Regional Variations in Innovation Resilience, PhD Employees and Digitalization efforts

Adelheid Holl
Institute of Public Goods and Policies (IPP)
CSIC – Spanish National Research Council
C/ Albasanz, 26-28; 28037 Madrid, Spain
a.holl@csic.es

Ruth Rama
Institute of Economics, Geography and Demography (IEGD)
CSIC – Spanish National Research Council
C/ Albasanz, 26-28; 28037 Madrid, Spain
ruth.rama@cchs.csic.es

1. Introduction and Motivation

The COVID-19 pandemic represented an unprecedented and systemic shock to firms' innovation activities, simultaneously disrupting supply chains, labour markets, and knowledge networks. While many firms experienced severe constraints on ongoing research and development (R&D), others demonstrated a remarkable capacity to adapt, reorient, or even expand their innovation efforts in response to the crisis. Understanding the sources of such innovation resilience—the ability of firms to sustain and transform innovation activities under conditions of extreme uncertainty—has become a central concern in innovation studies and regional economics.

This paper investigates the role of two key firm-level resources in shaping innovation resilience during the COVID-19 crisis: advanced human capital and digitalization efforts. We focus in particular on PhD-trained employees engaged in R&D and innovation activities and on firms' investments in digital technologies, proxied by expenditure on software and databases. These resources are analytically distinct but potentially complementary in crisis contexts. Advanced human capital represents a relatively fixed stock of highly specialised and adaptable knowledge, while digital technologies constitute more flexible inputs that can facilitate rapid organisational reconfiguration. At the same time, firms' access to and effective use of these resources is embedded in regional contexts characterised by heterogeneous innovation systems, industrial structures, and institutional environments.

Using firm-level microdata from the 2020 Spanish Innovation Survey, which includes a dedicated COVID-19 module, this paper analyses how these firm-level capabilities relate to three dimensions of crisis-induced innovation behaviour: (i) engagement in unplanned or non-expected innovation activities, (ii) involvement in COVID-19-related R&D, and (iii) increases in R&D expenditure triggered by the pandemic. Spain provides a particularly suitable setting for this analysis due to its pronounced regional heterogeneity in innovation capacity, digital infrastructure, and industrial specialisation.

The paper contributes to the emerging literature on innovation resilience in three main ways. First, it provides systematic micro-econometric evidence on the role of advanced human capital and digitalization in shaping firms' adaptive and opportunity-driven innovation responses to an exogenous shock. Second, it explicitly examines regional heterogeneity by estimating interaction effects between firm-level resources and regional context and by reporting region-specific average marginal effects. Third, it offers new insights into how digitalization may exhibit diminishing or context-dependent returns in more advanced regional innovation systems.

2. Conceptual Framework and Related Literature

The concept of innovation resilience builds on broader discussions of resilience in regional and organisational studies, referring to the capacity of economic actors to absorb shocks, adapt to changing conditions, and, in some cases, transform existing structures. At the firm level, innovation resilience depends on the availability of resources and capabilities that enable rapid problem-solving, recombination of knowledge, and organisational flexibility.

A growing body of literature emphasises the importance of human capital for firms' innovative performance and adaptability. Highly skilled employees, and particularly PhD-trained personnel, embody deep domain-specific knowledge, analytical skills, and the capacity to engage in exploratory problem-solving. Such capabilities are especially valuable in crisis situations, when firms face novel constraints and must develop non-routine solutions. Because advanced human capital is costly to build and difficult to adjust in the short run, its effects are expected to be particularly salient during unexpected shocks.

Digitalization has also been identified as a key enabler of innovation resilience. Digital technologies facilitate remote collaboration, real-time information processing, and the reconfiguration of production and R&D processes. During the COVID-19 pandemic, digital tools played a crucial role in maintaining continuity of operations and enabling new forms of innovation activity. However, the benefits of digitalization are unlikely to be uniform across contexts. Effective deployment of digital technologies depends on complementary organisational capabilities and skills, and returns to digital investment may be lower in environments where digital infrastructures and routines are already well developed.

Finally, the regional context matters for both the availability and effectiveness of firm-level resources. Regional innovation systems differ in terms of knowledge bases, institutional support, and industrial structures, shaping firms' innovation opportunities and constraints. Leading regions may offer rich ecosystems that support innovation but may also exhibit saturation effects or path dependencies that limit the marginal impact of additional investments. Less advanced regions, by contrast, may experience stronger gains from incremental improvements in firm-level capabilities, particularly during periods of disruption.

3. Data and Variables

The empirical analysis is based on microdata from the 2020 wave of the Spanish Innovation Survey, which follows the harmonised Community Innovation Survey framework and includes

a special module on firms' responses to the COVID-19 crisis. The survey covers firms across manufacturing and selected service sectors and provides detailed information on innovation activities, human capital, digital expenditure, and firm characteristics.

The dependent variables capture three dimensions of innovation resilience. First, a dummy variable indicates whether the firm engaged in unplanned or non-expected innovation activities in response to the pandemic. Second, a dummy variable captures whether the firm undertook R&D activities specifically related to COVID-19. Third, a dummy variable indicates whether the firm increased its R&D expenditure as a direct consequence of the crisis.

The first key explanatory variable measures advanced human capital. We construct a dummy variable equal to one if the firm employs a share of PhD-trained personnel engaged in R&D and innovation activities that exceeds the average share observed in its three-digit sector. This relative measure allows us to identify firms with an above-average concentration of advanced human capital within comparable technological environments. To ensure meaningful comparisons, part of the analysis restricts the sample to innovation-active firms.

The second main explanatory variable captures digitalization efforts. Digitalization is proxied by a dummy variable indicating whether the firm incurred expenditure on software and databases. This measure reflects discrete investments in digital tools that can support innovation processes and organisational flexibility.

A rich set of control variables is included, covering firm size, age, innovation expenditure, patenting activity, export status, group membership, multinational status, state ownership, sectoral affiliation, and engagement in biological sciences and technologies. Regional dummy variables identify firms located in Catalonia, Valencia, Madrid, and the Basque Country, with the rest of Spain serving as the reference category.

4. Empirical Strategy

The empirical analysis employs probit models to estimate the relationship between firm-level resources and the probability of engaging in each innovation resilience outcome. To facilitate interpretation in nonlinear models, results are reported in terms of average marginal effects. Baseline specifications include the main explanatory variables and the full set of controls, along with sector fixed effects.

To examine regional heterogeneity, interaction terms between the key firm-level variables and regional dummies are introduced. Rather than interpreting interaction coefficients directly, which can be misleading in nonlinear models, we compute region-specific average marginal effects. This approach allows us to assess how the marginal effect of advanced human capital and digitalization varies across regions.

Several robustness checks are conducted. These include alternative specifications of the advanced human capital variable, using a dummy based on sectoral thresholds, and alternative measures of firm size. The results are found to be robust across specifications.

5. Main Results

The baseline results indicate a strong and statistically significant association between advanced human capital and firms' innovation resilience during the COVID-19 crisis. Firms with an above-sector-average share of PhD-trained employees engaged in R&D and innovation activities exhibit substantially higher probabilities of engaging in unplanned innovation, conducting COVID-19-related R&D, and increasing R&D expenditure. These findings underscore the importance of highly specialised and adaptable knowledge for coping with unexpected disruptions.

Digitalization efforts also display positive and significant effects across all three outcomes. Firms that invested in software and databases are more likely to sustain and expand innovation activities during the crisis. The magnitude of these effects is particularly pronounced for unplanned innovation activities, highlighting the role of digital tools in enabling rapid reorganisation and experimentation.

Interaction analyses reveal limited regional variation in the relationship between advanced human capital and innovation resilience. The marginal effects of employing PhD-trained innovation personnel remain positive and significant across regions, suggesting that the benefits of advanced human capital are broadly transferable across different regional innovation systems.

In contrast, the relationship between digitalization and innovation resilience exhibits pronounced regional heterogeneity. While digitalization is positively associated with innovation resilience on average, region-specific marginal effects indicate that its contribution is attenuated in leading regions such as Madrid and Catalonia and becomes weak or insignificant in the Basque Country for some outcomes. These patterns are consistent with diminishing short-run returns to digital investment in regions where digital infrastructures and organisational routines were already well developed prior to the pandemic.

The robustness checks confirm the stability of the main findings. Replacing the continuous measure of advanced human capital with a binary indicator based on sectoral thresholds yields similar results. Likewise, using alternative measures of firm size does not affect the estimated relationships. These checks increase confidence in the validity of the results.

6. Discussion and Concluding Remarks

Taken together, the results highlight the multilevel and context-dependent nature of innovation resilience. Advanced human capital emerges as a robust driver of adaptive and opportunity-driven innovation responses across regions. Digitalization, while generally beneficial, exhibits context-specific effects that depend on regional innovation environments.

The findings suggest that policies aimed at strengthening innovation resilience should consider both firm-level capabilities and regional context. While investments in advanced skills and digital technologies are broadly supportive of resilience, their effectiveness may vary across regions. Future research could extend this analysis by examining longer-term outcomes and by exploring complementarities between digitalization and organisational change.

Table 1: Innovation resilience during COVID-19

	Non-expected innovation activities	COVID-19 related R&D activities	Increase in R&D expenditure due to COVID-19
	(1)	(2)	(3)
PhD employees (above sector average)	0.022***	0.016***	0.011***
	(0.006)	(0.003)	(0.003)
DIGI_invest	0.050***	0.018***	0.016***
	(0.003)	(0.002)	(0.002)
Region:			
Catalonia	0.009**	0.005**	0.002
	(0.004)	(0.002)	(0.002)
Valencia	0.016***	0.015***	0.006**
	(0.005)	(0.003)	(0.003)
Madrid	0.010**	0.008***	0.005**
	(0.004)	(0.003)	(0.002)
Basque Country	-0.009*	-0.001	0.005*
	(0.005)	(0.003)	(0.003)
Controls:			
PhD CEOs	-0.001	0.001	-0.005**
	(0.005)	(0.003)	(0.003)
BIO:	0.018***	0.020***	0.019***
	(0.007)	(0.004)	(0.003)
Size:			
small size	-0.030***	-0.020***	-0.021***
	(0.007)	(0.005)	(0.004)
medium size	-0.028***	-0.016***	-0.021***
	(0.008)	(0.005)	(0.005)
large size	-0.011	-0.012**	-0.021***
	(0.009)	(0.005)	(0.005)
Inno_exp (millions)	0.003***	0.0001**	0.0001*
	(0.0004)	(0.00001)	(0.00004)
Patents	0.079***	0.046***	0.020***
	(0.009)	(0.006)	(0.004)
Age (log)	0.003	-0.0003	-0.004***
	(0.002)	(0.002)	(0.001)
SOE	0.063***	0.044***	0.026**
	(0.016)	(0.013)	(0.011)
Group	-0.003	0.001	-0.004*
	(0.004)	(0.003)	(0.002)
Multinational	0.005	-0.003	-0.001
	(0.005)	(0.003)	(0.003)
Exporter	0.017***	0.011***	0.008***
	(0.003)	(0.002)	(0.002)
Sector fixed effects	Y	Y	Y
Observations	35620	30131	32483
Pseudo R2	0.085	0.195	0.157

Robust standard errors in parentheses. *,**,*** denotes significance at 10%, 5% and 1%, respectively.

Table 2: Innovation resilience among innovation active firms

	Non-expected innovation activities	COVID-19 related R&D activities	Increase in R&D expenditure due to COVID-19
	(1)	(2)	(3)
PhD employees (above sector average)	0.014	0.020***	0.013***
	(0.009)	(0.006)	(0.005)
DIGI_invest	0.051***	0.022***	0.020***
	(0.006)	(0.004)	(0.004)
Region:			
Catalonia	0.001	0.005	-0.0004
	(0.008)	(0.006)	(0.005)
Valencia	0.027***	0.026***	0.007
	(0.010)	(0.008)	(0.006)
Madrid	0.017**	0.015**	0.007
	(0.008)	(0.007)	(0.006)
Basque Country	-0.029***	-0.012*	0.002
	(0.009)	(0.006)	(0.006)
Controls:			
PhD CEOs	0.012	0.004	-0.009*
	(0.009)	(0.006)	(0.006)
BIO:	0.020*	0.036***	0.035***
	(0.012)	(0.006)	(0.006)
Size:			
small size	-0.002	-0.011	-0.013**
	(0.001)	(0.007)	(0.006)
medium size	-0.001	-0.006	-0.014**
	(0.011)	(0.008)	(0.008)
large size	0.041***	0.005	-0.014
	(0.014)	(0.011)	(0.009)
Inno_exp (millions)	0.003***	0.0002*	0.0001
	(0.001)	(0.0001)	(0.0001)
Patents	0.088***	0.071***	0.030***
	(0.012)	(0.009)	(0.007)
Age (log)	0.004	-0.002	-0.010***
	(0.005)	(0.004)	(0.003)
SOE	0.085***	0.093***	0.043**
	(0.030)	(0.028)	(0.021)
Group	-0.020**	-0.007	-0.015***
	(0.008)	(0.006)	(0.005)
Multinational	0.001	-0.003	-0.001
	(0.010)	(0.007)	(0.001)
Exporter	0.009	0.010**	0.007
	(0.007)	(0.005)	(0.004)
Sector fixed effects	Y	Y	Y
Observations	14217	12991	13618
Pseudo R2	0.061	0.100	0.071

Robust standard errors in parentheses. *,**,*** denotes significance at 10%, 5% and 1%, respectively.

Table 3: Interaction with Phd innovation employees

	Non-expected innovation activities	COVID-19 related R&D activities	Increase in R&D expenditure due to COVID-19
	(1)	(2)	(3)
PhD employees (above sector average)	0.025***	0.020***	0.015***
	(0.007)	(0.004)	(0.004)
Region x PhD employees:			
Catalonia	0.009**	0.005**	0.002
	(0.004)	(0.002)	(0.002)
Valencia	0.015***	0.014***	0.004*
	(0.005)	(0.003)	(0.003)
Madrid	0.010**	0.009***	0.004*
	(0.004)	(0.003)	(0.002)
Basque Country	-0.009*	-0.001	0.004
	(0.005)	(0.003)	(0.003)
DIGI_invest	0.050***	0.018***	0.015***
	(0.003)	(0.002)	(0.002)
Controls	Y	Y	Y
Sector fixed effects	Y	Y	Y
Observations	35620	30131	32483
Pseudo R2	0.085	0.196	0.160

Robust standard errors in parentheses. *,**,*** denotes significance at 10%, 5% and 1%, respectively.

Table 4: Interaction with digitalization effort

	Non-expected innovation activities	COVID-19 related R&D activities	Increase in R&D expenditure due to COVID-19
	(1)	(2)	(3)
PhD employees (above sector average)	0.021***	0.016***	0.011***
	(0.006)	(0.003)	(0.003)
DIGI_invest	0.054***	0.019***	0.017***
	(0.004)	(0.002)	(0.002)
Region x DIGI_invest:			
Catalonia	0.009**	0.005**	0.002
	(0.004)	(0.002)	(0.002)
Valencia	0.016***	0.014***	0.005**
	(0.005)	(0.003)	(0.003)
Madrid	0.010**	0.080***	0.004*
	(0.004)	(0.003)	(0.002)
Basque Country	-0.009*	-0.001	0.005
	(0.005)	(0.003)	(0.003)
Controls	Y	Y	Y
Sector fixed effects	Y	Y	Y
Observations	35620	30131	32483
Pseudo R2	0.085	0.196	0.158

Robust standard errors in parentheses. *,**,*** denotes significance at 10%, 5% and 1%, respectively.