and λ_t captures common shocks affecting all member states in a given year, including EU-wide policy cycles,

macroeconomic conditions, and global technology trends. Standard errors are clustered at the country level to account for serial correlation within countries over time.

The choice of fixed over random effects is motivated by theoretical rather than purely statistical considerations. The Hausman test does not reject the random effects specification ($\chi^2=3.12$, $p=0.999$), suggesting that the orthogonality condition is not statistically violated. However, the country fixed effects absorb time-invariant differences in institutional quality, geographic position, and historical path dependencies that are correlated with both the regressors and the dependent variable, and their inclusion is theoretically warranted under any interpretation of the absorptive capacity framework. The $p=0.999$ outcome reflects the limited within-country variation over a short panel rather than a genuine absence of correlation between country-level heterogeneity and the regressors; retaining fixed effects is therefore the conservative and theoretically consistent choice.

Stage 2: Sample-split analysis and parameter stability. The two-regime hypothesis predicts that slope coefficients differ systematically between high- and low-capacity innovation systems. Before estimating separate models, parameter stability is assessed using a Chow test that evaluates whether the coefficient vectors across the High and Low innovator subsamples are drawn from the same population. Rejection of the null of parameter equality justifies separate estimation and provides the first formal test of H2 and H3. The High and Low subsamples are estimated using the same two-way fixed effects specification as the baseline, with standard errors clustered by country within each group.

Stage 3: Panel threshold regression. The threshold analysis follows Hansen (1999), who develops a non-parametric method for estimating structural breaks in panel data models. The threshold variable is business R&D intensity (rd_biz), which the theoretical framework identifies as the operationalisation of private absorptive capacity. Panel threshold models have been applied to identify non-linear regime effects in related contexts, including the conditioning of TFP by absorptive capacity at the firm level (Huang et al., 2019). The model takes the form:

$$SII_{it} = \alpha_i + \lambda_t + \beta_1 new_doc_{it} \cdot I(rd_biz_{it} \leq \tau) + \beta_2 new_doc_{it} \cdot I(rd_biz_{it} > \tau) + \gamma X_{it} + \varepsilon_{it} \quad (2)$$

where τ is the threshold parameter to be estimated, $I(\cdot)$ is an indicator function, and X_{it} contains the remaining regressors (rd_pub , $tert_edu$, $foreign_doc$). The threshold is identified by grid search over the empirical distribution of rd_biz , minimising the concentrated sum of squared residuals. The significance of the threshold - that is, the null of a linear model against the threshold alternative - is evaluated using a bootstrap F-test, as standard asymptotic distributions do not apply when the threshold parameter is unidentified under the null. Confidence intervals for τ are constructed by inverting the likelihood ratio statistic.

The focus of the threshold analysis is the effect of new doctorate graduates on innovation performance, which the theoretical framework predicts will be large and significant below τ - where doctoral human capital is the residual innovation mechanism in the absence of private absorptive capacity - and substantially smaller above τ , where private R&D takes over as the dominant conversion engine. The

threshold τ^* is of direct policy interest: it identifies the floor of private R&D investment below which the standard complementarity mechanism between public knowledge production and private knowledge conversion is structurally absent.

All estimation is carried out in R. Fixed effects models use the `plm` package with within-country demeaning. The Hansen threshold model uses the `threshold` package, which implements the grid search and bootstrap inference procedure described above. Figures are produced using `ggplot2`.

Throughout, results are interpreted as conditional correlations with a theoretically coherent structure rather than causal effects in the strict econometric sense. The identification strategy controls for time-invariant country heterogeneity and common time shocks, but does not exploit exogenous variation in the regressors. The theoretical framework provides the basis for interpreting the direction and magnitude of the estimated associations, not a claim of policy-equivalent treatment effects.

Throughout, results are interpreted as conditional correlations with a theoretically coherent structure rather than causal effects in the strict econometric sense. Two potential sources of endogeneity warrant explicit discussion. First, simultaneity between SII and rd_biz within years: higher innovation performance may attract business R&D investment in the same year, biasing the coefficient on rd_biz upward. The direction of this bias would, however, work against finding the null result for public R&D - an upward bias on rd_biz would tend to crowd out the public R&D coefficient toward zero, consistent with what is observed. Second, reverse causality in the threshold variable: low SII might depress business R&D investment, causing rd_biz to fall below τ^* rather than the other way around. Against this interpretation, the below- τ^* regime is characterised by structurally low and persistent business R&D investment - eight member states spend below 0.44% of GDP in business R&D across substantial portions of the 2014–2024 period - a pattern more consistent with structural capacity constraints than with short-run SII feedback. The lagged specifications in Table A1 provide further evidence on this point: rd_biz at $t-1$ does not predict SII at t ($\beta=0.005$, $SE=0.007$), suggesting that the contemporaneous association reflects the role of the accumulated private R&D stock rather than a short-run flow susceptible to reverse causality at annual frequency.

Results

Descriptive Patterns: the Innovation Gradient and its Anomalies

Before turning to regression evidence, the data reveal a structural gradient that frames the analysis. Table 1 shows that Summary Innovation Index (SII) scores decline monotonically across performance groups — from 0.678 among Leaders to 0.274 among Emerging innovators — and this gradient is mirrored almost perfectly by business R&D intensity (1.93 vs. 0.47% of GDP). Public R&D follows a similar but considerably flatter gradient (0.93 vs. 0.40%), suggesting that the gap between innovation leaders and laggards is substantially wider in private than in public research effort.

One pattern breaks this orderly picture. Foreign doctorate students - a proxy for international research talent attraction - is higher among Strong innovators (33.4 %) than among Leaders (32.0 %), reversing the expected hierarchy. This non-monotonicity is not noise: it reflects a structural difference in how countries at different innovation levels use academic mobility. Leaders have consolidated domestic research capacity and depend less on inflows of foreign talent; Strong innovators actively recruit international doctoral students as a catch-up mechanism. This distinction will prove consequential when interpreting the regression results.

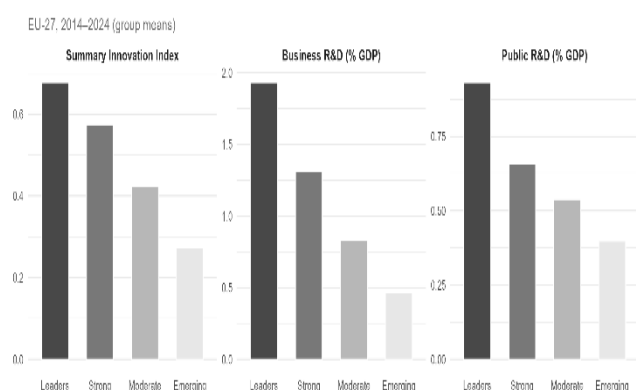


Figure 2. Innovation and R&D Intensity by EIS Performance Group. EU-27, 2014–2024 (group means). *Source: European Innovation Scoreboard (2021–2024); Eurostat rd_e_gerdact*

Baseline Estimates: the Asymmetric Role of Public R&D

Table 2 (column M1) presents the baseline two-way fixed effects estimates for the full EU-27 panel over 2014–2024. Two results stand out. First, business R&D intensity enters significantly and positively ($\beta=0.053$, $p<0.05$), consistent with the absorptive capacity hypothesis. Second - and central to the paper's argument - public R&D expenditure is statistically indistinguishable from zero ($\beta=0.026$, $p=0.397$) after controlling for country and year fixed effects.

This null result for public R&D is not a failure of measurement. Both variables are sourced from Eurostat with complete coverage across the panel, and the confidence interval for public R&D is narrow enough to rule out economically meaningful effects. The result is instead a structural finding: within-country increases in public R&D expenditure, holding private investment and human capital constant, do not translate into measurable improvements in innovation performance. Cohen and Levinthal's (1990) absorptive capacity argument provides the mechanism - public knowledge outputs require private organisational capacity to be converted into commercially viable innovation. Without that capacity, public R&D spending circulates within the academic system without productive spillovers.

Among human capital variables, new doctorate graduates enter significantly ($\beta=0.020$, $p<0.05$), while tertiary education attainment and foreign doctorate students show no significant within-country effect at the aggregate level. This aggregate picture, however, conceals heterogeneity that the next section exposes.

Table 2

Two-Way Fixed Effects Estimates of Innovation Performance (2014–2024)

	(1) Full panel	(2) High innovators	(3) Low innovators
	SII	SII	SII
Public R&D	0.0264 (0.0311)	0.0579 (0.0638)	0.0186 (0.0421)
Business R&D	0.0530* (0.0218)	0.0565* (0.0246)	0.0402 (0.0265)
New doctorates	0.0204* (0.0100)	0.0296 (0.0316)	0.0175* (0.0074)
Tertiary education	−0.0017 (0.0013)	−0.0060** (0.0019)	0.0007 (0.0013)
Foreign PhD students	0.0003 (0.0004)	0.0015* (0.0006)	−0.0005* (0.0002)
R^2 within	0.128	0.313	0.156
Observations	296	131	165
Countries	27	12	15
FE	Country + Year	Country + Year	Country + Year

Notes: Dependent variable: Summary Innovation Index (SII). All models include country and year fixed effects. Standard errors clustered at country level in parentheses. High innovators = Leaders + Strong innovators ($n = 12$ countries); Low innovators = Moderate + Emerging innovators ($n = 15$ countries). Chow test for parameter equality: $F = 10.98$, $p \approx 0$. Hausman test: $p = 0.999$. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Asymmetric Complementarity: where public R&D Fails and Where Human Capital Turns Against Itself

The Chow test rejects parameter stability across innovation groups at conventional significance levels ($F=10.98$, $p \approx 0$), justifying separate estimation for High innovators (Leaders and Strong, $n=131$) and Low innovators (Moderate and Emerging, $n=165$). The divergence between

the two subsamples is striking - and in some respects, counterintuitive.

Among High innovators, the results conform broadly to theory. Business R&D remains significant ($\beta=0.056$, $p<0.05$), confirming that within this group, private investment drives innovation performance at the margin. Foreign doctorate students enter positively and significantly ($\beta=0.0015$, $p<0.05$) - consistent with the descriptive finding

that Strong innovators leverage international academic mobility as a growth mechanism. The negative coefficient on tertiary education ($\beta=-0.006$, $p<0.01$) is not anomalous: it reflects a composition effect whereby, within high-performing countries, mass expansion of tertiary credentials without a corresponding increase in research-oriented human capital may dilute average productivity. Public R&D remains insignificant, even within this group where complementary private capacity is abundant.

The results for Low innovators tell a more sobering story. Business R&D loses significance entirely ($\beta=0.040$, $p=0.132$) - a direct implication of insufficient private absorptive capacity. New doctorate graduates remain the only consistently significant human capital channel ($\beta=0.018$, $p<0.05$). But the most striking result is the sign reversal on foreign doctorate students: the coefficient turns negative and significant ($\beta=-0.0005$, $p<0.05$). Within Moderate and Emerging economies, an increase in the share of foreign doctoral students is associated with lower innovation performance - a pattern consistent with a pattern of outward mobility, where internationally mobile talent uses peripheral economies as temporary hosts before relocating to stronger innovation ecosystems. The estimated association is consistent with a reversal of the mechanism compared to High innovators: rather than attracting talent that enhances local capacity, the data are consistent with net outflows of their most internationally competitive researchers.

Taken together, these results confirm H3: the complementarity between public R&D and innovation output is not simply weak — is not detectable in low-capacity economies. And human capital, the standard prescription for catching up, can become a mechanism of divergence when the productive system lacks the capacity to absorb and retain it.

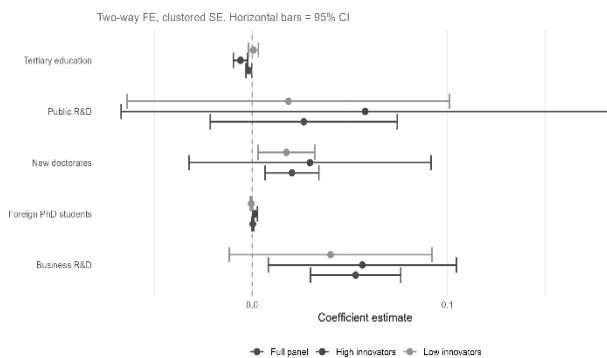


Figure 3. Estimated Coefficients by Innovation Group. Two-way FE, clustered SE. Horizontal bars = 95% CI. Own estimation. DV: Summary Innovation Index (EIS 2021–2024). Note: Chow test rejects parameter stability across groups ($F=10.98$, $p<0.001$)

Threshold Effects: the Absorption Capacity Floor

The threshold analysis provides a final piece of evidence that connects H1 and H3. Grid search over the

empirical distribution of business R&D intensity identifies an optimal threshold at $\tau^*\approx 0.43\text{--}0.44\%$ of GDP (20th percentile), with a pronounced RSS minimum that supports a genuine structural break (Figure 4, Panel A). The 95% confidence interval for τ^* , constructed by inverting the likelihood ratio statistic following Hansen (1999), is $[0.430, 0.449]\%$ GDP, indicating that the threshold is precisely estimated. The bootstrap F-test (500 residual-bootstrap replications under the null of a linear model) yields $F=19.69$ ($p<0.001$), strongly rejecting the null of no threshold. Below this threshold — a level so low that it characterises only 8 Member States across parts of the sample period — the effect of new doctorate graduates on SII is large and highly significant ($\beta=0.127$, $p<0.001$). Above it, the coefficient collapses to near zero ($\beta=0.013$, $p=0.058$), and the difference between regimes is strongly rejected ($F=19.64$, $p<0.001$).

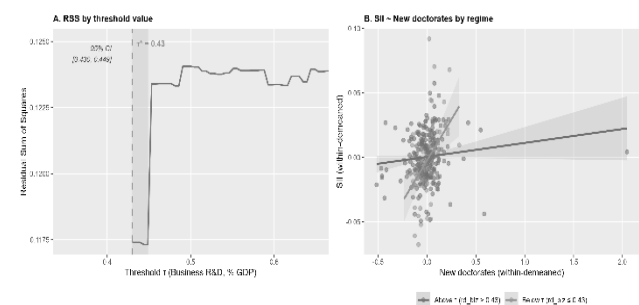


Figure 4. Threshold Effects in Private R&D Absorption Capacity. Panel A — RSS by threshold value; Panel B — SII ~ New doctorates by regime. Source: Own estimation. τ identified by grid search (Hansen 1999)

The interpretation requires care. The threshold does not suggest that human capital matters more in countries with weaker private R&D in any absolute sense. Rather, it reveals a substitution dynamic: when private R&D is essentially absent, new doctorates become the dominant innovation mechanism by default — the only structured knowledge-generation activity in the system. Once private absorptive capacity crosses the threshold, firms take over as the primary innovation engine, and the marginal contribution of additional doctoral graduates diminishes. The threshold is not a ceiling for human capital but a floor for private capacity, below which the economy's innovation system rests entirely on publicly trained researchers with no private counterpart to absorb their output.

One case merits brief note. Cyprus (CY) falls entirely below τ^* despite being classified as a Strong innovator — the only member of that group in this regime. This apparent anomaly reflects the multi-dimensional nature of the SII: Cyprus scores well on internationalisation and digital indicators but exhibits structural weakness in private R&D investment, illustrating that innovation group membership captures overall performance rather than sectoral balance. Cyprus represents, in concentrated form, the fragility that the threshold analysis identifies at the aggregate level.

Table 3

Panel Threshold Regression Results (Hansen, 1999)

	Threshold model
	SII
New doctorates $\times$ Below τ	0.1266*** (0.0226)
New doctorates $\times$ Above τ	0.0130 (0.0077)
Public R&D	0.0261 (0.0329)
Tertiary education	-0.0018** (0.0014)
Foreign PhD students	0.0001 (0.0004)
Threshold τ (Business R&D % GDP)	0.43
Observations below τ (%)	62 (20.9%)
Observations above τ (%)	234 (79.1%)
R ²	0.118
Observations	296
Threshold F-test (p-value)	19.64 (<0.001)

Notes: Dependent variable: Summary Innovation Index (SII). Threshold variable: Business R&D intensity (% GDP). Model includes country and year fixed effects. Threshold τ^* estimated by grid search minimising concentrated RSS over the empirical distribution of Business R&D. Significance of threshold assessed via bootstrap F-test (500 replications). Coefficient significance: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; . $p < 0.10$

Robustness Checks

Lagged specifications confirm the robustness of the main findings: new_doc remains positive and significant at $t-1$ ($\beta=0.021$, $p<0.01$) and $t-2$ ($\beta=0.022$, $p<0.01$), while rd_biz is not significant at $t-1$ ($\beta=0.005$, $SE=0.007$), consistent with the stock-accumulation argument in §5.1. The threshold estimate is stable across alternative control specifications: $\tau=0.444$ % GDP under the base model, 0.444 % GDP when foreign_doc is excluded from the control set, and 0.444 % GDP when foreign_doc enters as an additional regime variable. The below- τ regime is identified from 63 country-year observations concentrated in nine member states: Cyprus (11 years), Latvia (11), Malta (11), Romania (11), Lithuania (8), Croatia (4), Greece (3), Slovakia (3), and Poland (1). The robustness of the bootstrap F-statistic ($F=19.69$, $p<0.001$) and the narrow 95% confidence interval for τ^* [0.430, 0.449] % GDP confirm that the structural break is precisely estimated despite the relatively small below- τ sample.*

Discussion**Interpreting the Null Result for Public R&D**

The finding that public R&D expenditure has no statistically significant direct effect on innovation performance — in the full panel, in the High-innovator subsample, and in the Low-innovator subsample — is the result most likely to be misread as a failure of measurement or specification. It is not. The confidence intervals are narrow, the coverage is complete, and the controls are standard.

The null in the full panel is the expected product of regime mixing: H2 predicted precisely that the positive effect observable in high-capacity economies would be cancelled in aggregate estimation by the near-zero effect in

low-capacity economies. Confirming that prediction is not the analytically interesting part of the result.

The Brain Drain Reversal: from Talent Attraction to Transit Dynamics

The sign reversal on foreign doctorate students — positive and significant among High innovators, negative and significant among Low innovators — is the most theoretically distinctive result in the paper. The fixed-effects structure rules out the simplest alternative interpretation: this is not a selection effect whereby higher-performing countries attract more foreign doctoral students and simultaneously perform better for independent reasons. The result captures within-country changes in the composition of doctoral populations over time, and when EU member states in the High group increase their share of foreign doctoral students, innovation performance subsequently improves. When member states in the Low group do the same, it does not.

In low-capacity systems, the same indicator captures the opposite dynamic. Foreign doctoral students enrolled in peripheral systems do not, in general, remain after graduation. The private sector cannot offer the knowledge-intensive employment and education-selective return premiums that Mayr and Peri (2009) identify as the necessary conditions for positive selection among returnees. They accumulate human capital at the host country's expense and relocate to higher-capacity systems — the transit-flow mechanism the framework predicts. Petersen and Puliga's (2017) and Atoyan et al. (2016) document the empirical scale of this imbalance: a net 29% directional loss of high-skilled workers from eastern to western EU member states after the 2004 enlargement, disproportionately concentrated among young workers and largely permanent in character.

Policy Implications: the Threshold as a Target, Not a Diagnostic

The threshold $\tau^* = 0.43\%$ of GDP in business R&D intensity is, in one sense, a low bar: it falls at the 20th percentile of the sample distribution, and most EU member states clear it for most of the panel period. But its substantive significance lies not in its level but in its structural implications. Below this floor, the private sector has not accumulated sufficient absorptive capacity to function as a conversion engine for publicly generated knowledge or publicly trained human capital. The eight member states that fall below τ^* for substantial portions of the sample period - Cyprus, Latvia, Malta, Romania, Lithuania, Croatia, Greece, and Slovakia - are not simply spending less on R&D. They are operating in a qualitatively different innovation regime in which the standard policy prescriptions for catching up are, at best, incomplete and, at worst, counterproductive.

The first implication concerns the allocation of EU structural funds and Horizon Europe investment. The dominant framework for European innovation policy treats all member states as operating on the same production function with different input levels, and prescribes increased investment in R&D and human capital as the path to convergence. The results in this paper challenge that framework directly. For countries below τ^* , additional public R&D investment - whether nationally funded or EU co-funded - does not generate measurable innovation returns because the private absorptive infrastructure required to exploit public knowledge is absent. The priority for these economies is not to increase public research investment but to build the private sector conditions under which public investment becomes productive: R&D tax incentives targeted at minimum private investment thresholds, preferential procurement policies for research-intensive firms, and cluster development programmes that create the density of knowledge-intensive private activity required to cross the threshold.

The second implication concerns human capital policy. The finding that doctoral human capital is the primary innovation mechanism in below-threshold economies - with a coefficient almost ten times larger than in above-threshold economies - is not an argument for expanding doctoral training in peripheral EU systems. It is an observation about a substitution dynamic in the absence of private capacity: doctorates become the dominant mechanism by default, not by design. The problem is not the supply of doctoral graduates but their retention. The negative coefficient on foreign doctorate students in low-capacity systems implies that policies designed to internationalise peripheral research systems - attracting foreign doctoral students, funding international research stays - may accelerate the transit-flow dynamic rather than reverse it if the private sector absorption capacity is not simultaneously developed. Human capital investment and private sector development must be sequenced and co-designed, not pursued independently.

The third implication is methodological and concerns the evaluation of European cohesion policy. The standard approach evaluates innovation policy by asking whether regions or countries that receive more public investment in R&D and education subsequently improve their innovation

performance. The two-regime structure identified in this paper implies that this question is mis-specified below the threshold: the relevant question is not whether additional inputs improve performance within the existing regime, but whether the combination and sequencing of investments is sufficient to shift countries from the low-capacity to the high-capacity regime. That transition is not observable in annual variation - it requires sustained investment over a period long enough to accumulate the private R&D stock above τ^* , at which point the complementarity between public and private knowledge generation activates.

The threshold $\tau^* \approx 0.43\text{--}0.44\%$ GDP in business R&D intensity provides a concrete, measurable policy target. Member states currently below this floor - Cyprus, Latvia, Malta, Romania, Lithuania, Croatia, Greece, and Slovakia across substantial portions of the 2014–2024 period - should prioritise instruments that build private R&D participation before scaling public research investment. Appropriate instruments include: R&D tax credits targeted at first-time business R&D spenders and calibrated to minimum investment thresholds rather than to volume; preferential public procurement for research-intensive SMEs that creates demand-side incentives for private knowledge investment; and cluster development programmes designed to create the minimum density of knowledge-intensive private activity required to generate the inter-firm spillovers that sustain private R&D above the threshold. Once business R&D investment has been sustained above τ^* for a sufficient period to accumulate the stock, the complementarity between public and private knowledge generation becomes operative - at which point scaling public research investment becomes productive in a way that it is not below the threshold.

Conclusions

This paper began with a puzzle that the standard literature on European innovation divergence has not satisfactorily resolved: why do EU member states that spend nearly as much on public research as the innovation leaders produce a fraction of their innovation output? The answer proposed here is structural rather than parametric. The EU innovation space is not a continuum of greater or lesser efficiency operating on a common production function. It contains two qualitatively distinct regimes separated by a threshold in private absorptive capacity, below which the standard conversion mechanisms between knowledge inputs and innovation outputs are simultaneously inoperative.

Theoretical implications. The two-regime framework integrates three bodies of literature - absorptive capacity theory, public-private R&D complementarity, and the brain drain literature - that have developed largely independently and converge on the same structural implication without having formalised it jointly.

The sign reversal on international doctoral mobility deserves particular attention as a theoretical result. That the same indicator operates through diametrically opposite mechanisms depending on the innovation regime of the host country is a prediction that cannot be derived from any single-mechanism theory. It requires the joint application of absorptive capacity theory and the brain drain literature, and its empirical confirmation suggests that the two bodies of work are more deeply connected than either has recognised.

Innovation system theory needs a framework that can accommodate state-dependent returns to human capital, not merely heterogeneous ones.

Policy implications. The threshold τ^* carries a specific implication for the design of EU cohesion and Horizon Europe investment. For countries operating below the absorptive capacity floor, the dominant prescription - increased investment in R&D and human capital as the path to convergence - is incomplete at best and counterproductive at worst. The priority is not to increase public research investment but to build the private sector conditions under which public investment becomes productive.

Limitations

A first limitation concerns identification horizon. Fixed-effects estimation exploits within-country variation over an eleven-year panel. For public R&D — a variable that changes slowly relative to the structural configuration of the innovation system — annual variation is insufficient to identify effects that operate through long-run complementarity rather than short-run flows. The null result on public R&D should be interpreted as a within-country, medium-run estimate; it does not rule out cross-sectional or long-run effects of the kind that longer panels or regime-change episodes could identify. For the same reason, the coefficients throughout should be interpreted as conditional correlations consistent with the theoretical framework rather than as causal estimates in the strict econometric sense.

A second limitation concerns the operationalisation of private absorptive capacity. Business R&D expenditure as a share of GDP captures only one dimension of this construct. Alternative operationalisations - the density of knowledge-intensive firms, patent stock measures, firm-level R&D participation rates - may yield somewhat different threshold values and regime compositions. Robustness to alternative proxies for the threshold variable is a productive avenue for further investigation, one that would also help distinguish the specific channel through which private capacity conditions

innovation returns from the aggregate effect documented here.

Future research. Three extensions follow directly from the limitations of the current analysis. The most important is replication with sub-national NUTS-2 data, where cross-regional variation in private R&D intensity is substantially richer and the empirical basis for the threshold estimate correspondingly more secure. A second extension concerns the temporal dynamics of regime transition: the current panel identifies the threshold cross-sectionally but cannot trace the investment path through which a country moves from the low-capacity to the high-capacity regime. Longer panels covering the post-Soviet transition in Central and Eastern Europe, or case studies of countries that have historically crossed analogous thresholds, would illuminate the transition mechanism that policy must navigate. Third, the sign reversal on international doctoral mobility identified here invites investigation of the micro-level mechanisms that aggregate to the national-level result: whether the transit-flow dynamic operates through emigration of foreign graduates, retention failure of domestic graduates, or both, and whether specific institutional interventions - return premium structures, knowledge-intensive employment guarantees - can modify the emigration probability sufficiently to shift the balance from drain to gain within the low-capacity regime.

The EU's innovation divergence is not a temporary disequilibrium that convergence policy will eventually resolve. It is the stable equilibrium of a system in which the same inputs generate different returns depending on the structural configuration of the private sector. Understanding that configuration - and the threshold that separates its two states - is a precondition for designing policy that can change it. A fourth extension concerns external validity: whether the threshold value of $\tau \approx 0.43$ % GDP is specific to the EU institutional environment or reflects a more general empirical regularity would require applying the two-regime framework to OECD economies outside the EU and to emerging market contexts where absorptive capacity deficits are more severe.

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