

# Digital Ecosystem Maturity, Vulnerability, and Mental Health:

## A Within-Between Decomposition across European NUTS2 Regions

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### Summary

Higher regional digital maturity is often interpreted as beneficial for digitally vulnerable populations, yet it is unclear whether such associations reflect regional digital infrastructure, broader digital ecosystems, or cross-national institutional differences. This paper examines whether an apparent protective interaction between individual digital vulnerability and composite regional digital-service ecosystem maturity survives increasingly demanding identification and construct-validity tests. Combining European Health Interview Survey (EHIS) 2019 microdata with Eurostat NUTS2 indicators (N = 92,961 respondents, 85 NUTS2 regions, 13 EU countries), the paper reports one pooled logistic regression with cross-level interaction and three diagnostic analyses. The pooled cross-level interaction between individual vulnerability and composite regional digital-service maturity is negative and highly significant ( $\beta_3 = -0.281, p < 0.001$ ). A Mundlak within-between decomposition attributes nearly all of this interaction to between-country differences ( $D \times W_{\text{between}}: \beta = -0.304, p < 0.001$ ;  $D \times W_{\text{within}}: \beta = -0.058, p = 0.64$ ). A narrower platform-transaction index eliminates the interaction ( $\beta_3 \approx 0, p > 0.8$ ), and welfare-regime and country-specific estimates are sensitive to the regional-control specification and do not identify a stable regime-specific or country-replicated mechanism. The paper's contribution is a decomposition of an apparent protective effect that reveals sensitivity to measurement level, spatial scale, and institutional context — showing where such an apparent effect is empirically located rather than establishing that regional digital ecosystems causally protect vulnerable individuals.

### 1. Motivation and research questions

Composite digital-maturity indices are increasingly used in regional and public-health research to characterise the digital environment in which individuals live and interact with public services. A recurring finding in this literature is that regions with higher composite digital maturity appear to exhibit a smaller mental-health gap between digitally vulnerable and non-vulnerable individuals — a pattern often read as evidence that regional digital infrastructure protects vulnerable populations from elevated depression risk. Such indices, however, bundle infrastructural provision, individual uptake, and skills into a single regional score, and much of their variation lies between countries. Whether an apparent regional protective effect reflects (i) regional digital infrastructure, (ii) broader digital ecosystems including uptake and skills, or (iii) cross-national institutional differences correlated with digital-service environments cannot be read off the pooled point estimate.

The paper addresses three progressively narrower questions. First, is the cross-level interaction between individual digital vulnerability and composite regional digital maturity in the direction predicted by capability-substituting theory, and if so, is the digital-maturity slope among vulnerable respondents consistently negative? Second, does the interaction survive when identification is restricted to within-country regional variation, or does

it dissolve — indicating that the effect is driven by between-country differences? Third, when the interaction is subjected to alternative measurement and institutional decompositions, does it survive — specifically, does it reproduce under a narrower platform-transaction construct, and are welfare-regime-stratified estimates stable across model specifications?

## 2. Data and methods

The analysis combines individual-level microdata from EHIS 2019 with region-level indicators from Eurostat NUTS2 statistics. The 13 countries included are Austria, Belgium, Bulgaria, Croatia, Czechia, Denmark, Finland, Hungary, Lithuania, Poland, Slovakia, Slovenia, and Sweden. Country selection was constrained by EHIS microdata availability at NUTS2 resolution and by non-missing coverage of the seven ICT indicators used to construct the regional digital-maturity index. After applying common complete-case restrictions across the variables required for the main, decomposition, and pathway analyses, the analytical sample includes  $N = 92,961$  respondents aged 15+ from 85 NUTS2 regions across 13 EU countries.

The outcome `mh_case` is a binary indicator equal to one for the top decile of PHQ-8 scores in the pooled sample. The primary predictor `dig_demo` is a binary indicator equal to one if the respondent is aged 65+ or has ISCED 0–2 education (40.4 % of the sample). The key regional moderator `PUI_digital` is the first principal component (z-scored) of seven Eurostat NUTS2 ICT indicators (broadband household coverage, individuals using the internet at least three times a week, daily internet use, online purchases, e-government interaction, employees in the digital sector, and platform-mediated tourism nights) and explains 66.7 % of the pooled variance. A narrower construct `PUI_platform` is constructed from three service-platform indicators (e-government interaction, e-commerce, and e-banking) and used in the construct-validity check. Individual controls include five-category age, three-category ISCED education, sex, three-category urbanisation, five-quintile household income, a continuous z-scored chronic-condition count, and the three-category Oslo-3 social-support scale. Four NUTS2-level covariates (log GDP per capita, employment rate 20–64, hospital beds per 100,000, and physicians per 100,000) are included alongside country fixed effects.

The main specification is a logistic regression of `mh_case` on `dig_demo`  $\times$  `PUI_digital` and the covariate set, with cluster-robust standard errors at the NUTS2 level. Three diagnostic analyses complement the pooled model: (i) a Mundlak within-between decomposition that separates the interaction into a within-country component ( $D \times PUI\_within$ ) and a between-country component ( $D \times PUI\_between$ ); (ii) a construct-validity check that substitutes `PUI_platform` for `PUI_digital` in the interaction; and (iii) a welfare-regime-stratified analysis under two specifications (fully adjusted, retaining the regional-control block; and reduced, retaining only country fixed effects) to assess specification sensitivity in small strata.

## 3. Results

### 3.1 Pooled cross-level interaction

The pooled cross-level interaction is negative and highly significant. In the main specification,  $\beta_3 = -0.281$  (OR = 0.755, 95 % CI [0.70, 0.81],  $p < 0.001$ ). The associated digital-maturity slope differs across individual type:  $\beta_2 = +0.115$  ( $p = 0.061$ ) for the non-vulnerable and  $\beta_2 + \beta_3 = -0.167$  ( $p = 0.008$ ) for the digitally vulnerable. Only the vulnerable-group slope is statistically distinguishable from zero; the paper's principal empirical claim is the difference between the two slopes — captured by  $\beta_3$  — not either slope in isolation. The main coefficient on `dig_demo` itself is essentially zero ( $\beta_1 = -0.022$ ,  $p = 0.79$ ) once the granular age and education controls that `dig_demo` is built from are held constant, so the raw quintile-level gap between vulnerable and non-vulnerable respondents (approximately +10 pp at low `PUI_digital`, crossing zero at the highest quintile) should not be interpreted as an adjusted effect of the coarse `dig_demo` indicator.

### 3.2 Mundlak within-between decomposition

The Mundlak decomposition yields a pronounced contrast between the within-country and between-country components of the interaction. The within-country component is indistinguishable from zero ( $\beta = -0.058$ ,  $p = 0.64$ ); comparing NUTS2 regions to one another inside the same country produces no differential association between individual vulnerability and regional digital-service maturity. The between-country component ( $\beta = -0.304$ ,  $p < 0.001$ ) is essentially identical in magnitude to the pooled interaction estimate and accounts for nearly all of the pooled result. Because the between-country term is identified from only 13 country means, the p-value based on NUTS2-clustered inference should be read with country-level inference in mind; leave-one-country-out diagnostics show that the point estimate is stable in a range from  $-0.217$  (drop SE) to  $-0.350$  (drop BG) and does not depend on any single country.

### 3.3 Construct-validity check with PUI\_platform

Substituting the narrower platform-transaction index PUI\_platform for PUI\_digital in the interaction eliminates the association:  $\beta_3 = +0.011$  (SE = 0.054,  $p = 0.84$ ), with a vulnerable-group marginal effect  $\beta_2 + \beta_3 = -0.004$  ( $p = 0.91$ ). Under the narrower platform-transaction reading — the reading that would come closest to justifying the label 'digital infrastructure' — the interaction disappears. The pooled result is therefore not identified by infrastructure provision alone, but by the broader composite that mixes infrastructural, usage, and skills components. A sensitivity check retaining PUI\_digital while removing PUI\_platform from the main specification leaves  $\beta_3$  effectively unchanged ( $\beta_3 = -0.281$  with and  $-0.281$  without PUI\_platform), so the shared platform variance is not driving the pooled interaction.

### 3.4 Welfare-regime specification sensitivity

Welfare-regime-stratified estimates are sensitive to the inclusion of regional covariates in the small strata (Social-Democratic 18 NUTS2 regions, Conservative-Corporatist 20, Post-communist 47). The interaction  $\beta_3$  is comparatively stable across specifications (Social-Democratic:  $-0.246$  vs  $-0.223$ ; Conservative-Corporatist:  $-0.561$  vs  $-0.565$ ; Post-communist:  $-0.158$  vs  $-0.158$ ), but the main digital-maturity slope  $\beta_2$  shifts appreciably in the Social-Democratic and Conservative-Corporatist strata when regional covariates are added or removed, and the vulnerable-group slope  $\beta_2 + \beta_3$  inherits this sensitivity. Country-specific estimates within the two-country Conservative-Corporatist stratum also vary with model specification and do not identify a pattern replicated across Austria and Belgium. The stratified results are therefore treated as exploratory descriptive contrasts rather than as estimates of stable welfare-regime parameters.

## 4. Discussion and contribution

Three diagnostic analyses reshape the interpretation of the pooled result. First, the interaction is empirically concentrated in cross-national rather than within-country regional variation. Second, it is not reproduced by a narrower platform-transaction construct and instead depends on a broader composite of digital uptake, skills, and service-use environments. Third, welfare-regime and country-specific estimates are sensitive to the regional-control specification and do not identify a stable regime-specific or country-replicated mechanism. The empirical content of the pooled interaction is therefore not a within-country regional-infrastructure effect but a cross-national pattern correlated with country-average digital-service environments, population capabilities, and institutional contexts, none of which can be separately identified with the present data.

The paper's contribution is therefore best understood as a decomposition rather than a discovery. It performs, in sequence, a measurement decomposition (composite vs narrower platform-transaction construct), a spatial-scale decomposition (within- vs between-country components of a cross-level interaction), and a specification-sensitivity analysis of institutional stratification (welfare-regime and country-specific estimates under two covariate specifications). Read together, these analyses locate the apparent protective interaction primarily in the between-country component of a broader composite index whose institutional correlates the present data cannot pin down. This is a substantive finding for the regional-science literature on digital divides and health: apparent

regional protective effects derived from composite digital-maturity indices should not be read as within-country regional-infrastructure effects without an explicit within-between decomposition.

For policy, the implication is that digital-investment interventions cannot be expected to reproduce the pooled pattern; policy evaluation should distinguish infrastructure provision from service uptake, population capabilities, and institutional accessibility, rather than assume that infrastructure investment alone will reproduce the pooled association. The most direct extension of the present analysis is to assemble richer country-level institutional measures — welfare generosity, administrative-capacity indices, and cross-national indicators of service accessibility — that would allow the cross-national component isolated here to be probed more finely.

## **Keywords**

*regional digital services; mental health; welfare regime; capability approach; Mundlak decomposition; NUTS2; construct validity; identification*