Regional Variations in Innovation Resilience, PhD Employees and Digitalization efforts

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Abstract: This paper explores the relationship between PhD-level human capital and digitalization efforts and firms' innovation resilience during the COVID-19 pandemic, with particular attention to regional heterogeneity. Using microdata from the 2020 Spanish Innovation Survey that includes a dedicated COVID-19 module, we analyse firms' engagement in unplanned innovation activities, COVID-19-related R&D, and increases in R&D expenditure triggered by the pandemic. Our results show a significant positive relationship between firms employing PhD-trained personnel in R&D and innovation activities and firms investing in digital technologies and innovation resilience during the crisis, specifically for adaptive and opportunity-driven innovation responses. We also observe regional differences, with firms in Madrid and Valencia showing stronger adaptive responses. Interaction analyses indicate only small spatial variances of the relationship between PhD innovation employees and regional context, but digitalization effort generally shows a reduced relationship with resilience in industrial core regions.

Keywords: Innovation resilience; COVID-19; PhD employees; Human capital; Regional innovation systems; Spain

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1. Introduction

The COVID-19 pandemic constitutes a rare, large-scale, and exogenous shock that provides a quasi-experimental setting to study innovation resilience, understood as firms' ability to sustain, adapt, or redirect innovation activities in the face of severe disruption. While crises often depress R&D investment and innovative effort, prior research shows that firms react differently to crises and some firms are able to exploit turbulent periods as windows of opportunity, engaging in adaptive and opportunity-driven innovation activities (Paunov 2012; Archibugi et al., 2013a, b; Cruz-Castro et al, 2018) and this seems to hold true for the COVID-19 pandemic as well (Brancati, et al. 2020, Ferrigno and Cucino, 2021; Trunschke et al. 2024).

In this context, the skills and capabilities embedded in firms' R&D and innovation workforce become particularly important. Employees engaged in R&D activities typically possess advanced analytical abilities, problem-solving skills, and experience operating under uncertainty—attributes that are directly relevant during crisis situations. Among them, PhD-trained employees represent the top of formal human capital, bringing research expertise, methodological knowledge, and persistence developed through doctoral training.

Drawing on human capital theory, doctoral education not only expands specialized knowledge but also enhances learning capacity, creativity, and the ability to address complex and ill-defined problems. These characteristics suggest that PhD employees may play a key role in supporting firms' adaptive responses during periods of systemic disruption. Despite this, empirical evidence on whether PhD-level human capital contributes specifically to innovation resilience in crisis contexts remains scarce.

Alongside advanced human capital, digitalization has emerged as a critical firm-level capability shaping innovation resilience in crisis contexts (Abidi et al., 2023; Copestake et al, 2024; Trunschke et al., 2024). Digital technologies enable firms to reorganize R&D processes, support remote collaboration, accelerate experimentation, and rapidly reconfigure business models in response to abrupt disruptions. During the COVID-19 pandemic, firms with stronger pre-existing digital capabilities were, in general, better able to sustain innovation activities, adapt ongoing projects, and exploit new opportunities arising from changes in demand and production conditions (Trunschke et al., 2024. Importantly, the effectiveness of digital technologies depends not only on access to infrastructure but also on complementary skills and organizational capabilities, suggesting complementarities between highly skilled human capital and digitalization in supporting adaptive and opportunity-driven innovation under conditions of extreme uncertainty. By examining innovation efforts that emerge not through long-term planning but through rapid decision-making in times of disruptions and with mainly existing resources, the analysis contributes to a more dynamic understanding of innovation as a crisis-response capability rather than solely a planned, cumulative process.

Moreover, the COVID-19 pandemic has exhibited pronounced regional unevenness (Gajewski, 2022). Innovation, in turn, does not take place in a spatial vacuum but is also deeply embedded in regional contexts. The capacity to deploy digital technologies and data-driven processes is itself unevenly distributed across regions, reflecting differences in economic structures and institutional environments. In Spain, the innovation system is characterized by substantial regional heterogeneity in industrial composition, R&D intensity, institutional support, and the maturity of innovation ecosystems. These regional disparities are therefore likely to shape firms' innovation resilience and their ability to respond effectively to the COVID-19 shock.

Spain provides a particularly relevant case for analysing firms' innovative resilience during the COVID-19 crisis. The country was among those most severely affected by the pandemic and is characterised by a quasi-federal territorial organisation. This institutional setting allows for the analysis of regional heterogeneity in firms' responses to a major exogenous shock. Spain combines structural weaknesses with certain strengths. According to the European Innovation Scoreboard, Spain is classified as a moderate innovator, alongside countries such as Portugal, Italy, and Slovenia, whose innovative performance remains below the EU average. This position reflects persistent limitations in business R&D investment and a productive structure dominated by small firms. At the same time, Spain performs strongly in human capital development, with high levels of tertiary education attainment and doctoral graduation rates and also has relatively high levels of digitalisation (European Commission, 2025; Holl and Rama, 2024).

This raises a central question: are human capital and digitalization positively related to firms' adaptive and opportunity-driven innovation responses during the COVID-19 crisis? By focusing on Spain, the analysis offers insights not only into a highly heterogeneous innovation system under stress, but also into the broader relevance of human capital and digitalization for innovation resilience in countries facing similar structural conditions.

2. Related Literature

2.1. Innovation Resilience and External Shocks

A growing body of literature examines how firms' innovation activities respond to major external shocks such as economic downturns, institutional changes, and pandemics. Early work on the 2008 Great Recession has highlighted heterogeneous firm responses, with some firms scaling back R&D while others maintain or even intensify innovative activity as crisis response (Archibugi et al., 2013a, b; Holl & Rama; 2016). This strand of research introduced the concept of innovation resilience, emphasizing firms' capacity to absorb shocks and adapt innovation strategies. The COVID-19 pandemic has further stimulated interest in understanding short-term adaptive innovation responses under extreme uncertainty. While many firms curtailed R&D expenditures and postponed innovation projects, others accelerated their innovation efforts, especially in areas such as digitalization, product adaptation, and process reconfiguration (Diekhof et al., 2021; Holl and Rama, 2024; Holl et al., 2025).

This pronounced heterogeneity in firms' innovation responses has become central to the emerging literature on firm resilience. As stated, the literature conceptualizes resilience not merely as survival, but as the capacity to adapt and sustain value-creating activities under conditions of extreme uncertainty. Within this literature, innovation is consistently identified as key determinants of broader firms' resilience during crises (Battisti et al, 2023; Bergami et al., 2022). For instance, in a sample of Spanish firms, innovation effort mediates the relationship between labour flexibility – as measured by polyvalence -- and firms' adaptive capacity, including the capacity to launch new products into the market (Pérez-Calle et al., 2021).

2.2 Human Capital, PhDs, and Innovation Resilience

Highly skilled human capital—particularly PhD-trained employees—has long been recognized as a key driver of firms' innovative performance (Zucker et al., 1998; Barge-Gil et al., 2021). PhD personnel enhance firms' absorptive capacity, problem-solving abilities, and ability to reorient R&D activities in response to changing environments. Human capital also contributes to copying better with external shocks (Esteve-Pérez et al. 2024). Within the innovation literature, highly educated and research-oriented workers—plays a central role in shaping firms' adaptive capacity. The knowledge-based view of the firm emphasizes that sustained competitive advantage derives from the creation, integration, and application of specialized knowledge, much of which is embodied in skilled employees rather than in physical assets (e.g., Kogut and Zander, 1992). Under crisis conditions, when established routines, supply chains, and organizational practices are disrupted, this tacit, problem-solving knowledge becomes especially valuable.

Evidence from studies of knowledge-intensive enterprises shows that firms employing highly educated personnel—particularly those engaged in R&D and engineering activities—were more likely to sustain innovation and growth under pandemic conditions (Kosoupoulos et al., 2022). Importantly, this relationship extends beyond employees' purely technical skills. The aforementioned authors, analysing a sample of knowledge-intensive firms, find that firms' growth acceleration during the pandemic was strongly associated with employees' optimism following the onset of the health crisis. In turn, the most optimistic employees were those with relatively higher levels of education and innovative capabilities, whereas age, gender, and tenure played no significant role.

More broadly, higher R&D intensity and the presence of research-oriented staff enhanced firms' capacity to pivot toward new products—such as personal protective equipment, medical devices, and digital services—and to redesign production processes under severe operational constraints (Bergami et al., 2022). These findings suggest that highly skilled workers contribute not only through their technical expertise but also through cognitive and behavioural attributes that support adaptability, problem-solving, and opportunity recognition in times of crisis.

However, relatively little is known about whether PhD employees contribute specifically to innovation resilience during crises, and whether this contribution varies across regional contexts. PhD holders are trained in frontier problem-solving, experimental methods, and knowledge recombination—capabilities that are particularly valuable in contexts characterized by novelty, uncertainty, and rapidly evolving technological and market conditions. Compared with routine-based workers, PhD-level employees are more likely to explore alternative technological pathways, identify new applications for existing knowledge (Barge-Gil et al., 2021), and translate scientific advances into firm-specific innovations.

2.3 Digital Capabilities

Digitalization and the development of digital capabilities are also critical enablers for firms' resilience in the face of economic crises such as the COVID-19 pandemic (Abidi et al., 2023; Copestake et al, 2024; Trunschke et al., 2024; Holl et al, 2025). Digital technologies allow firms to maintain business continuity by enabling remote work, online sales, digital service delivery, and more flexible coordination along value chains. Beyond short-term adaptation, firms with stronger pre-existing digital capabilities are better positioned to reconfigure processes, accelerate innovation, and exploit new market opportunities under heightened uncertainty. Evidence from European as well as Middle Eastern and Central Asian contexts further highlights the role of digitalization as a crucial resilience factor -- effects that were especially salient for SMEs, which were disproportionately vulnerable to the shock (Bianco et al., 2023; Cugno et al., 2022; Fernández-Cerezo et al., 2021; Kumar and Ayedee, 2021).

For Spain, Benítez et al. (2023) show that the adoption of information technologies enabling remote work—when combined with larger firm size—positively affected post-pandemic survival prospects and even contributed to market leadership. Similarly, Pérez-Calle et al. (2021) find that Spanish firms with a higher degree of pre-pandemic implementation of Information and Communication Technologies (ICT) were more likely to withstand the COVID-19 shock. Their results further indicate that workforce polyvalence and firms' innovative capacity were critical determinants of resilience.

2.4 Regional Heterogeneity and Innovation Capacity

However, the role of human capital and digitalization for firms' innovative performance during a crisis does not happen in isolation. Firms are embedded within regional innovation systems that vary substantially in terms of research infrastructure and research institutions, such as, for example, the presence and quality of universities, industrial composition, innovation network density, and wider human and social capital. These differences shape how firms absorb and respond to external shocks.

Studies have shown the role of regional innovation systems in shaping firms' innovative behaviour in general but also during crises (Asheim et al., 2011; Cruz-Castro et al, 2018; Sargento and Lopes, 2024). Regions differ systematically in industrial specialization, human capital endowments, firm size distributions, and institutional support, all of which influence firms' resilience to shocks. During the COVID-19 pandemic, sectors experienced markedly uneven impacts; for instance, in Germany, pharmaceutical and ICT service industries even increased their global R&D expenditures (Diekhof et al., 2021). Given that regions typically exhibit distinct productive structures, such sectoral dynamics translated into heterogeneous regional outcomes.

Recent evidence suggests that resilience to the COVID-19 pandemic has been regional uneven (Gajewski, 2022) and that the innovation impacts of COVID-19 are also highly uneven across space and depend on pre-existing regional capabilities and structures (Balland et al., 2022). From this perspective, regional heterogeneity is not merely a control factor but a core dimension through which innovation resilience operates. Empirical evidence from Europe strongly supports this perspective. Regions with stronger pre-crisis innovation capacities proved more resilient during the Great Recession, whereas those with weaker innovation systems were disproportionately affected (Bristow and Healy, 2018). Similar patterns emerged during the COVID-19 pandemic. A study of major Spanish metropolitan areas documents highly heterogeneous impacts, with regional resilience shaped by a variety of factors, including their economic structure and innovation intensity (Salom-Carrasco et al., 2025). Large urban regions appear particularly well positioned to absorb shocks, owing to their more diversified economic bases and deeper innovation ecosystems (Boschma, 2023).

In Portugal, regions hosting strong universities, dense R&D networks, and vibrant knowledge spillovers were better able to mobilize scientific and technical expertise during the pandemic (Sargento and Lopes, 2022). Universities and public research organizations played a pivotal role in COVID-related R&D, technology transfer, and collaboration with firms, particularly in health, digital, and advanced manufacturing technologies (Bergami et al., 2022). Evidence from Central and Eastern Europe further indicates that universities rapidly mobilized research capabilities and engaged in regional collaboration during the pandemic, thereby strengthening local innovation systems (Bachmann and Frutos-Bencze, 2022). These regional knowledge infrastructures amplified the effectiveness of firm-level human capital by providing access to advanced equipment, collaborative opportunities, and frontier scientific developments.

Complementarily, social capital—reflected in the intensity of interactions among regional actors and sectors—has been shown to enhance regional resilience, as evidenced by Italian regions during the Great Recession (Marino et al., 2025).

Similarly, the presence of dense supplier networks in the Madrid Metropolitan Area facilitated the adoption of digitalization among SMEs. Consequently, pre-existing cooperative linkages enhanced firms' capacity to successfully withstand the COVID-19 shock, despite Madrid being one of the European cities most severely affected by the pandemic (Holl and Rama, 2024).

2.5 Research Questions

Taken together, the emerging literature on COVID-19 highlights the multilevel nature of innovation resilience. At the firm level, pre-existing innovation capabilities together with the availability of highly skilled human capital and internal digital capabilities shape firms' ability to adapt products, processes, and technologies under crisis conditions. At the same time, regional innovation systems provide differentiated institutional, industrial, and knowledge environments that condition firms' responses to systemic shocks.

Against this background, this paper addresses the following research questions:

1. To what extent is the presence of PhD-trained employees engaged in R&D and innovation activities in a firm related to its innovation resilience in response to the COVID-19 shock, in terms of adaptive, reoriented, and intensified innovation efforts?
2. How are firms' digitalization efforts related to innovation resilience during the COVID-19 crisis, in terms of adaptive, reoriented, and intensified innovation efforts?
3. How does firms' innovation resilience during the COVID-19 crisis vary across regions?

4. Data and Empirical Strategy

The empirical analysis is based on data from the Spanish Innovation Survey. The analysis focuses on the 2020 wave, which contains a special COVID-19 module providing detailed information on firms' innovation responses to the pandemic. This feature allows us to observe not only changes in innovation inputs and outputs, but also whether these changes were explicitly triggered by the COVID-19 shock.

Dependent variables: To capture innovation resilience, three complementary binary dependent variables are constructed:

1. Non-expected innovation activities due to COVID-19: a dummy indicating whether the firm undertook innovation activities that were not initially planned as a direct consequence of the pandemic. This variable captures *adaptive and proactive resilience*, reflecting firms' ability to respond flexibly to unforeseen challenges.
2. COVID-19-related R&D activities: a dummy indicating whether the firm carried out R&D activities specifically related to COVID-19. This outcome reflects *strategic reorientation* and opportunity-driven innovation, such as redirecting existing competencies toward urgent societal and market needs.
3. Increase in R&D expenditure due to COVID-19: a dummy capturing whether the pandemic led to an increase in R&D investment. This indicator reflects firms' willingness to reinforce innovation efforts under adverse conditions.

Given the binary nature of our dependent variables, the empirical strategy relies on probit models estimating the probability that a firm exhibits each dimension of innovation resilience.

Independent variables: We focus on two firm-level resources that are analytically distinct yet functionally complementary under crisis conditions. First, we consider advanced human capital. PhD-level employees represent highly specialized and adaptable knowledge that is costly to build and difficult to adjust in the short run, but that can be rapidly mobilized when firms face unexpected shocks. Importantly, information on PhD employees refers specifically to personnel engaged in R&D and innovation activities, allowing us to isolate the role of advanced human capital directly involved in knowledge creation. Based on this information, we construct a dummy variable equal to one if a firm's share of PhD employees in R&D and innovation activities exceeds the average share observed in its 2-digit sector. Given that we focus innovation resilience, in part of the empirical analysis, we restrict the sample to innovation-active firms. For this sub-sample the presence and intensity of PhD-level personnel in R&D and innovation activities are better comparable.

Firms may, in principle, reconstitute their knowledge base by recruiting new employees or develop new capabilities through processes of experimentation and trial-and-error learning. However, as Kogut and Zander (1992, p. 12) aptly observe, such strategies are "a luxury often too exorbitant for companies […] facing survival pressures." During a systemic crisis such as the COVID-19 pandemic, firms confront extreme uncertainty and severe time constraints that sharply limit their ability to engage in gradual capability building or to access new external knowledge through hiring. Instead, they are forced to rely on the human capital already embedded within the organization – with their existing skills, expertise, and problem-solving capacities. Safety concerns for both candidates and staff, competition for talent in certain industries, and logistical barriers often posed challenges to recruitment during the pandemic (Jabeeen et al., 2025). In this context, higher-level education and advanced skills become particularly salient, as they shape firms' ability to rapidly adapt, reorient, or intensify innovative activities in response to unforeseen constraints.

Second, digital technologies have also been identified as key enablers of firms' ability to adapt, reorganise, and sustain innovation activities during crisis (Trunschke et al., 2024). We proxy firms' digitalisation efforts by a dummy variable taking on 1 if the firms had expenditure on software and databases in 2020. This measure reflects firms' investment in digital tools and data, which are relatively flexible inputs that can be acquired quickly, but whose effective deployment depends critically on the skills and competencies available within the firm. In emergency contexts characterised by severe time pressure and recruitment constraints, firms are therefore more likely to invest in and benefit from digital tools when they already possess the cognitive and organisational capabilities required to integrate them into ongoing activities. In this respect, investments in software and databases can be interpreted not only as inputs of digital capital, but also as reflecting the presence of in-house digital skills and absorptive capacity, as such investments presuppose a workforce able to adopt, integrate, and rapidly learn to use new digital tools. This type of expenditure is closely related to the concept of complementary intangible assets. Brynjolfsson et al. (2002) emphasizes that the productivity and strategic value of IT investments depend critically, among others, on complementary investments in human capital and digital skills. Firms lacking such internal competencies are more likely to rely on outsourcing rather than in-house digital investments.

From this perspective, PhD human capital and digital investment are not alternative drivers of innovation resilience, but interconnected elements of a single adaptive process whereby firms activate existing skills through enabling technologies.

Third, regional heterogeneity is captured through dummy variables for Catalonia, Valencia, Madrid, and the Basque Country, constructed on the basis of the headquarter location of the firm. These regions represent the main economic and innovation centres of Spain, concentrating a large share of national R&D expenditure, highly skilled employment, innovative firms, and advanced industrial and service activities. They also differ markedly in terms of industrial structure, sectoral specialization, and regional innovation system characteristics, making them particularly relevant cases for examining heterogeneous innovation responses to systemic shocks. In all specifications, the comparison group consists of firms located in the rest of Spain, which serves as a national benchmark against which differences in innovation resilience in these leading regions can be identified.

Control variables: We include in our estimations a rich set of firm-level controls:

PhD-CEOs: dummy variable that captures whether the firm is led by a PhD-trained CEO, controlling for top-management human capital and strategic leadership capabilities.

BIO: dummy variable that indicates engagement in biological sciences and technologies, which are characterized by high R&D intensity and strong external knowledge relationships (Hall and Bagchi-Sen, 2001; Holl and Rama, 2012); accounting for BIO activities helps isolate the role of human capital and digital capabilities from sector-specific innovation dynamics.

Size: dummy variables for small, medium, and large firms, with firms with less than 10 employees as the reference group. Larger firms with their greater resource availability and organizational capabilities tend to show greater resilience to crisis (Antonioli and Montresor, 2021; Bartik et al, 2020; Cincera et al., 2012; Cruz-Castro et al., 2018).

Inno_exp: Innovation expenditure (in millions) captures the scale of firms' innovation activities, controlling for the overall intensity of resources devoted to innovation (Lien and Timmerman, 2023).

Patents: dummy variable indicating whether the firm registered patents during 2018-2020, proxying for technological capabilities and appropriability strategies. Firms with patents tend to be more resilient to crisis (Cincera et al., 2012; Cruz-Castro et al., 2018).

Age: log of years since the company has been established. Some research on resilience to crisis has found that older firms have been less likely to abandon innovation projects than younger ones (Cincera et al., 2012; Paunov, 2012). Firm age captures organizational experience and maturity, which may influence adaptability and risk-taking behaviour during crises.

SOE: dummy variable that identifies state-owned enterprises. Those firms may differ in innovation objectives, access to resources, and crisis response compared to private firms (García-Sánchez and Rama, 2022; Landoni, 2020).

Group: dummy variable that captures if the firms is part of a business group. Group membership can condition firms' innovation activities (García-Sánchez and Rama, 2022; Lincoln et al, 2017).

Multinational: dummy variable indicating whether the firm is part of a multinational enterprise. Multinational companies tend to have greater access to cross-border knowledge flows and organizational resources, which may influence their innovation strategies and crisis responses (Holl and Rama, 2014).

Exporter: dummy variable that controls for firms' engagement in international markets. Studies on the 2008 financial crisis found that exporters have been less likely to abandon R&D projects during (Paunov 2012; Cruz-Castro et al., 2018).

Moreover, sector fixed effects at the two-digit level are included to account for technological and market-specific conditions.

4. Results

4.1. Baseline results

We begin by presenting results for the full sample of firms (Table 1), which includes both innovation-active and non-innovation-active firms. We report average marginal effects and their robust standard errors. Across all three measures of innovation resilience, the presence of PhD-trained employees engaged in R&D and innovation activities is strongly and positively associated with firms' likelihood of exhibiting adaptive responses to the COVID-19 shock. The estimated coefficients indicate that firms with an above-sector-average concentration of PhD innovation employees compared to their 2-digit sector peers are significantly more likely to undertake non-expected innovation activities triggered by the pandemic, to reorient R&D toward COVID-19-related objectives, and to increase R&D expenditure as a direct response to the crisis. Specifically, such firms are, on average, 2.2 percentage points more likely to undertake non-expected innovation activities, 1.6 percentage points more likely to engage in COVID-19-related R&D, and 1.1 percentage points more likely to increase R&D expenditure as a direct response to the pandemic. This highlights the role of advanced human capital in enabling adaptive and opportunity-driven innovation under crisis conditions.

Digitalization efforts, proxied by a dummy variable indicating whether the firm incurred expenditure on software and databases, also shows a significant relationship with all three resilience outcomes. Firms that invested in digital technologies exhibit a 5.0 percentage point higher probability of undertaking unplanned innovation activities, a 1.8 percentage point higher probability of engaging in COVID-19-related R&D, and a 1.6 percentage point higher probability of increasing R&D expenditure in response to the pandemic. These results underscore the importance of internal digital capabilities in facilitating rapid reorganization of innovation activities during periods of severe disruption.

Clear regional differences in innovation resilience are observed. Firms located in Valencia and Madrid show higher probabilities of all three resilience outcomes relative to firms in the rest of Spain, while firms in Catalonia exhibit more modest but still positive coefficients for adaptive and COVID-related innovation. In contrast, firms in the Basque Country are less likely to engage in non-expected innovation activities, although they show a slightly higher probability of increasing R&D expenditure.

Turning to control variables, we observe that the presence of a PhD-trained CEO does not display a robust or statistically significant association with innovation resilience outcomes once other firm characteristics are controlled for. This suggests that resilience during the crisis is more closely related to the composition of the R&D workforce than to top-level education. Engagement in biological sciences and technologies is positively and significantly associated with all three resilience indicators, reflecting the strong relevance of bio-related activities during the pandemic. Patenting firms, state-owned enterprises, and exporters also display significantly higher probabilities of innovation resilience, consistent with prior evidence on the role of accumulated technological capabilities, institutional support, and international exposure. Firm size dummies indicate that, relative to micro firms, small and medium-sized firms are less likely to display resilient innovation responses, while effects for large firms are more mixed across outcomes.

The negative marginal effects associated with business group membership, although counterintuitive from a resource-based perspective, can be interpreted in light of organizational responses to acute systemic crises. While business groups benefit from superior access to financial and organizational resources in normal times, the early phase of the COVID-19 pandemic was characterised by extreme uncertainty, liquidity concerns, and a heightened emphasis on risk containment. Under such conditions, group-level decision-making tends to become more centralised, reducing subsidiary autonomy and delaying discretionary initiatives such as innovation (Bakonyi, 2018; Lien and Timmerman, 2023; Sporsem et al., 2021). Moreover, early pandemic innovations were often improvised and operational in nature, favouring smaller and more autonomous firms capable of rapid local adaptation. Group-affiliated firms may therefore have relied more heavily on internal reallocation and buffering strategies rather than immediate innovative responses, leading to a lower observed incidence of innovation during 2020. This interpretation is confirmed by results for the multinational variable. This finding does not contradict the established evidence that business groups may foster innovation over longer horizons; rather, it highlights how, in the context of an acute systemic shock, group affiliation may temporarily constrain firm-level innovative responses.

In contrast to business group affiliation, state ownership is positively and statistically significantly associated with firms' likelihood of engaging in rapid innovative responses during the early phase of the COVID-19 crisis, particularly with respect to unexpected and COVID-related activities (increases probability by 6.3% and 4.4 %, respectively). This result is consistent with the institutional role of state-owned enterprises during the pandemic. In 2020, SOEs were often directly involved in the provision of essential services and were subject to urgent requests from public authorities and national health systems, requiring rapid adaptation of processes, products, and organisational practices [1]. Unlike private firms, SOEs faced softer budget constraints and operated under emergency mandates that prioritised continuity of service and crisis response over profitability considerations. As a result, innovation in SOEs during this period appears to have been largely demand-driven and reactive, explaining their higher propensity to engage in rapid, unplanned innovation. While our data do not allow us to directly observe public procurement requests, the timing and nature of the innovations reported by SOEs strongly suggest a demand-driven response linked to the public health emergency. The effects of ownership are confirmed in the following tables.

Younger firms—particularly among the youngest cohorts—were more likely to increase R&D investment during the COVID-19 shock. This result is consistent with greater flexibility and growth orientation among younger firms

Table 2 restricts the analysis to innovation-active firms, allowing us to assess whether the role of PhD employees and digitalization differ once we focus only on firms engaged in innovation. Within this subsample, the positive association between PhD innovation employees and innovation resilience remains strong for COVID-19-related R&D and increases in R&D expenditure. Firms with an above-sector-average share of PhD innovation employees are 2.0 percentage points more likely to engage in COVID-related R&D and 1.3 percentage points more likely to increase R&D expenditure. The effect on non-expected innovation activities, while positive, is no longer statistically significant, suggesting that PhD

[1] About the engagement of SOEs in production of masks, ventilators and even vaccines, see World Bank documents https://blogs.worldbank.org/en/governance/state-owned-enterprises-during-crisis-assets-or-liabilities?utm and https://openknowledge.worldbank.org/entities/publication/9328459f-a61d-5f71-b47c-dfa02cee2b5d Accessed January 2026.

human capital plays a particularly important role in enabling strategic reorientation and reinforcement of R&D among already innovative firms.

Digitalization efforts continue to exert a robust and economically meaningful influence across all three outcomes, with marginal effects that are similar than those observed in the full sample. This finding highlights the central role of digital tools in sustaining and redirecting innovation activities even among firms with established innovation capabilities.

Third, regional effects become more nuanced once the sample is restricted. While Madrid and Valencia continue to exhibit positive associations for most outcomes, coefficients for other regions—most notably the Basque Country—become weaker or even negative, suggesting that regional heterogeneity in innovation resilience is partly driven by differences in the composition of innovation-active firms across regions. Particularly Madrid and Valencia appear to have supported rapid and adaptive firm-level innovation responses during the crisis.

While Basque firms are not less innovative overall, they display a lower propensity to undertake non-expected or improvised innovation activities during the pandemic. This result is unlikely to be driven by regional industrial structure or human capital endowments, as the analysis controls for sector fixed effects and measures PhD employment relative to two-digit industries. Instead, it suggests differences in the organisation of innovation responses across regional contexts. The Basque Country is characterised by a highly institutionalised innovation system, with strong technology centres, cooperative arrangements, and established channels for collaborative R&D (Ruiz Yánis, 2025). In such an environment, firms may have relied less on ad hoc experimentation and more on structured R&D mechanisms when responding to the crisis.

4.2. Interaction effects

Table 3 explores whether the relationship between PhD-level human capital and innovation resilience varies across regional contexts by interacting the indicator for above-sector-average PhD innovation employees with regional dummies.

The baseline marginal effect of PhD innovation employees remains positive and significant across all three outcomes, confirming their central role in fostering adaptive innovation responses during the pandemic. The interaction terms indicate that regional location does not substantially amplify the marginal effect of PhD human capital. Instead, the estimated marginal effects of PhD employees across regions closely mirror the baseline regional patterns observed in Table 1. Firms located in Valencia and Madrid exhibit higher probabilities of innovation resilience overall, but the incremental effect associated with PhD human capital is broadly similar across regions.

This pattern suggests that PhD innovation employees provide a resilience advantage that is largely region-invariant, supporting the interpretation that advanced human capital acts as a general-purpose capability that enables firms to adapt to systemic shocks regardless of regional context.

Table 4 examines whether the relationship between firms' digitalization effort—proxied by expenditure on software and databases—and innovation resilience varies across regions. The main average marginal effects of digitalization expenditure also remain positive and statistically significant for all three resilience outcomes, confirming that digitalization is, on average, resilience-enhancing and reinforcing the robustness of the baseline results. This reaffirms the central role of digital capabilities in enabling firms to adapt, reorient, and sustain innovation activities under crisis conditions.

As for regional differences, Table 4 reports the average marginal effect of digitalization for firms located in each region, thereby disaggregating the average relationship identified in Table 1. The non-reported interaction coefficients between digitalization expenditure and regional dummies are mostly negative in the probit estimations and the corresponding average marginal effects vary by region. Digitalization continues to exert a positive marginal effect on innovation resilience in Catalonia, Valencia and Madrid, although the magnitude of this effect is smaller than the overall average. In the Basque Country the relationship becomes weakly negative for non-expected innovation activities and statistically insignificant for COVID-related R&D and increases in R&D expenditure.

This pattern suggests that, in regions with strong pre-existing industrial and organizational capabilities, such as the Basque Country, additional digital investment during the crisis may have been directed primarily toward maintaining operational continuity rather than generating new or reoriented innovation activities. In contrast, in regions with lower pre-crisis digital intensity, crisis-induced digital investments appear to have had a stronger transformative impact, enabling firms to rapidly reorganize R&D processes, adopt remote collaboration tools, and explore new digital innovation pathways. These results are consistent with a catch-up or threshold effect, whereby digitalization plays a particularly important role in strengthening innovation resilience in less digitally mature regional contexts.

4.3. Robustness checks

We performed several robustness checks to assess the stability of the main findings. First, we replaced the binary indicator equal to one if the firm's share of PhD innovation employees exceeds the average share in its two-digit sector with a continuous measure of the number of PhD innovation employees and its squared term (Appendix Table A1). The results remain largely unchanged. Firms with more PhD innovation employees are significantly more likely to engage in all three forms of innovation resilience, confirming that the results are not driven by functional form. However, at the same time, the unreported negative and statistically significant squared coefficients suggest diminishing marginal returns, implying that the resilience-enhancing effect of PhD personnel is strongest at lower and moderate levels of PhD intensity.

Second, we replaced the binary indicator equal to one if the firm had data and software expenditures with the continuous measure based on the amount spend and its square term (Appendix Table A2. The results are again largely unchanged (expect for increases in R&D where the marginal effects loose significance) and the negative coefficients for the interaction term suggest again diminishing marginal returns.

Third, firm size was alternatively measured using the number of employees in 2018 rather than 2020, addressing concerns that firm size in 2020 may itself be affected by the pandemic (Appendix Table A3). The main coefficients of interest—PhD human capital and digitalization expenditure together with the regional effects remain again largely unchanged in terms of sign, magnitude, and statistical significance. This suggests that the observed relationships are not sensitive to potential endogeneity arising from crisis-induced employment adjustments.

5. Conclusions

This paper contributes to the literature in three main ways. First, it exploits unique survey information on firms' immediate innovation responses directly triggered by the COVID-19 pandemic, allowing for a fine-grained analysis of short-term adaptive and opportunity-driven innovation responses. Second, it provides new evidence on the role of PhD-level human capital and digitalization efforts in fostering innovation resilience during an unprecedented systemic shock. Third, it highlights the importance of regional heterogeneity in the degree of firms' resilience to crises and that the relationship between digitalization effort and adaptive resilience is conditioned by the broader regional environment.

Our findings indicate that regional context conditions not only the intensity but also the mode of innovation resilience under shock. In regions characterised by more developed innovation systems and higher pre-pandemic digital maturity, firms may rely relatively more on external infrastructures, networks, and shared knowledge bases, reducing the incremental impact of additional internal investments during the crisis. Conversely, in less developed regional innovation contexts, digital efforts play a more central role in sustaining innovation during time of crises. In these regions, PhDs may operate as a shock absorber. However, our results also suggest that both human and digital efforts foster innovation resilience, while their effectiveness is subject to diminishing returns in regions where such resources were already abundant prior to the shock.

From a policy perspective, the findings suggest that strengthening the integration of PhD-trained researchers into firms—particularly within R&D and innovation functions could facilitate innovation resilience. This could be achieved through subsidised industry-science collaborations, that lead to higher firm level innovation success as shown, for example, in Mulligan et al, (2022) for Ireland and in Carioli et al., (2026) for Germany. At the same time, facilitating business digitalization can further enhance resilience to future shocks.

Our study is not without limitation. The data do not permit a strict pre-pandemic versus post-pandemic identification strategy. Consequently, we do not claim causal effects. In particular, software and database expenditures recorded for 2020 may partly reflect investments undertaken after the onset of the pandemic. However, the short time horizon and widespread disruptions to labour markets make it unlikely that firms could rapidly recruit new digitally skilled or highly qualified personnel during this period. Consequently, post-March digital investments were more plausibly undertaken by firms that already possessed the relevant digital skills and human capital in-house. In contrast, PhD-level employment reflects a stock of highly specialised human capital that is unlikely to have been substantially altered during the pandemic, given widespread recruitment disruptions. Nevertheless, the results should only be interpreted as capturing firms' capacity to activate and complement existing capabilities under crisis conditions.

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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.

APPENDIX

Table A1: Innovation resilience during COVID-19: number of PhD employees and squared term

	Non-expected innovation activities	COVID-19 related R&D activities	Increase in R&D expenditure due to COVID-19
	(1)	(2)	(3)
PhD employees (number & squared term)	0.001**	0.001***	0.001***
	(0.0005)	(0.0003)	(0.0003)
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***	0.005**
	(0.005)	(0.003)	(0.003)
Madrid	0.010**	0.008***	0.004**
	(0.004)	(0.003)	(0.002)
Basque Country	-0.009*	-0.001	0.005*
	(0.005)	(0.003)	(0.003)
Controls:			
PhD CEOs	0.002	0.003	-0.003
	(0.005)	(0.003)	(0.002)
BIO:	0.021***	0.021***	0.020***
	(0.007)	(0.004)	(0.003)
Size:			
small size	-0.035***	-0.026***	-0.025***
	(0.007)	(0.005)	(0.005)
medium size	-0.034***	-0.023***	-0.026***
	(0.008)	(0.005)	(0.005)
large size	-0.017**	-0.021***	-0.026***
	(0.009)	(0.006)	(0.005)
Inno_exp (millions)	0.002***	0.0001	0.00003
	(0.0005)	(0.0001)	(0.00003)
Patents	0.082***	0.047***	0.020***
	(0.010)	(0.006)	(0.004)
Age (log)	0.003	-0.001	-0.004***
	(0.002)	(0.001)	(0.001)
SOE	0.062***	0.039***	0.023**
	(0.016)	(0.014)	(0.011)
Group	-0.003	0.002	-0.003
	(0.004)	(0.003)	(0.002)
Multinational	0.005	-0.002	-0.001
	(0.005)	(0.003)	(0.003)
Exporter	0.017***	0.011***	0.008***
	(0.003)	(0.002)	(0.001)
Sector fixed effects	Y	Y	Y
Observations	35620	30131	32483
Pseudo R2	0.084	0.194	0.156

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

Table A2: Innovation resilience during COVID-19: *DIGI_invest* amount and squared term

	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)	0.027***	0.018***	0.012***
	(0.006)	(0.003)	(0.003)
DIGI_invest (millions & squared term)	0.004***	0.001***	0.0004
	(0.001)	(0.0003)	(0.0002)
Region:			
Catalonia	0.010***	0.006**	0.003
	(0.004)	(0.002)	(0.002)
Valencia	0.018***	0.016***	0.006**
	(0.005)	(0.003)	(0.002)
Madrid	0.009**	0.008***	0.004**
	(0.004)	(0.003)	(0.002)
Basque Country	-0.007	-0.00003	0.006**
	(0.005)	(0.004)	(0.003)
Controls:			
PhD CEOs	0.003	-0.001	-0.005*
	(0.005)	(0.004)	(0.003)
BIO:	0.016***	0.020***	0.019***
	(0.007)	(0.004)	(0.003)
Size:			
small size	-0.030***	-0.019***	-0.021***
	(0.007)	(0.004)	(0.004)
medium size	-0.025***	-0.013***	-0.018***
	(0.008)	(0.005)	(0.005)
large size	-0.004	-0.008	-0.017***
	(0.009)	(0.006)	(0.005)
Inno_exp (millions)	0.003***	0.0001	0.0001
	(0.0005)	(0.0001)	(0.00005)
Patents	0.092***	0.052***	0.024***
	(0.010)	(0.006)	(0.005)
Age (log)	0.004**	- 0.001	-0.004***
	(0.002)	(0.002)	(0.001)
SOE	0.074***	0.049***	0.033***
	(0.017)	(0.014)	(0.012)
Group	-0.002	0.001	-0.003
	(0.004)	(0.003)	(0.002)
Multinational	0.001	-0.004	-0.002
	(0.005)	(0.003)	(0.003)
Exporter	0.024***	0.014***	0.011***
	(0.003)	(0.002)	(0.002)
Sector fixed effects	Y	Y	Y
Observations	35620	30131	32483
Pseudo R2	0.073	0.184	0.142

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

Table A3: Innovation resilience during COVID-19: with 2018 firm size

	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***	0.015***	0.011***
	(0.006)	(0.003)	(0.003)
DIGI_invest	0.050***	0.018***	0.016***
	(0.003)	(0.002)	(0.002)
Region:			
Catalonia	0.010**	0.005**	0.002
	(0.004)	(0.002)	(0.002)
Valencia	0.016***	0.014***	0.005**
	(0.005)	(0.003)	(0.003)
Madrid	0.011***	0.008***	0.005**
	(0.004)	(0.003)	(0.002)
Basque Country	-0.008*	-0.0003	0.005*
	(0.005)	(0.003)	(0.003)
Controls:			
PhD CEOs	0.001	0.0002	-0.005*
	(0.005)	(0.003)	(0.002)
BIO:	0.015***	0.019***	0.019***
	(0.007)	(0.004)	(0.003)
Size 2018:			
small size	-0.022***	-0.019***	-0.016***
	(0.005)	(0.004)	(0.003)
medium size	-0.023***	-0.015***	-0.015***
	(0.006)	(0.004)	(0.004)
large size	-0.011*	-0.013***	-0.015***
	(0.006)	(0.004)	(0.004)
Inno_exp (millions)	0.003***	0.0001	0.0001*
	(0.0005)	(0.0001)	(0.00004)
Patents	0.079***	0.047***	0.020***
	(0.010)	(0.006)	(0.004)
Age (log)	0.004**	0.001	-0.004***
	(0.002)	(0.002)	(0.001)
SOE	0.065***	0.044***	0.028**
	(0.016)	(0.014)	(0.011)
Group	-0.001	0.002	-0.004*
	(0.004)	(0.003)	(0.002)
Multinational	0.007	-0.002	-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	34162	28894	31143
Pseudo R2	0.084	0.191	0.158

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