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Population Ageing and Educational Digitalisation in Western Europe and Younger Economies

Maria de Lurdes Neves

maria.neves@isg.pt

Instituto Superior de Gestão

Natália Teixeira

Instituto Superior de Gestão

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Population Ageing and Educational Digitalisation in Western Europe and Younger Economies]
[1]Lurdes Neves a, b, c
aInstituto Superior de Gestão – Business Economics School, Lisbon, Portugal.
bCEFAGE - Center for Advanced Studies in Management and Economics, Évora, Portugal
cCIGEST - Management Research Center, Lisbon, Portugal
ORCID: https://orcid.org/0000-0002-1605-6848
R. Prof. Reinaldo dos Santos, Lisbon, Portugal
2]Natália Teixeira a, b, c
aInstituto Superior de Gestão – Business Economics School, Lisbon, Portugal.
bCEFAGE - Center for Advanced Studies in Management and Economics, Évora, Portugal
cCIGEST - Management Research Center, Lisbon, Portugal
ORCID: 0000-0002-8752-6149
Correspondence to: Lurdes Neves, mluneves@gmail.com, maria.neves@isg.pt

Abstract

This study examines the extent to which population ageing influences the capacity of educational systems to digitalise and adopt new technologies, contributing to the emerging literature on the grey digital divide (the digital exclusion experienced by older adults). Focusing on a comparative analysis of 12 countries (six Western European economies characterised by ageing demographic structures and six younger economies) the paper investigates whether demographic composition affects both the speed and effectiveness of digital transformation in education. Drawing on theoretical arguments linking ageing societies to lower technological adaptability, institutional inertia, and competing fiscal pressures, the study also considers the counterargument that more economically developed countries with ageing populations may offset these constraints through stronger financial and institutional capacities. Using panel data for the period 2001-2023, which encompasses both pre- and post-pandemic digital acceleration, the analysis explores the relationship between demographic ageing indicators and measures of educational digitalisation, proxied by internet usage as an indicator of broader digital readiness. The results reveal a non-linear and conditional relationship between population ageing and educational digitalisation. While ageing is positively associated with digitalisation when considered in isolation, this effect is significantly moderated by economic development. In more advanced economies, ageing may act as a constraint on further digital transformation, whereas in less developed contexts the relationship appears less restrictive. Digital infrastructure, measured by broadband access, emerges as a critical determinant of digitalisation, whilst public expenditure on education and research and development show statistically insignificant effects. The findings contribute to the literature on education systems and digital transformation by offering a comparative and conditional perspective on demographic influences, with important implications for policy design in ageing societies. The findings suggest that investments in digital infrastructure and targeted digital inclusion policies play a more significant role in addressing digital inequalities than increases in aggregate education expenditure alone, underscoring the importance of inclusive strategies for achieving equitable digital transformation in ageing societies. Methodologically, the study demonstrates the importance of modelling interaction effects to capture the conditional nature of demographic influences on digital transformation, moving beyond linear interpretations prevalent in earlier research.

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1 Introduction

The digitalisation of education systems has assumed a central role in enabling contemporary economies to adapt to the demands of the digital economy. The integration of digital technologies into education not only transforms pedagogical practices but also shapes human capital formation and long-term innovation capacity (OECD, 2023). However, both the pace and effectiveness of this transformation vary significantly across countries, suggesting the influence of underlying structural factors that merit systematic investigation.

Among these factors, demographic structure emerges as a potentially critical determinant. Western Europe is experiencing an advanced process of population ageing, characterised by an increasing proportion of individuals aged 65 and over. Demographic projections indicate that the proportion of individuals aged 65 and over will continue to increase substantially in OECD countries in the coming decades (OECD, 2025), intensifying concerns about the grey digital divide, and the digital exclusion experienced by older adults (UNESCO, 2025). This phenomenon may influence public policy priorities, investment patterns, and institutional adaptability in education systems. In contrast, countries with younger populations tend to exhibit greater demographic dynamism, which may translate into higher openness to technological innovation and stronger pressure to modernise education systems.

The COVID-19 pandemic served as a critical juncture that accelerated digital transformation in education globally, exposing both opportunities and persistent digital divides (OECD, 2023). Research indicates that 60% of educators adopted digital planning tools during the pandemic, whilst daily usage of digital instructional materials increased from 28% to 52% (EY-Parthenon, 2024). However, this rapid transformation also revealed significant disparities in digital readiness across demographic groups, with older populations facing challenges in adapting to remote and hybrid learning environments.

The literature suggests that population ageing may reduce the adoption of new technologies, although this relationship is not linear and depends on broader economic conditions (Acemoglu & Restrepo, 2017, 2020). Recent evidence from Eurostat (2024) demonstrates substantial age-related gaps in digital competence across Europe: only 25-34% of individuals aged 65-74 possess basic digital skills, compared to 69-71% in the 25-34 age group. Nevertheless, countries with ageing populations are often also more economically developed, providing them with greater financial and institutional capacity to invest in digital infrastructure and advanced education policies (World Bank, 2023). This duality raises important questions about whether ageing acts as a structural constraint on digitalisation or whether it is mitigated (or even offset) by broader socio-economic conditions.

In this context, it becomes particularly important to empirically assess whether, and to what extent, population ageing influences the digitalisation of education systems, as well as their capacity to absorb new technologies. Understanding this relationship is crucial for designing effective policies that promote inclusive digital transformation in ageing societies whilst addressing the specific needs of intergenerational learning and digital literacy development (UNESCO, 2025; OECD, 2024).

Despite growing attention to the digital transformation of education systems, the role of demographic structure (particularly population ageing) remains underexplored in comparative research. Existing studies have largely focused on economic, institutional, and technological determinants of digitalisation (OECD, 2021; UNESCO, 2023), often overlooking how demographic dynamics shape both the demand for and the capacity to adopt digital technologies. This gap is particularly relevant in the context of Western Europe, where ageing populations coexist with high levels of economic development and institutional capacity. Understanding this duality is essential to disentangle whether ageing acts as a structural constraint or whether it is mitigated by broader socio-economic conditions. Moreover, the heterogeneity within older populations (varying significantly by educational attainment, previous professional experience, and age cohort) suggests that the relationship between ageing and digitalisation is likely conditional rather than uniform (Helsper, 2021; van Dijk, 2020).

This study contributes to the literature by providing a comparative panel analysis of ageing and digitalisation across 12 countries with different demographic structures over the period 2001-2023. The empirical results highlight the importance of considering the interaction between demographic and economic factors, showing that the impact of ageing is conditional on the level of development. A comparative perspective is particularly valuable in this context, as it allows for the examination of how similar demographic trends may produce different outcomes depending on levels of economic development, institutional quality, and investment in education. Furthermore, this study contributes methodologically by explicitly modelling interaction effects, allowing for a more nuanced understanding of how demographic and economic factors jointly shape digitalisation outcomes. This reinforces the importance of adopting a conditional and comparative perspective when analysing digital transformation in education systems.

2 Population Ageing and Digitalisation in Education

The relationship between population ageing and digitalisation in education can be interpreted through complementary strands of literature in economics, sociology and education. From a macroeconomic perspective, Acemoglu and Restrepo (2017, 2020) argue that demographic ageing may alter the direction of technological change by increasing incentives for automation in labour-scarce environments, although the diffusion and effective use of new technologies depend on the institutional and human-capital conditions that shape absorptive capacity. This perspective is particularly relevant because it suggests that ageing does not necessarily reduce technological change in a uniform way; rather, it may transform the incentives and constraints through which technologies are adopted across sectors and countries.

At the micro and meso levels, Rogers' diffusion of innovations theory remains a foundational framework for understanding uneven patterns of technological adoption (Rogers, 2003). Rogers (2003) argues that adoption depends not only on the technical characteristics of innovations but also on social-system characteristics, including attitudes to risk, familiarity and perceived usefulness. In this respect, older adults are often less likely to adopt new technologies rapidly, not because of age alone, but because age intersects with prior exposure, confidence, learning opportunities and perceived relevance. This argument is reinforced by research on digital inequalities, which shows that digital inclusion is shaped by a combination of motivational, material, skills-related and usage-

related factors rather than by access alone.

This broader interpretation is consistent with van Dijk's work on the digital divide. Van Dijk (2020) argues that digital inequalities operate across several levels, including access, skills and effective use, and that these dimensions are mutually reinforcing. Helsper (2021) similarly shows that digital inequalities are embedded in wider social inequalities and that socio-economic position, education and life-course trajectories influence the extent to which individuals are able to benefit from digital technologies. Taken together, these perspectives suggest that ageing should be analysed not merely as a biological or demographic condition, but as a structural factor interacting with education, income, prior work experience and institutional support.

In the field of education, digitalisation is increasingly understood as a systemic transformation rather than a purely technical process (OECD, 2023; UNESCO, 2023). OECD analyses describe digital education as an ecosystem involving student information systems, learning management systems, digital assessment platforms, teachers' digital competences, governance arrangements and the broader conditions required to make digital education effective, equitable and trustworthy (OECD, 2023). In parallel, UNESCO's 2023 Global Education Monitoring Report argues that technology affects education through multiple channels, including access and inclusion, quality of teaching and learning, system management, governance and teacher preparation (UNESCO, 2023). This broader perspective is especially relevant for the present study because the dependent variable (internet use) captures the wider digital environment within which education systems operate, rather than a narrow indicator of classroom technology alone. It also helps explain why demographic change may influence educational digitalisation through several interconnected mechanisms, including the composition of the teaching workforce, public policy priorities, investment patterns, institutional capacity and differences in digital readiness across the population (OECD, 2021, 2023).

Within this debate, the concept of the grey digital divide has become particularly relevant (UNESCO Institute for Lifelong Learning, 2025). UNESCO defines the grey digital divide as the digital exclusion experienced by older adults and shows that this exclusion is shaped by barriers such as limited digital skills, accessibility constraints, insufficient age-friendly pedagogies and persistent stereotypes about older learners (UNESCO Institute for Lifelong Learning, 2025). This concept is analytically important because it moves the discussion beyond simple access to technology and towards questions of effective participation, autonomy and inclusion. For the purposes of the present article, the grey digital divide provides a useful conceptual bridge between demographic ageing and educational digitalisation, as it highlights how older individuals and ageing societies may face obstacles not only in accessing digital tools but also in transforming access into meaningful use within lifelong learning systems (UNESCO Institute for Lifelong Learning, 2025; OECD, 2024).

The literature also shows that the grey digital divide is not fixed or inevitable (UNESCO Institute for Lifelong Learning, 2025; OECD, 2024). UNESCO's recent work demonstrates that, with appropriate policy support, pedagogical design and technology environments, older adults can engage meaningfully in the digital world (UNESCO Institute for Lifelong Learning, 2025). Similarly, the OECD argues that policies to strengthen digital skills among older people must account for the specific barriers they face and should not rely on standardised approaches designed for the general population (OECD, 2024). These findings are highly relevant to education policy because they imply that digitalisation strategies must be inclusive by design and cannot depend on infrastructure expansion alone (OECD, 2024; UNESCO, 2023).

Recent empirical evidence reinforces the importance of this argument. Eurostat reports that in 2023 only 55% of people in the European Union aged 16–74 had at least basic overall digital skills (Eurostat, 2024). The same source shows that the gap in basic digital skills between highly educated individuals and those with low or no formal education reached 46 percentage points across the EU and 66 percentage points in Portugal (Eurostat, 2024). Eurostat also reports sharp age-related

disparities, with at least basic digital skills among women falling from 71% in the 25–34 age group to 25% in the 65–74 age group (Eurostat, 2024). These data are particularly relevant for the present study because they suggest that the effects of ageing are mediated by educational attainment and broader social inequalities, rather than reflecting a simple linear age effect (Eurostat, 2024).

The COVID-19 pandemic further intensified the relevance of these issues (UNESCO, 2023; OECD, 2023). The rapid expansion of remote and hybrid learning accelerated educational digitalisation worldwide but also exposed major inequalities in digital readiness and preparedness (UNESCO, 2023). Evidence reported by EY-Parthenon indicates that around 60% of educators using digital planning tools adopted them during the pandemic, while daily use of digital instructional materials increased from 28% before the pandemic to 52% afterwards (EY-Parthenon, 2024). For the present study, this matters because the period under analysis, 2001–2023, captures both gradual pre-pandemic digitalisation and the sharp acceleration associated with the pandemic period.

Taken together, these perspectives suggest that population ageing does not exert a uniform effect on digitalisation. Instead, its impact is conditional upon broader structural factors, particularly economic development and institutional capacity (Acemoglu & Restrepo, 2020; Bloom et al., 2010). The grey digital divide literature reinforces this argument by showing that age-related barriers to digital participation are mediated by education, prior experience and institutional support (UNESCO Institute for Lifelong Learning, 2025; van Dijk, 2020). This highlights the importance of adopting a multidimensional analytical framework that captures both direct and moderating effects, rather than assuming linear demographic determinism.

Based on the theoretical and empirical framework discussed above, the following research questions are proposed:

RQ1. Is population ageing associated with lower levels of educational digitalisation?

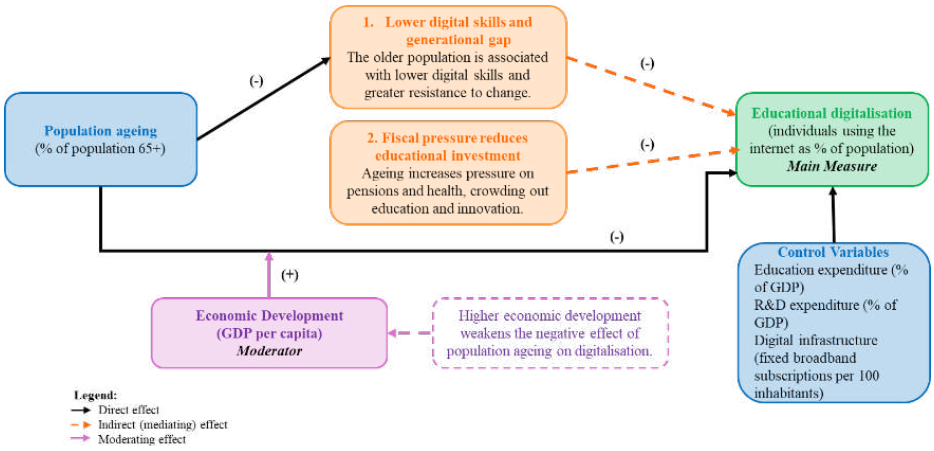
RQ2. To what extent does population ageing affect the capacity of education systems to adopt and absorb digital technologies?

RQ3. Does the level of economic development moderate the relationship between population ageing and educational digitalisation?

RQ4. Are there systematic differences between ageing and younger countries in this relationship?

To address these research questions, Figure 1 presents the conceptual framework guiding the empirical analysis. The framework proposes that population ageing affects the digitalisation of education systems both directly and indirectly. On the one hand, ageing may reduce technological adoption due to lower digital skills and greater resistance to change (Rogers, 2003; Eurostat, 2024). On the other hand, it may increase fiscal pressures, limiting public investment in education and innovation (Bloom et al., 2010). However, these effects are expected to be moderated by the level of economic development, as countries with higher GDP per capita may offset demographic constraints through stronger institutional capacity and superior digital infrastructure (OECD, 2023). Control variables such as education expenditure, R&D investment and broadband access further influence the level of digitalisation.

Figure 1. Conceptual framework: Population ageing and digitalisation of education systems



Source: Own elaboration

3 Methodology

3.1 Data and Sample

This study employs a panel data approach covering the period 2001–2023, enabling the analysis of the evolution of educational digitalisation across countries with distinct demographic structures over time. The sample comprises 12 countries divided into two groups based on demographic characteristics: six Western European economies characterised by advanced population ageing (Italy, Portugal, Germany, Spain, Greece and Finland) and six younger economies (India, Indonesia, Brazil, Turkey, Vietnam and Colombia).

These countries were selected to maximise variation in both demographic structure and economic development whilst ensuring sufficient data availability across the 23-year period. The Western European group represents mature economies experiencing pronounced demographic ageing, with the share of population aged 65 and above ranging from approximately 15% to 24% in 2023. The younger economies group includes middle-income countries with substantially younger age structures, where the elderly population share ranges from approximately 4.5% to 11%. This comparative design allows for the examination of whether demographic effects differ systematically across development levels and demographic contexts.

Data are obtained primarily from the World Bank's World Development Indicators database, ensuring consistency and comparability across countries and over time (World Bank, 2023). Additional data from UNESCO are used for descriptive purposes and robustness checks. The panel is unbalanced due to occasional missing observations for specific variables in certain country-years, particularly for R&D expenditure in some developing economies. The final analytical sample comprises 192 country-year observations across the 12 countries.

3.2 Variables and Measurement

The dependent variable is educational digitalisation, operationalised as the percentage of individuals using the Internet (Internet users, % of population). Whilst this measure does not capture classroom-level digitalisation directly, it provides a reliable cross-country indicator of the broader digital environment within which education systems operate and reflects both access to digital technologies and digital readiness (OECD, 2023; UNESCO, 2023). This proxy is particularly appropriate for comparative analysis because it is consistently measured across countries and correlates strongly with more specific educational technology indicators where available.

Population ageing, the key independent variable, is measured primarily by the share of the population aged 65 and above. This indicator is widely used in demographic research and directly

captures the intensity of population ageing (United Nations, 2019). Alternative specifications employ the old-age dependency ratio (population aged 65+/population aged 15-64) to test robustness and assess sensitivity to alternative demographic measures.

Economic development is captured by GDP per capita measured in purchasing power parity (PPP, constant 2017 international dollars). The logarithmic transformation of GDP per capita is used in all regression specifications to improve interpretability, reduce scale effects and allow coefficients to be interpreted as elasticities (Wooldridge, 2010).

To test the moderating role of economic development (the central hypothesis of this study) an interaction term between population ageing and log GDP per capita is included. This specification follows standard practice in moderation analysis, where the coefficient on the interaction term captures how the effect of the focal predictor varies across levels of the moderator (Aiken & West, 1991; Hayes, 2017).

The model includes three control variables capturing structural and institutional factors affecting digitalisation. Public expenditure on education (as a percentage of GDP) controls for policy effort and investment priorities. Research and development expenditure (as a percentage of GDP) captures innovation capacity and technological orientation. Digital infrastructure is measured by fixed broadband subscriptions per 100 inhabitants, representing the availability of high-speed connectivity necessary for effective digital education (World Bank, 2023).

3.3 Empirical Strategy

The empirical strategy relies on fixed effects panel regressions, which control for unobserved time-invariant country-specific heterogeneity (Baltagi, 2021; Wooldridge, 2010). Fixed effects are preferred over random effects for two main reasons. First, the theoretical framework suggests that unobserved country characteristics (such as institutional quality, cultural attitudes towards technology, historical education trajectories and governance capacity) are likely correlated with both demographic structure and digitalisation outcomes. Under such conditions, random effects would produce inconsistent estimates, whilst fixed effects remain consistent (Wooldridge, 2010). Second, fixed effects are preferred on econometric grounds, as unobserved country-specific characteristics are likely to be correlated with the explanatory variables included in the model.

Robust standard errors are employed throughout to account for heteroskedasticity, a common feature of cross-country panel data arising from differing variances across countries (Stock & Watson, 2008). All estimations are conducted using the R statistical software, specifically the plm package for panel data econometrics (R Core Team, 2024).

The baseline regression model is specified as follows:

$$\text{Internet}_{it} = \beta_0 + \beta_1 \text{PopulationAgeing}_{it} + \beta_2 ln(\text{GDPpcit}) + \beta_3 (\text{PopulationAgeing}_{it} \times ln(\text{GDPpcit}) + \beta_4 \text{EducationExpe}$$

where i indexes countries, t indexes years, α_i represents country fixed effects capturing all time-invariant country-specific characteristics, and ε_{it} is the idiosyncratic error term. The parameter of primary interest is β_3, which captures the moderating effect of economic development on the relationship between population ageing and digitalisation. A negative coefficient would indicate that the positive association between ageing and digitalisation diminishes (or becomes negative) as countries become more economically developed.

3.4 Robustness Checks

To assess the robustness of the main findings, alternative model specifications are estimated. First, the old-age dependency ratio is used as an alternative measure of population ageing to verify that results are not sensitive to the specific demographic indicator employed. Second, sequential exclusion of control variables is performed to test for potential specification sensitivity. These

robustness analyses allow for a more comprehensive assessment of the stability and reliability of the main empirical findings.

4 Empirical Analysis

4.1 Descriptive Statistics

Table 1 presents the descriptive statistics for the main variables used in the analysis. The sample exhibits substantial heterogeneity across countries and over time, reflecting the diversity of the 12 economies included in the study.

Table 1. Descriptive statistics

Variable	Mean	Std. Dev.	Min	Max
Internet	50.291	28.366	0.660	95.446
Population ageing (65+)	13.153	6.837	4.461	24.219
GDP per capita (log)	10.036	0.798	8.067	11.062
Educ_exp	4.426	1.265	0.864	7.172
R&D	1.309	0.913	0.048	3.734
Broadband	15.546	13.494	0.001	45.381

Notes: The table reports mean, standard deviation, minimum and maximum values for 192 country-year observations across 12 countries for the period 2001–2023. The number of observations varies across variables due to missing data.

Source: Own elaboration based on World Bank data.

The average level of Internet usage stands at approximately 50%, but the range from less than 1% to over 95% reveals substantial cross-country variation in digital readiness. Population ageing also displays considerable heterogeneity, with the share of individuals aged 65 and over ranging from 4.5% to over 24%, confirming the marked demographic contrast between the Western European and younger economy groups. Broadband subscriptions similarly exhibit high variability (standard deviation of 13.5 per 100 inhabitants), suggesting uneven digital infrastructure development that is likely to influence educational digitalisation outcomes. These patterns support the relevance of a comparative empirical approach that accounts for both demographic and economic diversity.

4.2 Correlation Analysis

Table 2 reports Pearson correlation coefficients between the main variables, providing preliminary insights into the bivariate relationships in the data.

Table 2. Correlation matrix

	Internet	Population ageing (65+)	GDP per capita (log)	Educ_exp	R&D	Broadband
Internet	1	.	.	.	.	.
Population ageing (65+)	.632	1	.	.	.	.
GDP per capita (log)	.698	.880	1	.	.	.
Educ_exp	.458	.321	.455	1	.	.
R&D	.673	.605	.673	.647	1	.

	Internet	Population ageing (65+)	GDP per capita (log)	Educ_exp	R&D	Broadband
Broadband	.897	.786	.712	.364	.670	1

Source: Own elaboration based on World Bank data.

Several noteworthy patterns emerge from the correlation matrix. Internet usage is strongly correlated with both broadband access (r = 0.897) and GDP per capita (r = 0.698), consistent with prior research emphasising the centrality of infrastructure and economic resources in digital transformation (OECD, 2023). Population ageing is positively correlated with digitalisation (r = 0.632), which may appear counterintuitive given theoretical expectations about older populations and technology adoption (Rogers, 2003). However, this positive association likely reflects the fact that ageing is concentrated in economically advanced countries with greater overall digital capacity.

Crucially, the high correlation between ageing and GDP per capita (r = 0.880) raises potential concerns about multicollinearity. However, this collinearity is substantively meaningful rather than purely statistical, as it reflects the real-world association between demographic and economic development (Bloom et al., 2010). The inclusion of an interaction term between these variables is therefore both theoretically justified and methodologically appropriate, as it allows the effect of ageing to vary across levels of development whilst mitigating multicollinearity concerns (Aiken & West, 1991).

4.3 Main Regression Results

Table 3 presents the fixed effects regression results for the baseline specification, which includes the interaction between population ageing and economic development alongside control variables.

Table 3. Fixed effects regression results

	Dependent variable: **Internet**
Population ageing (65+)	47.650***
	(11.467)
GDP per capita (log)	54.102***
	(11.254)
Ageing × GDP per capita	-4.262***
	(1.022)
Educ_exp	0.594
	(2.053)
R&D	6.091
	(5.408)
Broadband	1.239***
	(0.360)
Observations	192
R^2	0.923
Adjusted R^2	0.915
F Statistic	345.203*** (df = 6; 174)

Notes: Robust standard errors in parentheses. Country fixed effects included. * p < 0.1, ** p < 0.05, *** p < 0.01.

Source: Own elaboration based on World Bank data.

The results provide consistent evidence of a conditional relationship between population ageing and educational digitalisation. The coefficient on population ageing is positive and statistically significant at the 1% level (β = 47.650, p < 0.01), suggesting that, on average, countries with higher shares of elderly populations exhibit higher levels of Internet usage. However, this finding must be interpreted in conjunction with the interaction term, as it reflects the effect of ageing when GDP per capita is at its mean value.

The interaction term between ageing and GDP per capita is negative and highly significant (β = -4.262, p < 0.01), indicating that the positive association between ageing and digitalisation diminishes as countries become more economically developed. This finding directly addresses *RQ3* and provides empirical support for the hypothesis that economic development moderates the relationship between demographic ageing and digitalisation. In more advanced economies, ageing may constrain further digital transformation, potentially due to fiscal pressures, institutional rigidity or shifting policy priorities (Bloom et al., 2010), whilst in less developed contexts the relationship appears less restrictive.

Among the control variables, broadband access emerges as a statistically significant determinant of digitalisation, with a coefficient of 1.239 (p < 0.01). This result aligns with the OECD (2023) emphasis on digital infrastructure as a foundational element of educational technology ecosystems. In contrast, neither education expenditure nor R&D expenditure achieves statistical significance, suggesting that structural and technological factors (particularly connectivity infrastructure) may be more immediately relevant than aggregate public spending for explaining cross-country digitalisation patterns.

The model exhibits high explanatory power (R^2 = 0.923), indicating that the fixed effects specification with demographic, economic and infrastructural variables accounts for the majority of observed variation in Internet usage across countries and over time.

4.4 Robustness Checks

To assess the sensitivity of the main findings to alternative specifications, Table 4 presents results using the old-age dependency ratio as an alternative measure of population ageing.

Table 4. Robustness checks

	Dependent variable:	
	Internet	
	(1)	**(2)**
Population ageing (65+)	47.650***	
	(11.467)	
Old-age dependency ratio		0.321
		(0.602)
GDP per capita (log)	54.102***	45.385***
	(11.254)	(10.287)
Ageing × GDP per capita	-4.262***	
	(1.022)	
Educ_exp	0.594	2.759
	(2.053)	(2.781)
R&D	6.091	6.734
	(5.408)	(7.799)
Broadband	1.239***	1.480***
	(0.360)	(0.305)

	Dependent variable: Internet	
	(1)	(2)
Observations	192	192
R^2	0.923	0.880
Adjusted R^2	0.915	0.869
F Statistic	345.203*** (df = 6; 174)	255.909*** (df = 5; 175)

Notes: Robust standard errors are reported in parentheses. * p < 0.1, ** p < 0.05, *** p < 0.01.

Source: Own elaboration based on World Bank data.

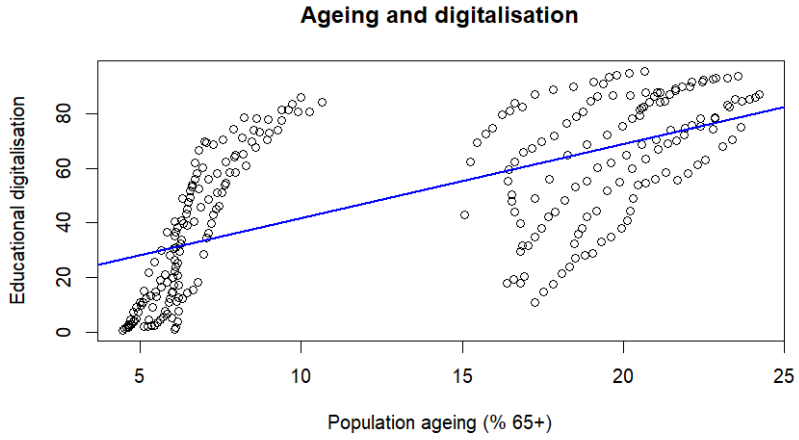
The robustness analysis reveals that results are sensitive to the choice of demographic indicator. When the old-age dependency ratio replaces the population share aged 65+, the coefficient becomes statistically insignificant ($\beta = 0.321$, $p > 0.10$). This suggests that the specific operationalisation of demographic ageing matters for empirical findings, a result consistent with broader methodological literature on demographic measurement (United Nations, 2019).

Nevertheless, the overall pattern remains qualitatively consistent: GDP per capita retains its strong positive effect ($\beta = 45.385$, $p < 0.01$), and broadband infrastructure continues to emerge as a significant determinant ($\beta = 1.480$, $p < 0.01$). This reinforces the conclusion that, whilst demographic ageing plays a role, its impact is complex, conditional and mediated by broader structural conditions, particularly economic development and digital infrastructure.

4.5 Graphical Analysis and Marginal Effects

Figure 2 illustrates the bivariate relationship between population ageing and educational digitalisation. A positive association can be observed, although the dispersion of observations suggests that ageing alone does not fully explain cross-country variation in digitalisation. This visual pattern is consistent with the positive correlation reported in Table 2 and indicates that countries with older populations tend, on average, to display higher levels of Internet use. However, the figure also suggests that this relationship may be influenced by other structural factors, particularly economic development and digital infrastructure.

Figure 2. Relationship between ageing and digitalisation

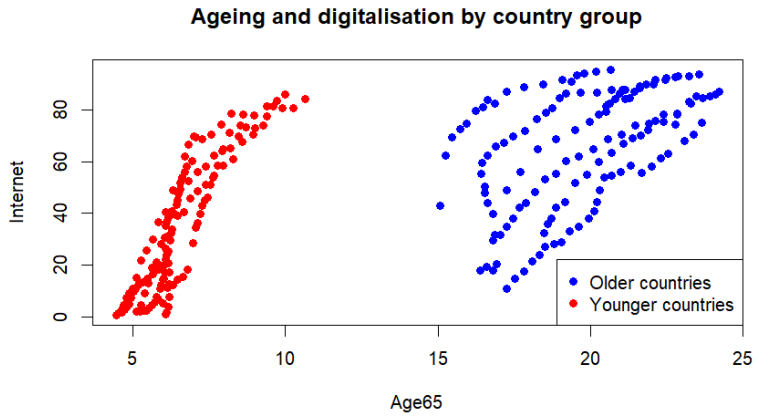


Source: Own elaboration based on World Bank data.

Figure 3 extends this descriptive analysis by comparing ageing and digitalisation across the two country groups included in the sample. Western European countries tend to cluster at relatively

high levels of both population ageing and digitalisation, whereas younger economies exhibit lower levels of ageing and greater variation in digital outcomes. This distinction is important because it suggests that the positive bivariate association observed in Figure 2 may partly reflect differences in development levels between the two groups rather than a direct positive effect of ageing itself.

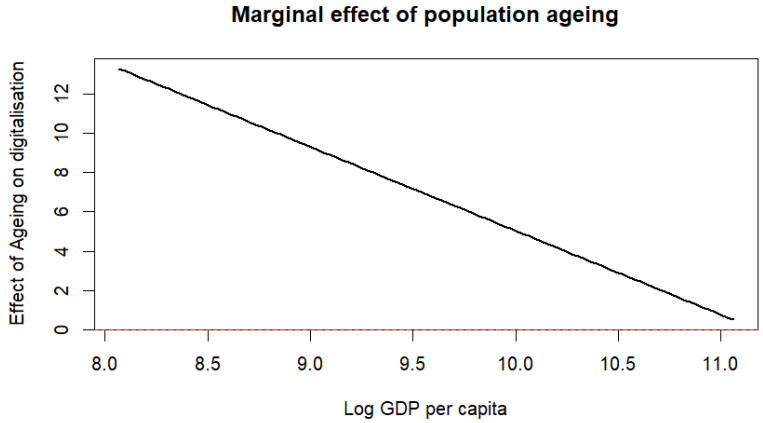
Figure 3. Ageing and digitalisation by country group



Source: Own elaboration based on World Bank data.

Figure 4 provides a more precise interpretation of this relationship by presenting the marginal effect of population ageing across different levels of economic development. In line with the regression results reported in Table 3, the marginal effect of ageing declines as GDP per capita increases, eventually becoming negative at higher income levels. This pattern confirms the presence of a moderating effect and supports the argument that the relationship between ageing and educational digitalisation is conditional rather than linear.

Figure 4. Marginal effect of population ageing



Source: Own elaboration based on World Bank data.

Taken together, the three figures complement the regression analysis by showing that the association between ageing and digitalisation changes once broader structural conditions are taken into account. While the descriptive evidence initially suggests a positive relationship, the marginal effects analysis demonstrates that this pattern is contingent on the level of economic development. The graphical evidence therefore reinforces the central conclusion of the study: population ageing is not inherently associated with lower or higher levels of educational digitalisation; rather, its effect depends on the economic and institutional context in which it occurs.

5 Conclusion

This study examined the relationship between population ageing and the digitalisation of education systems, with a particular focus on how this relationship varies across countries with different demographic and economic structures. Using panel data covering 12 countries over the period 2001–2023, the analysis provides empirical evidence of a non-linear and conditional relationship between demographic ageing and educational digitalisation.

The findings address the four research questions proposed at the outset. Regarding *RQ1*, the results show that population ageing is positively associated with digitalisation when considered in isolation, suggesting that ageing societies are not inherently less digitalised. However, this bivariate pattern masks a more complex underlying relationship. In response to *RQ2* and *RQ3*, the analysis demonstrates that the capacity of education systems to adopt and absorb digital technologies depends critically on the interaction between demographic structure and economic development. The negative and statistically significant interaction term between ageing and GDP per capita indicates that the positive association between ageing and digitalisation diminishes as countries become more economically developed, and may even turn negative in high-income contexts.

These findings provide a direct answer to *RQ4* by showing that there are indeed systematic differences between ageing and younger economies. Whilst ageing is associated with higher levels of digitalisation in less developed contexts (possibly reflecting the broader correlation between demographic transition and economic development) it may act as a constraint in more advanced economies, potentially due to institutional rigidity, shifting public expenditure priorities, or reduced adaptability in older populations (Bloom et al., 2010; Rogers, 2003).

The analysis also reveals the central role of digital infrastructure in shaping educational digitalisation outcomes. Broadband access emerges as the most consistent and statistically significant determinant across all model specifications, reinforcing the OECD's (2023) emphasis on connectivity as a foundational element of digital education ecosystems. In contrast, aggregate measures of public spending on education and R&D do not achieve statistical significance, suggesting that the quality and strategic focus of investment may matter more than expenditure levels alone.

Methodologically, the study highlights the importance of explicitly modelling interaction effects when analysing demographic influences on digital transformation. The conditional relationship identified here would have been obscured by a linear specification, underscoring the value of adopting a more nuanced empirical approach (Aiken & West, 1991). The robustness analysis further demonstrates that the specific operationalisation of demographic ageing matters, as results are sensitive to the choice between the share of population aged 65+ and the old-age dependency ratio. This finding has important implications for future empirical research on ageing and technological change.

Overall, this study contributes to the literature on education systems and digital transformation by offering a comparative and conditional perspective on the role of population ageing. It moves beyond linear interpretations and demonstrates that the implications of demographic change depend critically on the broader structural context in which they occur. The findings challenge simplistic narratives about ageing as either a barrier to or an enabler of digital transformation, showing instead that its effects are mediated by economic development, institutional capacity and digital infrastructure.

These results carry implications for both research and policy. For researchers, the study reinforces the need to account for heterogeneity and conditionality when examining demographic effects on technological adoption. For policymakers, the findings suggest that digital infrastructure investment and context-sensitive strategies are likely to be more effective than uniform approaches to educational digitalisation.

6 Policy Implications

The findings of this study carry important implications for education policy, particularly in the context of demographic change and digital transformation. The results demonstrate that population ageing does not exert uniform effects on educational digitalisation, and that policy responses must therefore be tailored to countries' specific demographic and economic circumstances.

For advanced ageing economies, the results suggest that policymakers should pay particular attention to potential constraints associated with demographic transition. The negative interaction between ageing and economic development indicates that, in high-income contexts, ageing may limit further digital transformation, potentially due to institutional rigidity, competing fiscal pressures or reduced adaptability in older populations (Bloom et al., 2010). To counteract these effects, policies should focus on three key areas. First, ensuring sustained investment in digital infrastructure, particularly broadband connectivity, which emerges as the most consistent determinant of digitalisation across all specifications. Second, maintaining institutional flexibility and innovation capacity within education systems, avoiding the risk that demographic pressures lead to conservative policy orientations. Third, designing inclusive digitalisation strategies informed by the grey digital divide literature, which emphasises the importance of supporting older educators and learners in acquiring and using digital skills (UNESCO Institute for Lifelong Learning, 2025; OECD, 2024).

For younger and less developed economies, the findings suggest a different set of priorities. Whilst these countries do not face the same demographic constraints as advanced ageing societies, they encounter significant challenges related to digital access, infrastructure quality and skill formation. In these contexts, policies should prioritise expanding broadband connectivity, strengthening digital competences across the population, and improving the overall quality and governance of educational systems (UNESCO, 2023). The positive association between ageing and digitalisation observed in less developed contexts likely reflects the broader process of economic and demographic transition, suggesting that investments in education and digital infrastructure can simultaneously support both economic development and technological adoption.

Across all contexts, the central role of digital infrastructure underscores the need for sustained public and private investment in connectivity. The strong and consistent effect of broadband access across all model specifications confirms that infrastructure availability is a necessary (though not sufficient) condition for educational digitalisation (OECD, 2023). Policies that focus solely on expanding access without addressing pedagogical innovation, teacher training and institutional capacity are unlikely to achieve meaningful digital transformation.

The findings also highlight the limitations of aggregate spending measures. The lack of statistical significance for education expenditure and R&D investment suggests that the quality, targeting and strategic orientation of investment may matter more than total expenditure levels. This implies that policy effectiveness depends not only on resource availability but also on governance arrangements, implementation capacity and alignment between digital strategies and broader education objectives.

Finally, the conditional nature of the relationship between ageing and digitalisation reinforces the need for context-sensitive policy design. A one-size-fits-all approach is unlikely to be effective, as the implications of demographic change depend critically on economic development, institutional quality and digital readiness. Policymakers should therefore adopt integrated frameworks that simultaneously address demographic structure, economic conditions and technological capacity, recognising that these factors interact in complex and non-linear ways.

7 Limitations and Future Research

This study is subject to several limitations that should be acknowledged when interpreting the results. First, the dependent variable used in the empirical analysis (Internet use as a percentage of the population) captures the broader digital environment within which education systems operate, but it does not directly measure the quality, intensity or pedagogical effectiveness of digitalisation within schools, universities or other educational institutions. Although this proxy is suitable for comparative cross-country analysis, it cannot fully capture differences in classroom integration, teacher preparedness, digital pedagogy or institutional uses of technology.

Second, the analysis is constrained by data availability. While the use of internationally comparable indicators from the World Bank allows consistency across countries and over time, it limits the inclusion of more specific variables related to educational digital transformation, particularly institutional-level indicators and comparable measures of digital skills within education systems. The relatively small sample of countries, divided into two contrasting groups, is analytically useful for comparative purposes, but it also limits the generalisability of the findings beyond the specific cases examined in this study.

Third, the results indicate that the relationship between ageing and digitalisation is sensitive to the way demographic structure is operationalised. The robustness analysis shows that replacing the share of population aged 65 and over with the old-age dependency ratio changes the statistical significance of the ageing variable, suggesting that empirical conclusions may vary according to the demographic indicator selected. This underlines the importance of conceptual and methodological caution when interpreting the effects of population ageing.

A further limitation concerns the scope of the explanatory framework. Although the model includes relevant structural controls such as GDP per capita, education expenditure, R&D expenditure and broadband access, other potentially important factors are not explicitly captured, including institutional quality, digital governance, teacher training, cultural attitudes towards technology and policy implementation capacity. These omitted dimensions may help explain part of the cross-country variation in digitalisation outcomes and deserve greater attention in future work.

Future research could address these limitations in several ways. First, it would be valuable to employ more granular indicators of educational digitalisation, including school-level or system-level measures of ICT integration, digital pedagogy, teacher digital competences and student outcomes. Second, future studies could expand the country sample or examine regional panels in order to test whether the conditional relationship identified here holds across different institutional and developmental contexts. Third, further research could incorporate institutional and governance variables more explicitly, allowing a deeper analysis of how demographic structure interacts with policy capacity and educational systems.

In addition, future work could explore alternative empirical strategies, including non-linear models, dynamic panel specifications and more disaggregated demographic indicators. Such approaches would help determine whether the patterns identified in this study remain robust under different modelling assumptions and whether the relationship between ageing and educational digitalisation changes over time or across institutional settings. In this sense, the present article should be seen as a starting point for a broader research agenda on the interaction between demographic change and digital transformation in education.

Data Availability Statement

All data generated or analysed during this study are included in this published article and are publicly available from the World Bank World Development Indicators database and UNESCO

databases.

Dataset sources:

- World Bank World Development Indicators Database: `https://databank.worldbank.org/source/world-development-indicators`
- UNESCO Institute for Statistics (UIS): `https://uis.unesco.org/`

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