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Original Article

Digital Readiness and Public Education Expenditure in the European Union: Evidence from Panel Data

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Abstract

Digital transformation has become a strategic priority across the European Union, yet evidence on its relationship with public education investment remains limited. This study examines the association between digital readiness and public education expenditure in 26 EU countries from 2015 to 2022. We construct a composite Digital Readiness Index (DRI) from internet use and the share of information and communication technology specialists in total employment. The analysis uses pooled Ordinary Least Squares, Random Effects, Country Fixed Effects, and Two-Way Fixed Effects models, with country-clustered HC1 standard errors for the main inference. In the preferred Two-Way Fixed Effects specification, the DRI is positively associated with public education expenditure ($\beta = 2.056$, SE = 0.903, $p = 0.024$), implying that a 0.10-point increase in the DRI is associated with approximately 0.21 percentage points higher education expenditure as a share of gross domestic product. The positive association persists across several sensitivity analyses, although its statistical strength weakens under more conservative inference, additional fiscal controls, and an alternative expenditure measure. The findings support a positive conditional association between digital readiness and public education expenditure but do not establish causality.

Categories: Social systems (economies, governments, industry), Digital business, Sustainable Economic Development

Keywords: digital readiness, education expenditure, internet use, european union, panel data

JEL Classifications: O52, H52, I22, C23, O33

Introduction

Digital transformation has become a defining feature of contemporary economic and social development. Across Europe, digital technologies are increasingly associated with productivity, innovation, human capital formation, and long-term competitiveness (Romer, 1990) (Castells, 2010) (Baller et al., 2016). The European Union (EU) has placed digitalization at the center of its policy agenda through initiatives such as the Digital Education Action Plan and the Digital Decade framework. These initiatives emphasize digital skills, connectivity, and educational institutions' digital capacity (European Commission, 2024a, 2024b).

Public expenditure on education is a central instrument for investment in human capital and long-term economic development (Becker, 1993) (Hanushek and Woessmann, 2020) (Psacharopoulos and Patrinos, 2018). Education systems must increasingly respond to demands related to digital literacy, technological competencies, lifelong learning, and workforce adaptation (UNESCO, 2023) (OECD, 2021) (World Bank, 2018). Meeting these demands may require investment in infrastructure, teacher training, and digital learning resources. Substantial differences remain across European countries in both the level and effectiveness of education spending (OECD, 2024).

The growing integration of digital technologies into education has generated considerable academic interest. Previous studies have examined digital infrastructure, internet access, educational technologies, and digital learning environments in relation to educational outcomes and institutional performance (Bond et al., 2021) (Gil-Flores et al., 2017). Evidence suggests that digital technologies can improve educational opportunities when supported by appropriate infrastructure, teacher training, governance, and institutional capacity (Bond et al., 2021) (Van Laar et al., 2019) (UNESCO, 2023).

Less attention has been devoted to the relationship between digital readiness and public education expenditure. Existing research largely focuses on the effects of digital technologies on educational outcomes or on the determinants of digital transformation itself (Gil-Flores et al., 2017) (Van Laar et al., 2019). It remains unclear whether higher levels of digital readiness are associated with greater public resource allocation to education. This gap is particularly relevant in the EU, where digital transformation and educational modernization are closely linked policy priorities (Czernich et al., 2011) (European Commission, 2024b) (UNESCO, 2023).

From an economic and public-finance perspective, the relationship between digital readiness and education expenditure may operate through several interconnected channels. Greater digital readiness may coincide with increased demand for human capital, digital skills, educational infrastructure, and workforce adaptability. Broader digital diffusion may also generate additional requirements for digital infrastructure, learning technologies, and teacher training within education systems. Governments allocate education resources within broader fiscal constraints and competing expenditure priorities. Fiscal capacity, demographic pressures, and national and EU-level policy frameworks may therefore shape how governments respond to the demands associated with digital transformation. These channels provide a conceptual basis for expecting a positive association between digital readiness and public education expenditure. The empirical analysis identifies this association rather than the individual causal mechanisms through which it may arise.

This study examines the relationship between digital readiness and public education expenditure in EU countries during 2015-2022. Public education expenditure is defined as public expenditure on education from pre-primary to tertiary education, expressed as a percentage of gross domestic product (GDP). The study constructs a Digital Readiness Index (DRI) based on internet use and the share of ICT specialists, estimates the relationship using alternative panel-data models, and evaluates the robustness of the findings. The study contributes to the literature by connecting two areas often examined separately - digital transformation and public education financing - and by examining their relationship within the broader context of fiscal constraints and government expenditure priorities. Based on this rationale, the study tests the following hypothesis:

H1: Higher levels of digital readiness are positively associated with public education expenditure in EU countries.

Literature review

Digitalization has become a central component of educational modernization strategies worldwide (Castells, 2010) (OECD, 2021). Recent studies emphasize that digital technologies can improve access to educational resources, support innovative teaching methods, and strengthen learning opportunities when accompanied by appropriate institutional and policy frameworks (Bond et al., 2021) (UNESCO, 2023). The effects of digital technologies are often context-dependent and influenced by infrastructure quality, governance capacity, and investment levels (Selwyn, 2021) (Van Laar et al., 2019). The European Commission's DigCompEdu framework emphasizes that the educational value of digital technologies depends not only on their availability but also on how they are integrated into teaching and learning practices and supported by appropriate institutional conditions (Redecker and Punie, 2017).

The growing importance of digital readiness has also attracted considerable attention in European policy discussions (OECD, 2021) (European Commission, 2024a). The EU identifies internet connectivity, digital skills, and the availability of ICT specialists as key pillars of the Digital Decade strategy (European Commission, 2024a). Recent assessments indicate that progress toward digital targets remains uneven across member states, while shortages of digitally skilled workers remain a significant challenge (European Commission, 2024b) (European Investment Bank, 2024a). EU institutions increasingly emphasize investment in digital education, digital skills development, and technological capacity building as prerequisites for long-term competitiveness and social inclusion (European Commission, 2024a). Existing empirical research has largely focused on the relationship between digitalization and educational outcomes rather than on the

determinants of education financing (Gil-Flores et al., 2017) (Bond et al., 2021). Recent evidence suggests that digital capital, including digital competencies and ICT-related resources, is positively associated with educational performance and student achievement (Van Laar et al., 2019) (Fraillon et al., 2020). Studies on school digitalization highlight the importance of leadership, infrastructure, and institutional support in enabling successful digital transformation in education systems (Petko et al., 2018) (Selwyn, 2021). The literature provides limited evidence on whether countries with higher levels of digital readiness allocate more public resources to education.

From a policy perspective, digital transformation may influence public education expenditure through several channels (Becker, 1993) (Romer, 1990). Expanding internet access, strengthening digital infrastructure, promoting digital literacy, and supporting teacher training require sustained public investment (Czernich et al., 2011) (European Commission, 2024a) (UNESCO, 2023). Recent European policy recommendations explicitly recognize that successful digital education depends on adequate financial resources and long-term institutional commitment (European Commission, 2024a). As digital technologies become increasingly integrated into educational systems, governments may face growing pressure to allocate additional resources to support digital inclusion and human capital development (OECD, 2024) (Psacharopoulos and Patrinos, 2018). Despite these developments, empirical evidence linking digital readiness to public education expenditure remains scarce, particularly in a comparative European context. This study addresses this gap by examining whether higher levels of digital readiness are associated with higher public education expenditure across EU member states.

From a public-finance perspective, this study examines how limited fiscal resources are allocated across competing policy priorities. Public education expenditure reflects not only educational needs but also broader budget constraints, demographic pressures, fiscal capacity, and government spending priorities. Digital transformation may interact with these considerations by creating new demands for skills, infrastructure, and institutional adaptation, while governments remain constrained by their overall fiscal environment. This study positions digital readiness as one potential correlate of education expenditure within a broader public-finance setting rather than as an isolated determinant of government spending. This perspective also motivates the additional sensitivity analysis controlling for school-age population and total general government expenditure.

Research Method

Methodology

Data and Variables

This study uses an unbalanced panel dataset covering EU member states from 2015 to 2022. Data were obtained from Eurostat and the World Bank's World Development Indicators (WDI) database. The dependent variable is public education expenditure as a percentage of GDP. Digital readiness is measured through a composite index constructed from internet use and the share of information and communication technology (ICT) specialists in total employment. The resulting DRI should be interpreted as a parsimonious measure capturing broad digital diffusion and specialized ICT human capital rather than as a comprehensive measure of all dimensions of digital transformation.

The initial dataset comprised 216 potential country-year observations for 27 EU member states from 2015 to 2022. Public education expenditure was unavailable for 20 observations: Denmark in 2015; Estonia in all years from 2015 to 2022; Greece in 2016, 2020, and 2021; Croatia in 2015; and Ireland from 2016 to 2022. One additional observation, France in 2020, had a missing value for internet use and consequently for the constructed DRI. The missing education-expenditure observations and the missing DRI observation did not overlap. The remaining observations had complete control variables. Restricting the analysis to complete cases for the dependent variable, DRI, and all baseline controls therefore reduced the estimation sample from 216 to 195 country-year observations. We excluded Estonia because public education expenditure was unavailable for the entire study period. The final unbalanced regression panel consequently comprises 26 EU member states and 195 observations.

Sample-Reconciliation Step	Observations
Initial dataset (27 countries × 8 years)	216
Missing education expenditure	−20
Remaining observations	196
Missing DRI due to missing internet use	−1
Missing control variables among remaining observations	0
Final estimation sample	195

TABLE 1: Reconciliation of the Analytical Sample

Note: The 20 missing education-expenditure observations and the single missing DRI observation do not overlap. Estonia has no education-expenditure observations during 2015–2022 and is therefore absent from the final estimation sample. DRI, Digital Readiness Index. Source: Author's calculations

Table *1* reconciles the analytical sample and documents the exclusion of observations with missing data. Starting with 216 potential country-year observations, we excluded 20 observations with missing public education expenditure data and one additional observation with missing information required to construct the DRI. The final estimation sample comprises 195 country-year observations across 26 European Union member states.

We extracted data for 2015-2022 and harmonized them using country and year identifiers. We obtained public education expenditure from the Eurostat dataset educ_uoe_fine06, internet use from isoc_ci_ifp_iu, and ICT specialist employment from isoc_sks_itspt. We obtained GDP per capita, unemployment, and inflation from the WDIs. We merged the country-year series using harmonized country and year identifiers, then restricted the analytical sample to observations with complete information on public education expenditure, the DRI, and all baseline control variables. Table *2* reports the definitions, measurements, and data sources of the variables used in the baseline analysis. The analytical datasets, variable documentation, and R code are publicly available through Zenodo (Meçaj, 2026).

Variable	Definition	Measurement	Source
Education Expenditure	Public expenditure on education from pre-primary to tertiary education	% of GDP	(Eurostat, 2026a)
Digital Readiness Index (DRI)	Composite indicator of digital development	Index (0–1) constructed from standardized indicators	Authors' calculations based on Eurostat
Internet Use	Individuals regularly using the internet	% of individuals	(Eurostat, 2026b)
ICT Specialists	ICT specialists in total employment	% of employment	(Eurostat, 2026c)

GDP per Capita	Economic development level	Natural logarithm of GDP per capita (constant prices)	(World Development Indicators, 2015a)
Unemployment	Labor market conditions	% of total labor force	(World Development Indicators, 2015b)
Inflation	Macroeconomic stability	Annual CPI inflation rate (%)	(World Development Indicators, 2015c)

TABLE 2: Variable Definitions and Data Sources

Source: Author's compilation based on Eurostat and World Development Indicators. ICT, Information and Communication Technology; GDP, Gross Domestic Product

The principal explanatory variable is the DRI, constructed to capture two complementary dimensions of digital development. Internet use reflects the diffusion of digital technologies across society, whereas the share of ICT specialists captures the availability of specialized digital skills within the labor force. The following subsection describes the exact standardization, equal-weight aggregation, and min-max normalization procedure used to construct the DRI.

The baseline empirical specification includes three macroeconomic control variables. Economic development is measured by the natural logarithm of GDP per capita, unemployment captures labor-market conditions, and annual CPI inflation captures macroeconomic conditions relevant to the fiscal environment. The robustness analysis adds demographic and fiscal controls to assess the sensitivity of the baseline estimates.

Construction of the Digital Readiness Index

The DRI is constructed from two indicators: internet use, measured as the percentage of individuals using the internet, and ICT specialists, measured as the share of ICT specialists in total employment. Because the two indicators are measured on different scales, we first standardize each component using a z-score transformation. We perform standardization across pooled country-year observations for the full 2015-2022 study period, rather than separately for each year.

For each component k, country i, and year t, the standardized value is calculated as:

$$z_{(k,it)} = \frac{x_{(k,it)} - \bar{x}_k}{s_k} (1)$$

where $x_{(k,it)}$ denotes the observed value of component k, $\bar{x}_k$, is its mean across the pooled country-year observations, and s_k is the corresponding standard deviation.

The two standardized components are then combined using equal weights:

$$DRI_{it}^{*} = 0.5 z_{(Internet,it)} + 0.5 z_{(ICT,it)} (2)$$

Equal weighting is used as a transparent, non-data-driven aggregation rule because no established theoretical basis supports assigning a larger a priori weight to either component. Thus, internet use and ICT-specialist employment contribute equally to the composite measure. The resulting composite score is subsequently rescaled to the interval $[0, 1]$ using pooled min-max normalization:

$$DRI_i t = \frac{DRI_i t^{*} - \min(DRI^{*})}{\max(DRI^{*}) - \min(DRI^{*})} (3)$$

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where the minimum and maximum are calculated across the pooled study sample; a value closer to 1 therefore indicates higher digital readiness relative to the other country-year observations in the sample. In comparison, a value closer to 0 indicates lower relative digital readiness.

The initial panel contains 216 potential country-year observations for 27 EU member states over 2015-2022. Internet-use data are available for 215 observations, with one missing observation for France in 2020, while ICT specialist data are available for all 216 observations. We can construct the DRI for 215 country-year observations. After combining the DRI with public education expenditure and the macroeconomic controls and restricting the analysis to complete cases, the final regression sample comprises 195 observations across 26 EU member states.

The DRI is a relative, sample-based composite index and has no intrinsic real-world unit. Its values should therefore be interpreted as relative positions in digital readiness within the observed 2015-2022 sample rather than as absolute thresholds of digital development. The equal-weighting assumption is further examined through component-level sensitivity analysis, in which internet use and ICT specialist employment are entered jointly into the two-way fixed-effects model.

Econometric Specification

The preferred Two-Way Fixed Effects specification is expressed as follows:

$$EducationExp_{it} = a_i + \lambda_t + \beta_1 DRI_{it} + \beta_2 \ln GDPpc_{it} + \beta_3 Unemployment_{it} + \beta_4 Inflation_{it} + \varepsilon_{it} (4)$$

In Equation (4), $EduExp_it$ denotes public education expenditure as a percentage of GDP in country i and year t. DR_{it} represents the Digital Readiness Index, while $lnGDPpc_it$, $Unemployment_it$ and $Inflation_it$ are the control variables, capturing economic development, labor market conditions, and inflation, respectively.

The terms a_i and λ_t denote country and year fixed effects, respectively, and ε_it are the idiosyncratic error term. The coefficient β_1 captures the within-country association between changes in digital readiness and changes in public education expenditure, conditional on the included controls and common year effects.

The empirical analysis begins with pooled Ordinary Least Squares (OLS) estimation and subsequently applies Random Effects (RE), Country Fixed Effects (FE), and Two-Way Fixed Effects (TWFE) models. The FE estimator controls for unobserved time-invariant country-specific characteristics that may be correlated with the explanatory variables, whereas the RE model assumes that country-specific effects are uncorrelated with the regressors.

We assess model selection using a regression-based Hausman test with a country-clustered HC1 covariance estimator. We prefer this robust version to the conventional Hausman test because the diagnostic analysis indicates heteroskedasticity and serial correlation. The robust Hausman test rejects the null hypothesis that the RE specification is consistent ($\chi^2(4) = 13.006$, $p = 0.011$), supporting the FE approach. A joint Wald test using country-clustered covariance estimates rejects the null hypothesis that the year effects are jointly zero ($\chi^2(7) = 28.626$, $p < 0.001$), supporting the inclusion of year fixed effects. The Two-Way FE model with country and year effects is therefore used as the principal specification.

Additional diagnostic tests examine heteroskedasticity, serial correlation, and cross-sectional dependence. Because these features can invalidate conventional standard errors, inference in the principal specifications uses country-clustered HC1 standard errors, which account for heteroskedasticity and within-country dependence. This choice also reflects the panel's relatively short time dimension ($T = 8$) and the presence of 26 country clusters. Given the relatively small number of clusters, we also employ a wild cluster bootstrap-t procedure with 9,999 replications as a small-cluster robustness check. We evaluate the statistical evidence using both the country-clustered HC1 estimates and the more conservative bootstrap inference. All statistical analyses were conducted in R version 4.5.2, using the plm (version 2.6-7), lmtest (version 0.9-40), and sandwich (version 3.1-2) packages for panel-data estimation, diagnostic testing, and robust covariance estimation.

Results And Discussion

Empirical results

Descriptive Statistics

Variable	N	Mean	Std. Dev.	Minimum	Maximum
Education Expenditure (% GDP)	195	4.740	1.050	2.580	7.340
Digital Readiness Index (DRI)	195	0.507	0.202	0.000	1.000
Internet Use (%)	195	84.400	9.470	55.800	98.900
ICT Specialists (% employment)	195	4.150	1.340	1.600	8.600
Log GDP per capita	195	10.200	0.604	8.890	11.600
Unemployment (%)	195	7.170	3.720	2.020	25.000
Inflation (%)	195	2.480	3.570	−2.100	19.700

TABLE 3: Descriptive Statistics for the Estimation Sample

Note: Descriptive statistics are calculated using the common estimation sample of 195 country-year observations. The within-country standard deviation of the DRI is 0.087. Source: Author's calculations. ICT, Information and Communication Technology; GDP, Gross Domestic Product

Table *3* reports descriptive statistics for the common estimation sample of 195 country-year observations. Public education expenditure averages 4.74% of GDP, while the mean DRI is 0.507. Because the DRI is normalized to the study sample, its mean does not represent a substantive threshold of digital readiness. The DRI varies meaningfully within countries over time, with a within-country standard deviation of 0.087. Across countries, the average change between the first and last available observation is 0.233 index points, and the median change is 0.251. This temporal variation is important because the fixed-effects estimates are identified from within-country changes over time. Internet use averages 84.4%, while ICT specialists account for an average of 4.15% of employment. The estimation sample also exhibits substantial variation in macroeconomic conditions, including unemployment and inflation.

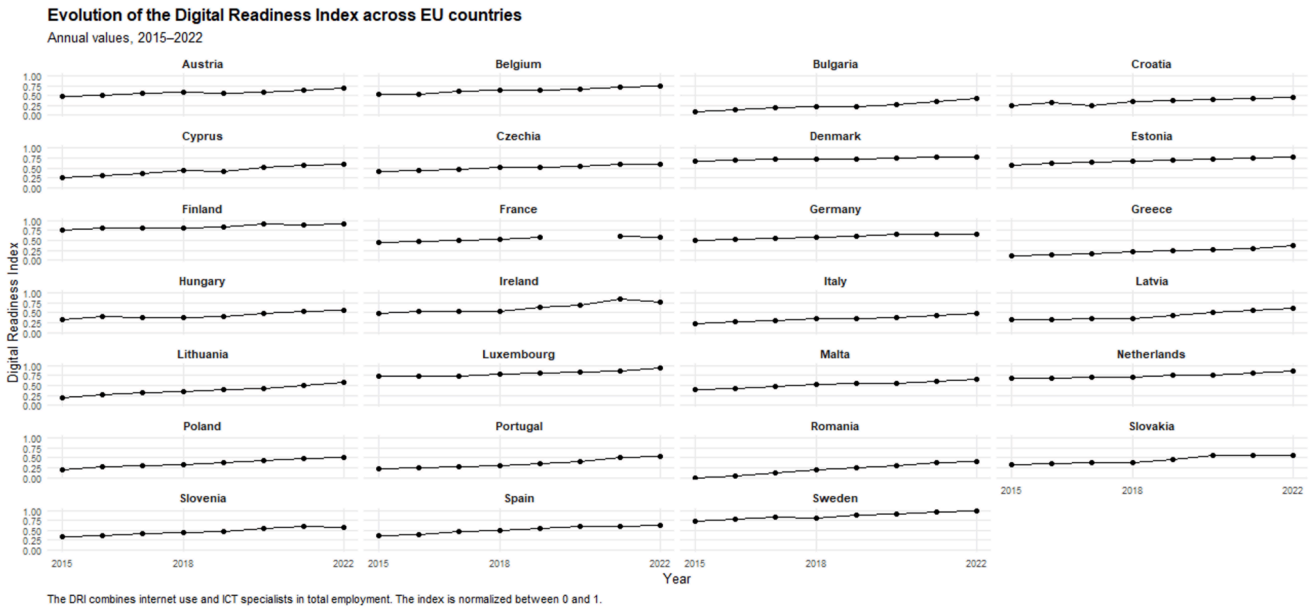


FIGURE 1: Evolution of the Digital Readiness Index in EU Countries (2015–2022)

Source: Author's calculations based on Eurostat data. EU, European Union

Figure *1* illustrates the evolution of the DRI across EU member states between 2015 and 2022. The figure reveals a general upward trend in digital readiness throughout the EU, reflecting improvements in internet diffusion and the increasing importance of digital skills. Significant disparities remain between countries, indicating unequal progress toward digital transformation objectives.

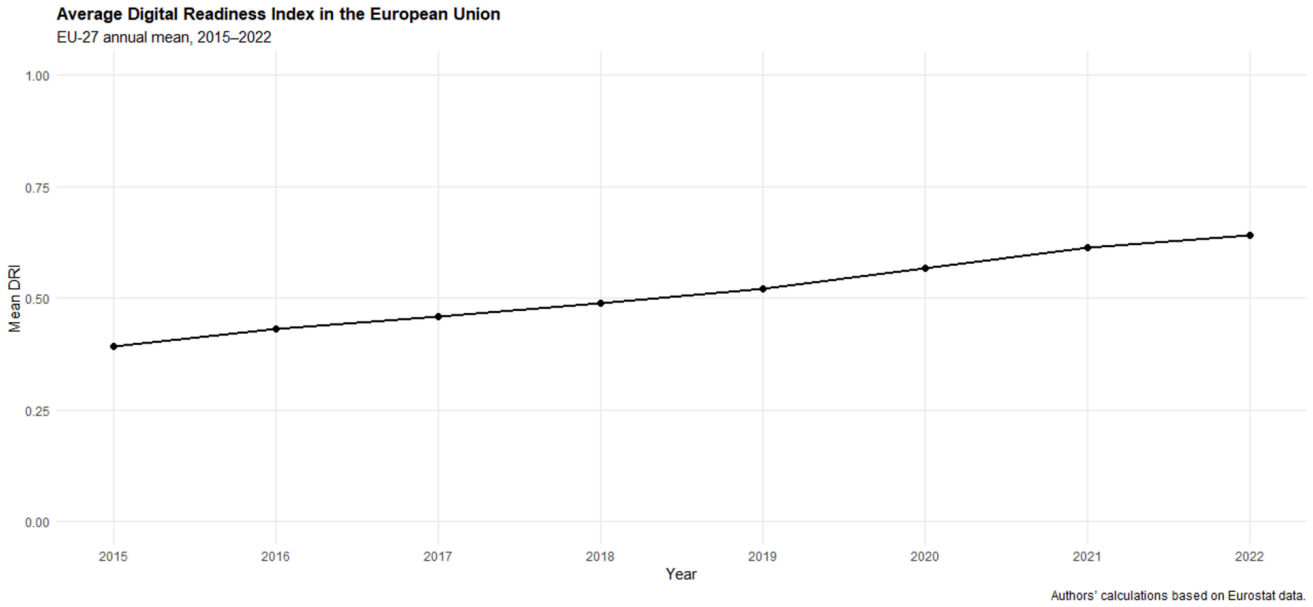


FIGURE 2: Average Digital Readiness Index across EU Member States, 2015–2022

Source: Author's calculations based on Eurostat data. EU, European Union

Figure 2 shows the evolution of the average DRI across EU member states from 2015 to 2022. The average DRI increases over the study period, indicating a general upward trend in digital readiness. This figure summarizes the aggregate temporal pattern and is not intended to measure or demonstrate cross-country disparities in digital readiness. The average series alone cannot capture such disparities. The descriptive DRI dataset covers 27 EU member states, with one missing internet-use observation for France in 2020. By contrast, the regression sample comprises 26 member states because Estonia is excluded owing to the absence of public education expenditure data throughout the study period.

Correlation Analysis

Variable	DRI	Education Expenditure	Internet Use	ICT Specialists
DRI	1.000	0.618	0.940	0.941
Education Expenditure	0.618	1.000	0.543	0.620
Internet Use	0.940	0.543	1.000	0.769
ICT Specialists	0.941	0.620	0.769	1.000

TABLE 4: Correlation Matrix

Source: Author's calculations. DRI, Digital Readiness Index; ICT, Information and Communication Technology

Table 4 reports the Pearson correlation coefficients among the study variables. The results reveal a positive association between digital readiness and public education expenditure (r = 0.618), suggesting that countries characterized by higher levels of digital development tend to allocate a larger share of GDP to education. As expected, DRI exhibits strong positive correlations with both internet use (r = 0.940) and ICT specialists (r = 0.941), reflecting the fact that these indicators constitute the underlying components of the composite index.

Multicollinearity Diagnostics

Because the baseline specification includes the composite DRI together with the macroeconomic control variables, multicollinearity was assessed for the regressors entering that specification.

Variable	VIF	Tolerance
DRI	4.040	0.247
Log GDP per capita	3.660	0.273
Unemployment	1.240	0.805
Inflation	1.300	0.767

TABLE 5: Multicollinearity Diagnostics

Source: Author's calculations. VIF, Variance Inflation Factor; DRI, Digital Readiness Index; GDP, Gross Domestic Product

Table 5 presents the variance inflation factor (VIF) statistics. The highest VIF value is observed for the DRI (4.040), followed by GDP per capita (3.660). All values remain below commonly accepted thresholds, indicating that multicollinearity is not a serious concern. Tolerance values exceed the minimum recommended level of 0.10, further confirming that the explanatory variables can be included simultaneously in the regression models without compromising coefficient stability or statistical inference.

Panel Regression Results

Variable	Pooled OLS	Random Effects	Country FE	Two-Way FE
DRI	4.323***	1.968***	2.305***	2.056**
	(1.124)	(0.319)	(0.395)	(0.903)
Log GDP per capita	−0.284	−0.181	−2.269***	−2.434***
	(0.564)	(0.338)	(0.761)	(0.869)
Unemployment	0.020	0.046**	0.029*	0.010
	(0.033)	(0.020)	(0.017)	(0.024)
Inflation	−0.089***	−0.036***	−0.019***	0.034*
	(0.018)	(0.007)	(0.006)	(0.019)
Observations	195	195	195	195
R^2/Within R^2	0.465	0.193	0.232	0.124
Country FE	No	No	Yes	Yes
Year FE	No	No	No	Yes
SE	Country-clustered HC1	Country-clustered HC1	Country-clustered HC1	Country-clustered HC1

TABLE 6: Panel Regression Results

Notes: Country-clustered HC1 standard errors are reported in parentheses (26 country clusters). For the fixed-effects specifications, the reported R^2 is the within R^2. *p < 0.10, **p < 0.05, ***p < 0.01. Source: Author's calculations. GDP, Gross Domestic Product; DRI, Digital Readiness Index; OLS, Ordinary Least Squares; FE, Fixed Effects

Table 6 presents the results from four panel specifications estimated on the common sample of 195 country-year observations. We report country-clustered HC1 standard errors for all specifications. The DRI coefficient is positive across all four models and remains statistically significant in the preferred two-way fixed-effects specification (β = 2.056, SE = 0.903, p = 0.024). Because the DRI is a sample-normalized index without an intrinsic real-world unit, interpret its magnitude cautiously. For scale, a 0.10-point increase in the DRI is associated with approximately 0.206 percentage points

higher public education expenditure as a share of GDP. A one-standard-deviation within-country change in the DRI (0.087 index points) corresponds to approximately 0.18 percentage points of GDP. These quantities represent conditional associations rather than causal effects.

Log GDP per capita is negatively associated with education expenditure in the two-way fixed-effects specification (β = −2.434, SE = 0.869, p = 0.006), whereas unemployment is not statistically significant. Inflation is positive but only marginally significant (β = 0.034, SE = 0.019, p = 0.083). Changes in the unemployment and inflation coefficients across specifications reflect differences in how we treat unobserved country heterogeneity and common year-specific shocks. We interpret these coefficients as specification-sensitive conditional associations rather than causal effects.

Model Diagnostics and Preferred Specification

Test	Statistic	p-value	Conclusion
Breusch–Pagan Test	43.278	<0.001	Heteroskedasticity present
Wooldridge Test	40.260	<0.001	Serial correlation present
Pesaran CD Test	−1.949	0.0514	Cross-sectional independence not rejected at 5%
Robust Hausman Test	$\chi^2(4) = 13.006$	0.011	Fixed Effects preferred
Joint Wald Test of Year Effects	$\chi^2(7) = 28.626$	<0.001	Year effects jointly significant

TABLE 7: Diagnostic Tests

Note: The robust Hausman test is regression-based and uses a country-clustered HC1 covariance estimator. The joint Wald test evaluates the null hypothesis that all year fixed effects are jointly zero and also uses country-clustered covariance estimates. Source: Author's calculations

Table *7* reports the diagnostic and model-selection tests conducted to assess heteroskedasticity, serial correlation, cross-sectional dependence, and the appropriateness of the fixed-effects specification. The results support using country-clustered robust standard errors and including both country and year fixed effects in the preferred econometric model.

The Breusch-Pagan and Wooldridge tests provide clear evidence of heteroskedasticity and serial correlation, respectively. The Pesaran CD test does not reject cross-sectional independence at the 5% significance level (p = 0.0514), although the result is borderline. Given the short time dimension of the panel (T = 8) and the presence of 26 country clusters, inference in the principal specifications is therefore based on country-clustered HC1 standard errors.

Under country-clustered inference, the DRI coefficient in the two-way fixed-effects specification remains positive and statistically significant (β = 2.056, SE = 0.903, p = 0.024). Log GDP per capita also remains statistically significant (β = −2.434, SE = 0.869, p = 0.006), while unemployment is not statistically significant and inflation is only marginally significant. These results indicate that the estimated association between digital readiness and public education expenditure is not dependent on conventional standard errors.

Because the number of country clusters is relatively small, we conducted an additional wild cluster bootstrap-t procedure with 9,999 replications for the DRI coefficient. The resulting bootstrap p-value was 0.060. Thus, while the DRI coefficient is statistically significant at the 5% level under the country-clustered HC1 specification, the evidence is weaker under the more conservative small-cluster bootstrap procedure and is supported at the 10% level. We interpret the statistical significance of the main association cautiously.

We further assessed model selection using a regression-based Hausman test with a country-clustered HC1 covariance estimator, given the documented heteroskedasticity and serial correlation. The robust test rejected the null hypothesis that the random-effects specification is consistent ($\chi^2(4) = 13.006$, $p = 0.011$), supporting the fixed-effects approach. In addition, a joint Wald test using country-clustered covariance estimates strongly rejected the null hypothesis that the year effects were jointly zero ($\chi^2(7) = 28.626$, $p < 0.001$), supporting the inclusion of year fixed effects. These results support using the two-way fixed-effects specification with country and year effects as the principal model.

Robustness and Sensitivity Analyses

To assess the robustness of the baseline results, we conducted a series of complementary sensitivity analyses addressing the composition of the DRI, the COVID-19 period, alternative measurement of education expenditure, temporal ordering, EU expenditure allocations, additional demographic and fiscal controls, and the influence of individual countries.

To examine whether the association between digital readiness and public education expenditure differs across the two components of the DRI, we entered Internet Use and ICT Specialists into the two-way fixed-effects model simultaneously. Table *8* reports the results.

Variable	Joint Component TWFE
Internet use (%)	0.032***
	(0.010)
ICT specialists (%)	0.062
	(0.097)
Log GDP per capita	−2.868***
	(0.834)
Unemployment (%)	0.020
	(0.025)
Inflation (%)	0.033*
	(0.018)
Country FE	Yes
Year FE	Yes
Observations	195
Within R^2	0.146
Test: β Internet = β ICT, p-value	0.748

TABLE 8: Joint Component Analysis of Digital Readiness

Notes: Country-clustered HC1 standard errors are reported in parentheses (26 country clusters). The equality test evaluates the null hypothesis that the coefficients on Internet Use and ICT Specialists are equal. *p < 0.10, **p < 0.05, ***p < 0.01. Source: Author's calculations. ICT, Information and Communication Technology; GDP, Gross Domestic Product; TWFE, Two-Way Fixed Effects; FE, Fixed Effects

Internet Use is positively associated with public education expenditure (β = 0.032, SE = 0.010, p = 0.002), whereas the coefficient for ICT Specialists is not statistically significant (β = 0.062, SE = 0.097, p = 0.527). In substantive terms, the Internet Use coefficient implies that a 10-percentage-point increase in internet use is associated with approximately 0.32 percentage points higher public education expenditure as a share of GDP, conditional on the other covariates and fixed effects. A formal test of coefficient equality fails to reject the null hypothesis that the two coefficients are equal (p = 0.748). Although Internet Use is individually statistically significant in the joint specification, the results provide no statistical evidence that its association with education expenditure is stronger than that of ICT specialist employment. Given the observational design, the estimated magnitude represents a conditional association rather than a causal effect.

To assess whether the baseline association is driven by the exceptional macroeconomic conditions of the COVID-19 period, we re-estimated the two-way fixed-effects model after excluding 2020 and 2021. The DRI coefficient remained positive and statistically significant (β = 2.361, SE = 1.060, p = 0.028; N = 148), compared with β = 2.056 (SE = 0.903, p = 0.024; N = 195) in the baseline specification. The persistence of the association after excluding both pandemic years indicates that the baseline result is not solely attributable to the unusual combination of GDP contraction and accelerated digital adoption during 2020-2021.

To address the denominator sensitivity inherent in measuring education expenditure as a percentage of GDP, we re-estimated the two-way fixed-effects model using public education expenditure per pupil/student in Purchasing Power Standards (PPS) as the dependent variable. This alternative outcome reduced the estimation sample to 188 observations across 25 countries because comparable data were unavailable for Ireland. The DRI coefficient remained positive (β = 1,193.705, SE = 1,271.858) but was not statistically significant (p = 0.349). In substantive terms, a 0.10-point increase in the DRI corresponds to approximately 119 PPS higher expenditure per pupil/student, although the estimate is imprecise. While excluding the pandemic years preserves the baseline association, the evidence is not robust to replacing expenditure as a share of GDP with expenditure per pupil/student. This result indicates that the finding is sensitive to how education expenditure is measured and warrants cautious interpretation of the baseline estimate.

To examine temporal ordering and potential reverse causality, we re-estimated the two-way fixed-effects model using one- and two-year lags of the DRI. Lagged DRI values were constructed from the original country-year panel before restricting the data to the complete-case estimation sample. The one-year lag remained positively and statistically significantly associated with public education expenditure (β = 2.278, SE = 0.994, p = 0.024; N = 170; within R^2 = 0.151). With a two-year lag, the coefficient remained positive but was smaller and no longer statistically significant (β = 1.390, SE = 0.899, p = 0.125; N = 146; within R^2 = 0.105). These results provide some evidence that the positive association persists when digital readiness is measured one year before education expenditure, whereas the evidence weakens at a two-year horizon. The lagged specifications improve temporal ordering but do not eliminate potential endogeneity or establish causality and are interpreted as sensitivity checks rather than causal estimates.

We controlled for annual EU expenditure allocated to each member state, expressed per capita to account for differences in country size. Including this control left the estimated DRI coefficient largely unchanged (β = 1.994, SE = 0.915, p = 0.031; N = 194), compared with β = 2.056 (SE = 0.903, p = 0.024; N = 195) in the baseline specification. The EU expenditure per capita coefficient was negative and marginally significant (β = −0.00035, SE = 0.00019, p = 0.075). Controlling for cross-country and temporal variation in EU expenditure allocations does not materially alter the estimated positive association between digital readiness and public education expenditure.

We augmented the two-way fixed-effects specification with two additional controls capturing demographic demand and the broader fiscal environment: the share of the population aged 5-19 years and total general government expenditure as a percentage of GDP-the extended specification retained all 195 observations. The DRI coefficient remained positive but decreased in magnitude and was statistically significant only at the 10% level ($\beta = 1.291$, SE = 0.683, $p = 0.060$). The school-age population share was not statistically significant ($\beta = 0.166$, SE = 0.129, $p = 0.199$), whereas total government expenditure was positively and strongly associated with education expenditure ($\beta = 0.048$, SE = 0.013, $p < 0.001$). The within R^2 increased from 0.124 in the baseline specification to 0.276 in the extended model. These results suggest that part of the baseline DRI association overlaps with broader fiscal conditions, although the estimated association remains positive after accounting for demographic composition and overall government expenditure.

To assess whether any single country disproportionately influences the baseline association, we conducted a leave-one-country-out sensitivity analysis, re-estimating the two-way fixed-effects model 26 times while sequentially excluding each country. The DRI coefficient remained positive in all 26 specifications, ranging from 1.408 to 2.413, with a mean coefficient of 2.055, virtually identical to the baseline estimate of 2.056. The coefficient was statistically significant at the 5% level in 22 of the 26 specifications and at the 10% level in all 26 specifications. The smallest estimate occurred when Denmark was excluded ($\beta = 1.408$, SE = 0.770, $p = 0.069$), whereas the largest occurred when the Czech Republic was excluded ($\beta = 2.413$, SE = 0.861, $p = 0.006$). These results indicate that the positive association is not attributable to any single country in the estimation sample.

Discussion

The findings indicate a positive association between digital readiness and public education expenditure across EU member states. In the preferred two-way fixed-effects specification, the DRI coefficient is positive and statistically significant under country-clustered inference ($\beta = 2.056$, SE = 0.903, $p = 0.024$). The positive coefficient is also preserved across several sensitivity analyses, although its statistical precision varies. In particular, the association remains significant when the COVID-19 years 2020 and 2021 are excluded ($\beta = 2.361$, $p = 0.028$) and when the DRI is lagged by one year ($\beta = 2.278$, $p = 0.024$). It also remains positive when controlling for EU expenditure allocations ($\beta = 1.994$, $p = 0.031$). Significance weakens under the wild cluster bootstrap procedure ($p = 0.060$) and after adding school-age population share and total government expenditure ($\beta = 1.291$, $p = 0.060$). When public education expenditure per pupil/student in PPS is used as an alternative outcome, the DRI coefficient remains positive but is not statistically significant ($\beta = 1{,}193.705$, $p = 0.349$). These results provide support for the hypothesized positive association, while also showing that its statistical strength is sensitive to the choice of inference, additional controls, and the measurement of education expenditure. The evidence should be interpreted as supporting a conditional association rather than a causal relationship.

The magnitude of the baseline association also requires careful interpretation because the DRI is a sample-normalized index without an intrinsic real-world unit. In the baseline specification, a 0.10-point increase in the DRI is associated with approximately 0.21 percentage points higher public education expenditure as a share of GDP. In terms of observed within-country variation, a one-standard-deviation within-country increase in the DRI (0.087 index points) corresponds to about 0.18 percentage points of GDP. These estimates indicate the magnitude of the association but should not be interpreted as causal effects.

Several mechanisms could potentially account for the observed relationship. More digitally developed education systems may face expenditure needs for digital infrastructure, connectivity, teacher training, digital learning resources, and integrating technology into teaching and administration. These mechanisms align with conceptual and policy frameworks emphasizing that effective digital integration in education requires both technological capacity and institutional support (Redecker and Punie, 2017) (UNESCO, 2023), as well as European policy priorities linking digital transformation to investment in skills and human capital (European Commission, 2024b). This study's expenditure measure captures aggregate public education expenditure as a share of GDP and does not distinguish among specific spending categories. These channels should therefore be regarded as plausible mechanisms rather than mechanisms directly tested by the empirical analysis.

The component-level analysis provides additional nuance. When internet use and ICT specialist employment are entered jointly into the two-way fixed-effects model, internet use is positively associated with public education expenditure (β = 0.032, SE = 0.010, p = 0.002). In contrast, the coefficient for ICT specialists is not statistically significant (β = 0.062, SE = 0.097, p = 0.527). A 10-percentage-point increase in internet use is associated with approximately 0.32 percentage points higher public education expenditure as a share of GDP. A formal test does not reject equality between the two component coefficients (p = 0.748). The evidence does not support the stronger conclusion that internet use is a more important component of digital readiness than ICT specialist employment. The component results should be viewed as complementary evidence on the dimensions underlying the composite DRI.

The negative coefficient of GDP per capita in the baseline two-way fixed-effects model should also be interpreted in relation to the definition of the dependent variable. Because public education expenditure is measured as a percentage of GDP, a lower expenditure share does not necessarily imply lower education spending in absolute terms. GDP may grow faster than education expenditure, thereby reducing education expenditure as a share of GDP even when spending levels are maintained or increase. This interpretation matters especially when comparing countries with different levels and trajectories of economic development (OECD, 2024).

The additional demographic and fiscal controls further qualify the baseline findings. When the share of the population aged 5-19 years and total general government expenditure as a percentage of GDP are added to the model, the DRI coefficient remains positive but decreases in magnitude and is significant only at the 10% level. The school-age population share is not statistically significant, whereas total government expenditure is positively and strongly associated with public education expenditure. The increase in within R^2 from 0.124 to 0.276 indicates that broader fiscal conditions account for an important share of within-country variation in education expenditure. These results suggest that the relationship between digital readiness and education expenditure should be considered alongside the broader fiscal environment rather than interpreted as an independent or exclusively digital process.

The findings suggest that digital readiness and public education expenditure are related dimensions of educational and digital transformation in the EU. Still, the analysis does not establish the direction of causality. The lagged specifications improve temporal ordering but do not eliminate potential reverse causality, and unobserved political, institutional, demographic, and fiscal factors may still influence both digital readiness and education expenditure. The results are best interpreted as evidence of a positive conditional association whose magnitude and statistical precision vary across alternative specifications and measures.

Study Limitations

This study has several limitations. The analysis is restricted to EU member states, which limits the generalizability of the findings to other regional and economic contexts. The DRI is based on internet use and the share of ICT specialists. Due to data availability, broader measures such as DESI could not be used consistently for all countries over the 2015-2022 period. The index does not capture all dimensions of digital transformation, including digital public services, business digitalization, and advanced digital infrastructure. The study also focuses on public education expenditure as a percentage of GDP and does not assess the efficiency, effectiveness, or composition of educational spending. Although we estimated an alternative specification using expenditure per pupil/student as a sensitivity analysis, the DRI coefficient was not statistically significant under this alternative outcome, indicating that the findings are sensitive to how education expenditure is measured.

Omitted-variable bias cannot be entirely excluded. Although we introduced additional demographic and fiscal controls, other political, institutional, and policy-related factors may influence both digital readiness and public education expenditure. Reverse causality also remains possible, as higher public education expenditure may itself contribute to improvements in digital readiness over time. The lagged specifications improve temporal ordering but do not eliminate this concern.

The panel's relatively short time dimension (T = 8) and limited number of country clusters require caution in statistical inference. Although the baseline DRI coefficient is statistically significant under country-clustered HC1 standard errors, its statistical significance weakens under the more conservative wild cluster bootstrap procedure. These limitations reinforce

the interpretation of the findings as conditional associations rather than causal effects.

Conclusions

This study examined the relationship between digital readiness and public education expenditure in 26 EU countries from 2015 to 2022. The baseline results indicate a positive association between digital readiness and public education expenditure. In the preferred two-way fixed-effects specification with country-clustered standard errors, the DRI coefficient is positive and statistically significant ($\beta = 2.056$, $SE = 0.903$, $p = 0.024$). The positive association holds across several sensitivity analyses, including excluding the COVID-19 years, using a one-year lag of the DRI, controlling for EU expenditure allocations, and conducting leave-one-country-out estimates. However, the statistical evidence weakens under the wild cluster bootstrap, after adding demographic and fiscal controls, and when using expenditure per pupil/student as an alternative outcome. These findings provide qualified support for Hypothesis H1 rather than evidence of a uniformly robust relationship across all specifications. The component-level analysis provides additional insight into the construction of the DRI. When internet use and ICT specialist employment are included jointly in the model, internet use is positively and statistically significantly associated with public education expenditure, whereas the coefficient for ICT specialist employment is not statistically significant. The formal test of coefficient equality does not indicate a statistically significant difference between the two components. Therefore, the results do not establish that one dimension of digital readiness is more strongly related to education expenditure than the other.

Overall, the findings suggest that digital readiness and public education expenditure are interconnected dimensions of educational and digital development in the EU. The sensitivity of the estimates to broader fiscal controls and the alternative expenditure measure highlights the importance of interpreting this relationship cautiously. The analysis identifies a conditional association and does not establish that improvements in digital readiness cause higher public education expenditure or determine how education resources are allocated. From a policy perspective, the results suggest that policymakers should not consider digital transformation and education financing in isolation. Because the dependent variable captures aggregate public education expenditure as a share of GDP, the study cannot determine whether expenditure is directed specifically toward digital infrastructure, digital skills, teacher training, or technology-enhanced learning. These remain plausible policy channels rather than mechanisms directly tested by the analysis. Future research could examine more disaggregated categories of education expenditure and employ research designs better suited to addressing reverse causality and other sources of endogeneity.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Xhuljeta Meçaj

Acquisition, analysis, or interpretation of data: Xhuljeta Meçaj

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Critical review of the manuscript for important intellectual content: Xhuljeta Meçaj

Supervision: Xhuljeta Meçaj

Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue.

Animal subjects: All authors have confirmed that this study did not involve animal subjects or tissue.

Conflicts of interest: In compliance with the ICMJE uniform disclosure form, all authors declare the following:

- **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work.
- **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work.
- **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

Data Availability Statements

The analytical datasets and R code supporting the principal analyses and selected robustness checks are publicly available on Zenodo (Meçaj, 2026), https://zenodo.org/records/22755779. Additional sensitivity analyses use publicly available Eurostat and European Commission data.

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