# Digital Ecosystem Maturity, Vulnerability, and Mental Health:

## A Within-Between Decomposition across European NUTS2 Regions

Seungshin Lee

*Ph.D. Student, Graduate School of Environmental Studies, Seoul National University*

*Corresponding Author: In Kwon Park*

## Abstract

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. Because widely used composite indices bundle these dimensions together, an apparent regional protective effect may in fact be identified from cross-country variation rather than from within-country regional differences. This paper examines whether an apparent protective interaction between individual digital vulnerability and composite regional digital maturity survives increasingly demanding identification and construct-validity tests. Combining European Health Interview Survey (EHIS) 2019 microdata with Eurostat NUTS2 indicators, we estimate a logistic regression with country fixed effects and cluster-robust standard errors at NUTS2 of PHQ-8 top-decile depression risk on N = 92,961 respondents across 85 NUTS2 regions in 13 EU countries. The pooled cross-level interaction between individual digital vulnerability (age $\geq 65$ or ISCED 0–2) and a composite regional digital ecosystem index PUI_digital — the first principal component of seven Eurostat ICT indicators that mixes infrastructural provision, usage behaviour, and skills — is negative and significant ($\beta_3 = -0.281$, OR = 0.755, $p < 0.001$).

Three diagnostic analyses reshape the interpretation of this pooled result. First, a Mundlak within-between decomposition shows that the interaction is almost entirely attributable to between-country differences: the country-level component is negative and highly significant (D × W_between: $\beta = -0.304$, $p < 0.001$), whereas the within-country component is essentially zero (D × W_within: $\beta = -0.058$, $p = 0.64$). Comparing NUTS2 regions inside the same country reveals no corresponding moderation of vulnerability-related depression risk. Second, a construct-validity check with a narrower platform-transaction index PUI_platform, restricted to e-government interaction, e-commerce, and e-banking, eliminates the interaction ($\beta_3 \approx 0$, $p > 0.8$), indicating that the pooled association 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 inclusion of regional covariates and do not support a stable regime-specific mechanism.

These findings caution against interpreting composite digital-maturity indices as evidence that regional digital ecosystems causally protect vulnerable populations. We do not find that a narrower platform-transaction construct by itself accounts for the association with vulnerability-related depression risk, nor that more digitally mature regions within the same country differentially protect vulnerable respondents. Instead, the pooled interaction reflects cross-national differences in broader digital-service ecosystems, population capabilities, and institutional contexts. The paper's contribution is therefore not the discovery of a regional infrastructural protective effect but a decomposition of an apparent protective effect that reveals sensitivity to measurement level, index composition, and cross-national institutional context. For policy, the implication is that digital-investment interventions cannot be expected to reproduce the pooled pattern; the observed association may instead reflect broader cross-national differences in digital-service environments, population capabilities, and institutional contexts, none of which can be separately identified with the present data. Future policy evaluation should distinguish infrastructure provision from uptake, capability, and institutional accessibility.

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

# 1 Introduction

Across the European Union, service delivery in public administration, healthcare, banking, and social welfare has migrated to digital channels at an accelerating pace (OECD/EU, 2022). The vulnerable populations who depend most on these services — older adults, the less educated, residents of lagging regions — occupy a specific structural position: their access to essential provisions is increasingly mediated by environments they navigate poorly. Two theoretical streams converge on a common empirical prediction. Digital divide research (van Dijk, 2020; Helsper, 2012; Scheerder et al., 2017) documents that cumulative disadvantage widens as digitalisation deepens. Relative deprivation theory (Runciman, 1966; Festinger, 1954) adds a psychological pathway from widening between-group gaps to mental-health outcomes. On both readings, the vulnerability–outcome gap in depression risk should grow with regional digital maturity.

A competing theoretical strand, drawing on Sen's (1992, 1999) capability approach and Robeyns's (2017) distinction between capability-demanding and capability-substituting environmental conversion factors, generates the opposite prediction: infrastructure that substitutes for individual endowment deficits should protect the vulnerable more strongly than the non-vulnerable, producing an asymmetric protective effect. This paper's central identification question follows: to what extent is any observed differential protection a property of digital infrastructure per se, and to what extent is it a property of the welfare-institutional configuration in which infrastructure is embedded?

This paper contributes empirical answers to three progressively narrower questions. First, is the cross-level interaction between individual vulnerability and composite regional digital maturity in the direction predicted by capability-substituting theory ($\beta_3 < 0$), and if so, does the digital-maturity slope among vulnerable respondents remain consistently negative ($\beta_2 + \beta_3 < 0$)? Second, does the interaction survive when identification is restricted to within-country variation, or does it dissolve — indicating that the effect is driven by between-country differences that co-vary with welfare-regime type? Third, when the sample is stratified by welfare regime following the canonical typologies of Esping-Andersen (1990), Ferrera (1996), and Fenger (2007), how sensitive are regime-stratified estimates to model specification, and do they support any stable institutional pattern?

We show, using EHIS 2019 microdata linked to Eurostat NUTS2 indicators on N = 92,961 respondents in 85 NUTS2 regions across 13 EU countries, that the pooled cross-level interaction is negative and significant, but that a Mundlak within-between decomposition assigns essentially all of it to the between-country component with the within-country component null. A narrower platform-transaction index eliminates the interaction, 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 empirical content of the pooled interaction is therefore not a within-country regional infrastructure effect but a cross-national digital-service ecosystem pattern that our data cannot attribute either to a narrower infrastructure-provision construct or to welfare-institutional capacity as a substantiated mechanism.

This paper makes three contributions. First, it extends digital-divide research by linking digital vulnerability to mental-health risk rather than to access or usage outcomes alone. Second, it performs a measurement decomposition of a composite digital-maturity index by distinguishing composite digital-service maturity from a narrower platform-transaction construct, and shows that the apparent protective interaction is not reproduced by the narrower construct. Third, it performs a spatial-scale decomposition of the cross-level interaction into within-country and between-country components, demonstrating that the pooled pattern is empirically concentrated in cross-national variation rather than from regional variation within countries. The paper's contribution is therefore not to show that regional digital ecosystems causally protect vulnerable individuals, but to demonstrate why an apparent protective interaction cannot be interpreted as a regional infrastructure effect by decomposing it across measurement, spatial scale, and institutional context.

## 2 Theoretical Framework

Sen's (1992, 1999) capability approach reframes individual well-being as the substantive freedom to convert resources into valuable functionings. The conversion is mediated by three classes of factors — personal, social, and environmental. Robeyns (2017) distinguishes two operating modes of environmental conversion factors that are central to the paper's conceptual claim. In a capability-demanding mode, the environment presupposes individual ability and amplifies whatever endowments the individual brings; in a capability-substituting mode, the environment absorbs individual deficits and delivers the functioning regardless of the individual's endowment. This distinction is originally presented as a property of an environment as a whole. We adapt it in a way that is essential to our reinterpretation: capability-substituting effects can operate asymmetrically across endowments — an environment can be more substituting for those with lower individual capabilities than for those with higher capabilities. This asymmetric operation is a candidate explanation for cross-level protective effects that fall disproportionately on the vulnerable.

Applied to regional digital service infrastructure, this generates a testable prediction. If regional infrastructure operates in a capability-substituting mode more strongly for the digitally vulnerable than for the non-vulnerable, then in a logistic regression model with individual vulnerability D and regional maturity W, the infrastructure marginal effect on outcomes should be $\partial \text{logit} / \partial W = \beta_2 + \beta_3 \cdot D$, with both $\beta_2$ and $\beta_2 + \beta_3$ negative but $|\beta_2 + \beta_3| > |\beta_2|$. We label this the Spatial Resource Substitution Hypothesis (SRSH).

SRSH serves as a theoretical benchmark against which the empirical decomposition is evaluated. The analysis below shows that the strong SRSH condition is not satisfied as a within-country regional-infrastructure claim: the pooled model yields opposite subgroup slopes and the interaction is isolated to between-country variation.  SRSH nevertheless provides a theoretical benchmark for interpreting the cross-national heterogeneity explored below. Graham and Marvin (2001) argue that the twentieth-century modernist infrastructural ideal — universal service, cross-subsidy, uniform provision — has been historically unbundled into market-segmented service tiers with substantial cross-regional variation in the degree of unbundling. In their account, digital-service ecosystems produce universalist welfare functions only where the institutional circuitry that supports that ideal — welfare-state intermediation, cross-subsidised provision, analogue backup — has been preserved. Where the ideal has been dismantled or was never fully consolidated, infrastructure exists but its social efficacy is different: it functions as a market-segmented commodity that does not produce cross-group welfare externalities.

The territorial welfare literature (Kazepov, 2010; Andreotti et al., 2012) reinforces this reading at the European scale. Welfare provision in Europe has been organised for four decades under Esping-Andersen's (1990) tripartite distinction of Social-Democratic, Conservative-Corporatist, and Liberal regimes, supplemented by Ferrera's (1996) identification of a Southern Mediterranean model and Fenger's (2007) empirical extension to post-communist Central and Eastern Europe. These regimes differ systematically in the degree to which infrastructural provision is cross-subsidised, analogue-supported, and welfare-intermediated. Welfare-regime categories are used in this study as exploratory institutional groupings rather than as directly identified mechanisms; the stratified analysis is intended to probe whether the apparent asymmetric association varies across cross-national institutional heterogeneity, not to estimate stable regime-specific parameters.

# 3 Data and Methods

## 3.1 Data sources and analytic sample

We combine individual-level microdata from the European Health Interview Survey (EHIS) 2019 wave with region-level indicators from Eurostat's NUTS2 statistics. After applying common complete-case restrictions across the variables required for the main, decomposition, and pathway analyses (individual controls, four regional covariates, PUI z-scores and within-country deviations, mh_index, and unmet_need), the analytical sample includes N = 92,961 respondents aged 15+ from 85 NUTS2 regions across 13 EU countries. The 13 countries 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 maturity index. The sample notably does not include Italy, Spain, Portugal, or Greece, so the Ferrera (1996) Southern Mediterranean welfare-regime stratum is empty.

### 3.2 Measures

Table 1 gives full variable definitions and data sources. The primary outcome, mh_case, is a binary indicator flagging the top decile of PHQ-8 scores in the pooled sample (Kroenke et al., 2009). Four parallel operationalisations are used for robustness. 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, explaining 66.7 % of pooled variance. 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 (from EHIS CD1A–CD1O), and the three-category Oslo-3 social support scale (SS1–SS3). Employment status (MAINSTAT) is reported in the descriptive table but not used as a covariate in the estimated model. Regional controls (four NUTS2-level z-scored covariates) are log GDP per capita, employment rate for 20–64-year-olds, hospital beds per 100,000, and physicians per 100,000. Country fixed effects absorb time-invariant country-level intercept differences in the pooled specifications.

*Table 1. Variable definitions, coding, and data sources.*

| Variable | Level | Role | Definition and coding | Source |
|---|---|---|---|---|
| **A. Outcomes (five parallel operationalisations of depression risk)** | | | | |
| **mh_case** | Individual | Primary Y | Binary = 1 if PHQ-8 total ≥ p90 in pooled sample. Pooled cutoff yields a high-symptom indicator that averages 13.02 % of the sample; response-style heterogeneity between countries is treated as a remaining identification concern. | EHIS 2019 (MH1A–MH1H) |
| **mh_case10** | Individual | Robustness Y | Binary = 1 if PHQ-8 total ≥ 10. Clinical cutoff of Kroenke et al. (2009). | EHIS 2019 (MH1A–MH1H) |
| **mh_ord** | Individual | Robustness Y | 4-cat ordinal: minimal (0–4) / mild (5–9) / moderate (10–14) / severe (≥ 15) from PHQ-8 total. | EHIS 2019 (MH1A–MH1H) |
| **mh_index** | Individual | Robustness Y | Continuous 1–4 index from PHQ-8 quartile-based rescaling. | EHIS 2019 (MH1A–MH1H) |
| **PHQ-8 total** | Individual | Robustness Y | Raw PHQ-8 total score, integer 0–24. | EHIS 2019 (MH1A–MH1H) |
| **B. Primary individual predictor — digital vulnerability** | | | | |
| **dig_demo** | Individual | Predictor | Binary = 1 if age ≥ 65 OR education ≤ ISCED 2. 40.4 % of sample. | EHIS 2019 (AGE, HATLEVEL derived) |
| **(age ≥ 65)** | Individual | Subgroup | Age criterion only: age ≥ 65 AND education > ISCED 2. 20.7 % of sample. | EHIS 2019 (AGE) |
| **(ISCED 0–2)** | Individual | Subgroup | Education criterion only: education ≤ ISCED 2 AND age < 65. 12.4 %. | EHIS 2019 (HATLEVEL) |
| **(both)** | Individual | Subgroup | Age ≥ 65 AND education ≤ ISCED 2. 7.0 % of sample. | EHIS 2019 |
| **C. Individual-level covariates** | | | | |
| **age category** | Individual | Control | 5 bins: 15–34 / 35–49 / 50–64 / 65–74 / 75+. Ref: 15–34. | EHIS 2019 (AGE) |
| **education** | Individual | Control | 3-level ISCED: 0–2 / 3–4 / 5–8. Ref: 0–2. | EHIS 2019 (HATLEVEL) |
| **sex** | Individual | Control | Binary: female (1) / male (0). Ref: male. | EHIS 2019 (SEX) |
| **urbanisation (degurba)** | Individual | Control | 3-category: 1 densely populated / 2 intermediate / 3 thinly populated. Ref: densely. | EHIS 2019 (DEG_URB) |
| **employment status** | Individual | Descriptive only | 8 categories in EHIS 2019 (MAINSTAT); reported descriptively in Table 2 but not included as a covariate in the estimated model. | EHIS 2019 (MAINSTAT) |

| | | | | |
|---|---|---|---|---|
| **income quintile** | Individual | Control | Household equivalised income, 5 quintiles. Ref: Q1. | EHIS 2019 (HHINCOME) |
| **chronic condition count** | Individual | Control | Continuous count of chronic conditions from 15 items, z-scored (cd_count_z). | EHIS 2019 (CD1A–CD1O) |
| **social support (Oslo-3)** | Individual | Control | 3-level Oslo-3-based: weak / moderate / strong. Ref: weak. | EHIS 2019 (SS1, SS2, SS3) |
| **D. Regional (NUTS2) key predictor — PUI_digital** | | | | |
| **PUI_digital** | NUTS2 | Predictor W | First principal component of the seven Eurostat ICT indicators listed below. 66.7 % of variance explained. Positive loadings on all seven. z-score. | PCA of Eurostat isoc series, NUTS2 (2019) |
| **(1) HH internet access** | NUTS2 | PUI component | Households with internet access at home, %. | Eurostat isoc_r_iuse_i (2019, NUTS2) |
| **(2) Mobile internet use** | NUTS2 | PUI component | Individuals using mobile internet on the move via 3G/4G, %. | Eurostat isoc_r_iumd_i (2019, NUTS2) |
| **(3) E-commerce** | NUTS2 | PUI component | Individuals who ordered goods or services online in the last 12 months, %. | Eurostat isoc_r_blt12_i (2019, NUTS2) |
| **(4) E-government interaction** | NUTS2 | PUI component | Individuals interacting with public authorities online, %. | Eurostat isoc_r_gov_i (2019, NUTS2) |
| **(5) E-health** | NUTS2 | PUI component | Individuals seeking health-related information online in the last 3 months, %. | Eurostat isoc_r_iuse_i / isoc_bde15cua (2019, NUTS2) |
| **(6) Cloud services** | NUTS2 | PUI component | Individuals using internet storage space to save documents/pictures/music, %. | Eurostat isoc_r_cux_i (2019, NUTS2) |
| **(7) Digital / ICT skills** | NUTS2 | PUI component | Individuals with basic or above-basic overall digital skills (DESI composite), %. | Eurostat isoc_sk_dskl_i (2019, NUTS2) |
| **E. Robustness regional predictor** | | | | |
| **PUI_platform** | NUTS2 | Robustness W | First PC restricted to three platform-transaction indicators: e-government, e-commerce, e-banking. z-score. | Subset PCA of Eurostat isoc_r_gov_i, isoc_r_blt12_i, isoc_bde15b (2019, NUTS2) |
| **F. Regional (NUTS2) covariates** | | | | |
| **real GDPpc** | NUTS2 | Control | Real GDP per capita, PPS, log-transformed and z-scored (gdp_pps_log_z). | Eurostat nama_10r_2gdp (2019, NUTS2) |
| **employment rate 20–64** | NUTS2 | Control | Employment rate among persons aged 20–64, %, z-scored (emp_rate_2064_z). | Eurostat lfst_r_lfe2emprt (2019, NUTS2) |

| | | | | |
|---|---|---|---|---|
| **hospital beds** | NUTS2 | Control | Hospital beds per 100,000 population, z-scored (beds_per_100k_z). | Eurostat hlth_rs_bdsrg (2019, NUTS2) |
| **physicians** | NUTS2 | Control | Physicians per 100,000 population, z-scored (phys_per_100k_z). | Eurostat hlth_rs_prsrg (2019, NUTS2) |
| **G. Country-level** | | | | |
| **country FE** | Country | Fixed effects | 13 country dummies: Belgium (ref) · Austria · Bulgaria · Croatia · Czechia · Denmark · Finland · Hungary · Lithuania · Poland · Slovakia · Slovenia · Sweden. | EHIS 2019 (COUNTRY) |

*Note. All Eurostat NUTS2 indicators are taken at the 2019 reference year to align with EHIS 2019 microdata. Where an indicator is not published at NUTS2 for a particular country, NUTS1 or national value is used as fallback (< 6 % of cells). ISCED levels: 0 pre-primary, 1 primary, 2 lower secondary, 3 upper secondary, 4 post-secondary non-tertiary, 5–8 tertiary.*

## 3.3 Estimation strategy

The main specification is a logistic regression of mh_case with country fixed effects and cluster-robust standard errors at the NUTS2 level:

$$logit\ Pr(Y\_ij = 1) = \beta_0 + \beta_1 \cdot D\_ij + \beta_2 \cdot W\_j + \beta_3 \cdot (D\_ij \times W\_j) + \beta_4 \cdot W\_platform\_j + \gamma' X\_ij + \delta' Z\_j + \theta' c\_c(j),$$

where D_ij is dig_demo, W_j is PUI_digital, W_platform_j is the narrower PUI_platform index (retained as an additional regional control), X_ij individual controls (five-category age, sex, three-category ISCED education, five-quintile income, three-category urbanisation, continuous chronic-condition z-score, three-category Oslo-3 social support), Z_j the four NUTS2 covariates (log GDP per capita, employment rate 20–64, hospital beds per 100,000, physicians per 100,000), and c_c(j) the country fixed-effect dummies. The digital-maturity slope on the outcome is $\partial \text{logit} / \partial W = \beta_2 + \beta_3 \cdot D$ — the paper's principal quantity of interest, which we compute separately for D = 0 and D = 1. PUI_platform is included as an additional regional control to distinguish the association of the broader PUI_digital construct from variation shared with the narrower platform-transaction index. A sensitivity check removing PUI_platform leaves $\beta_3$ effectively unchanged ($\beta_3 = -0.281$ with and $-0.281$ without PUI_platform).

Three complementary specifications probe the identification boundary. MH1 excludes the interaction. MH_CWC re-estimates the interaction after centering PUI_digital within country (Enders and Tofighi, 2007), removing the between-country component of PUI_digital while retaining the remaining covariates in their original form. Most importantly, MH_SD, MH_CS, and MH_PC re-estimate the interaction specification within each welfare-regime stratum. Assigning countries per Esping-Andersen (1990), Ferrera (1996), and Fenger (2007), this yields three operative strata for the analysis; the Southern Model (Ferrera 1996) stratum is empty because no Mediterranean country is present in the EHIS 2019 sample.

The main models are estimated unweighted because the estimand is a model-based cross-level association rather than a design-based population prevalence. EHIS individual sampling weights vary substantially across countries and would confound cross-national comparisons in a between-country decomposition; we therefore report unweighted estimates as the primary specification. Robustness checks with country-rescaled EHIS individual weights (available on request) produce substantively similar conclusions. Inference is based on cluster-robust standard errors at NUTS2 for the main and stratified models; the between-country component of the Mundlak decomposition should additionally be read with country-level inference in mind.

Because the welfare-regime strata contain only 18, 20, and 47 NUTS2 regions, respectively, we report two stratified specifications for each regime. The fully adjusted specification retains the regional covariates used in the pooled analysis, while the reduced specification retains country fixed effects but omits the regional covariate block. We use the comparison to assess specification sensitivity rather than to select a preferred regime estimate.  The stratified models are therefore interpreted as exploratory descriptive decompositions, not as estimates of stable welfare-regime parameters.

# 4 Results

## 4.1 Univariate patterns motivating the regression analysis

Table 2 reports descriptive statistics for the analytical sample by welfare regime. Two features are worth noting before we turn to the outcome distribution. First, the pooled sample rate of mh_case is 13.02 %, with Social-Democratic countries returning the highest rate (15.44 %) — an inversion of what a naïve reading of welfare-state generosity would predict. This reflects, in part, the well-established cross-country reporting-style heterogeneity in PHQ-8-style self-report instruments (Jürges, 2007; Salomon et al., 2004): Nordic respondents are more willing to endorse depressive-symptom items than their Central and Eastern European counterparts. Second, the three regimes differ starkly in mean PUI_digital: Social-Democratic +1.77 SD, Conservative-Corporatist +0.26 SD, Post-communist −0.54 SD. These distributional facts anchor the regime-stratified analysis that follows.

*Table 2. Descriptive statistics of the analytical sample, by welfare regime.*

| | Pooled | Social Democratic | Conservative-Corporatist | Post-communist |
|---|---|---|---|---|
| **Sample size** | | | | |
| **N (respondents)** | 92,961 | 19,070 | 22,249 | 51,642 |
| **Countries** | 13 | 3 | 2 | 8 |
| **NUTS2 regions** | 85 | 18 | 20 | 47 |
| **Outcome variables (depression risk)** | | | | |
| **mh_case (PHQ-8 ≥ p90)** | 13.02 % | 15.44 % | 12.71 % | 12.27 % |
| **mh_case10 (PHQ-8 ≥ 10)** | 5.99 % | 7.66 % | 6.26 % | 5.25 % |
| **PHQ-8 total, mean (SD)** | +2.76 (3.77) | +3.13 (4.17) | +2.90 (3.66) | +2.58 (3.65) |
| **Digital vulnerability** | | | | |
| **dig_demo (= 1 if age ≥ 65 OR ISCED ≤ 2)** | 40.22 % | 40.04 % | 38.18 % | 41.16 % |
| **Age 65+** | 29.88 % | 30.34 % | 25.34 % | 31.66 % |
| **ISCED 0–2 (lower secondary or less)** | 19.38 % | 18.08 % | 22.83 % | 18.38 % |
| **Age category distribution** | | | | |
| **15–34** | 21.15 % | 22.12 % | 23.94 % | 19.59 % |
| **35–49** | 30.73 % | 29.76 % | 32.67 % | 30.26 % |
| **50–64** | 18.24 % | 17.78 % | 18.05 % | 18.49 % |
| **65–74** | 17.38 % | 18.58 % | 13.38 % | 18.67 % |
| **75+** | 12.49 % | 11.76 % | 11.96 % | 13.00 % |
| **Education (ISCED)** | | | | |
| **ISCED 0–2** | 19.38 % | 18.08 % | 22.83 % | 18.38 % |
| **ISCED 3–4** | 47.52 % | 38.73 % | 45.75 % | 51.53 % |
| **ISCED 5–8** | 33.10 % | 43.19 % | 31.43 % | 30.09 % |
| **Sex** | | | | |
| **Female** | 55.29 % | 53.69 % | 53.19 % | 56.79 % |
| **Urbanisation (DEG_URB)** | | | | |
| **Densely populated** | 29.95 % | 40.24 % | 25.88 % | 27.91 % |
| **Intermediate** | 31.98 % | 32.82 % | 35.09 % | 30.33 % |

| | | | | |
|---|---|---|---|---|
| **Thinly populated** | 38.07 % | 26.94 % | 39.04 % | 41.76 % |
| **Employment status** | | | | |
| **Employed** | 48.83 % | 52.73 % | 51.56 % | 46.22 % |
| **Unemployed** | 4.04 % | 2.96 % | 3.50 % | 4.67 % |
| **Retired** | 33.33 % | 28.23 % | 30.38 % | 36.49 % |
| **Other inactive** | 13.18 % | 13.90 % | 14.10 % | 12.52 % |
| **Household income quintile** | | | | |
| **Q1 (lowest)** | 18.64 % | 16.01 % | 19.16 % | 19.39 % |
| **Q2** | 19.12 % | 17.69 % | 18.81 % | 19.78 % |
| **Q3** | 21.47 % | 19.98 % | 22.42 % | 21.61 % |
| **Q4** | 20.78 % | 22.77 % | 20.90 % | 19.99 % |
| **Q5 (highest)** | 19.99 % | 23.55 % | 18.72 % | 19.22 % |
| **Chronic condition count** | | | | |
| **0** | 35.70 % | 30.24 % | 35.10 % | 37.98 % |
| **1** | 23.08 % | 27.11 % | 24.84 % | 20.83 % |
| **2 or more** | 41.22 % | 42.66 % | 40.06 % | 41.19 % |
| **Social support (Oslo-3)** | | | | |
| **Weak** | 57.33 % | 43.70 % | 65.83 % | 58.70 % |
| **Moderate** | 30.51 % | 38.89 % | 22.86 % | 30.72 % |
| **Strong** | 12.15 % | 17.41 % | 11.30 % | 10.58 % |
| **Regional Digital Service Ecosystem Maturity** | | | | |
| **PUI_digital (regional z-score; individual-weighted exposure)** | +0.12 (1.13) | +1.77 (0.22) | +0.26 (0.39) | -0.54 (0.88) |

*Note. The analytic sample is the common complete-case sample defined across the variables required for the main, decomposition, and pathway analyses (mh_case, mh_index, dig_demo, unmet_need, PUI z-scores, PUI within-country deviations, individual controls, four regional covariates, region_nid, country); N = 92,961. Employment status is reported here descriptively but is not used as a covariate in the estimated models. Welfare-regime assignment follows Esping-Andersen (1990), Ferrera (1996), and Fenger (2007). The Southern Model stratum (Ferrera 1996) is empty in this sample. Standard deviations are shown in parentheses for continuous variables; all other cells are percentages.*

Turning to age structure: across all five outcome operationalisations, an 'elderly break' emerges (Figure 1). Mean PHQ-8 stays flat across ages 15–74, then jumps at 75+; the mh_case rate rises from a 10–12 % band below age 75 to over 20 % at 75+ in most countries.

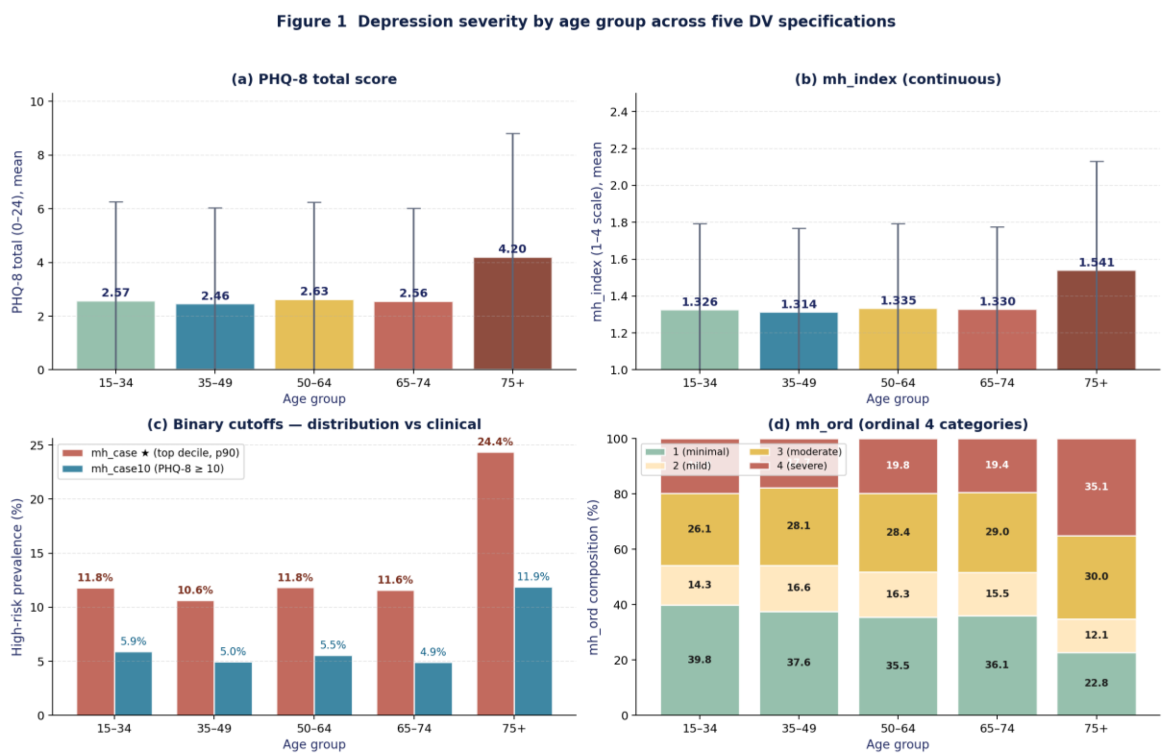


*Figure 1. Depression severity by age group across five outcome operationalisations. Panel (a) PHQ-8 total, (b) mh_index, (c) two binary cutoffs, (d) mh_ord four-category composition.*

The elderly-break pattern is unevenly distributed across the 85 NUTS2 regions. In Denmark, Sweden, and Belgium, elderly mh_case rates run 1.8–2.3 percentage points BELOW the non-elderly rate; Finland is approximately flat (−0.04 pp). Austria — nominally Conservative-Corporatist in the welfare-regime typology adopted in this paper — displays a different pattern with an elderly gap of +15.2 pp, closer to that of the Post-communist countries in the sample. Across the eight Post-communist countries the elderly gap ranges from +14.2 pp (Lithuania) to +23.3 pp (Poland). Country-level Digital Service Ecosystem Maturity (PUI_digital) ranges from +1.83 SD (Finland) at the top to −2.61 SD (Bulgaria) at the bottom, with Denmark at +1.70, Belgium at +0.50, and Austria at +0.02; among the Post-communist countries only Czechia (+0.10) sits above the sample mean, and Croatia (−1.06) and Bulgaria (−2.61) anchor the low end. Both distributions track welfare-regime typology closely, but with the two exceptions worth flagging — Austria on the elderly gap and Czechia on the ecosystem-maturity ranking.

When individuals are grouped by quintile of PUI_digital, the raw vulnerable–non-vulnerable gap in the mh_case rate is substantially smaller in the highest maturity quintiles and crosses zero at Q5 (Figure 2). This pattern anticipates the pooled interaction, although the subsequent decomposition shows that it primarily reflects cross-national rather than within-country regional variation.

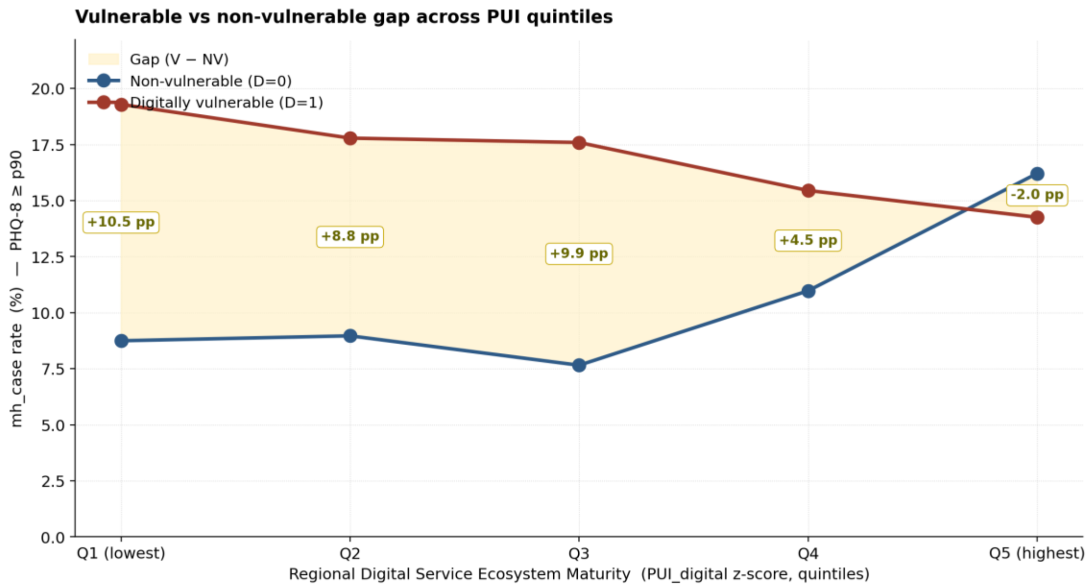


*Figure 2. Vulnerable–non-vulnerable gap in the mh_case rate across quintiles of regional PUI_digital. The gap declines from approximately +10.5 percentage points at Q1 to −2.0 percentage points at Q5.*

## 4.2 Integrated main analysis

Table 3 presents the pooled main-effects model, the pooled cross-level interaction model, and the within-country centered specification side by side. Welfare-regime-stratified estimates are reported separately in Table 5. Three empirical results emerge and permit direct comparison across the identification specifications.

*Table 3. Pooled main effects, pooled interaction, and within-country-centered specification.*

*Cross-level interaction between individual digital vulnerability (D) and regional Digital Service Ecosystem Maturity (W). Pooled and within-country-centered specifications.*

| | **MH1** **Pooled** **main effects** | **MH2** **Pooled** **cross-level interaction** | **MH_CWC** **Within-country** **centered W** |
|---|---|---|---|
| **$\beta_1$ · dig_demo (D)** | **-0.1059** **(0.0572)** | **-0.0223** **(0.0822)** | **-0.1056** **(0.0574)** |
| *OR [95 % CI]* | 0.8995 [0.804,1.006] | 0.9780 [0.832,1.149] | 0.8997 [0.804,1.007] |
| *p* | 0.064 | 0.786 | 0.066 |
| **$\beta_2$ · PUI_digital (W)** | **-0.0339** **(0.0593)** | **+0.1147** **(0.0612)** | **-0.0070** **(0.0938)** |
| *OR [95 % CI]* | 0.9667 [0.861,1.086] | 1.1216 [0.995,1.264] | 0.9931 [0.826,1.194] |
| *p* | 0.568 | 0.061 | 0.941 |
| **$\beta_3$ · dig_demo × PUI_digital** | **—** | **-0.2812** **(0.0380)** | **-0.0547** **(0.1554)** |
| *OR [95 % CI]* | — | 0.7549 [0.701,0.813] | 0.9468 [0.698,1.284] |
| *p* | — | < 0.001*** | 0.725 |
| **★ $\beta_2 + \beta_3$ W slope, vulnerable (D = 1)** | **—** | **-0.1665** **(0.0632)** | **-0.0616** **(0.1013)** |
| *OR* | — | 0.8466 | 0.9402 |
| *p* | — | 0.008** | 0.543 |

| | | | |
|---|---|---|---|
| **N (respondents)** | **92,961** | **92,961** | **92,961** |
| NUTS2 regions | 85 | 85 | 85 |
| Countries | 13 | 13 | 13 |
| *Individual controls* | yes | yes | yes |
| *Country fixed effects* | yes | yes | yes |
| *Cluster-robust SE at NUTS2* | yes | yes | yes |

*Note. Cell entries: point estimate on log-odds scale with cluster-robust standard error in parentheses; second row gives the odds ratio with 95 % CI in brackets; third row gives the p-value. Significance: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. $\beta_2 + \beta_3$ (shaded row) is the marginal effect of W on the log-odds for the digitally vulnerable (D = 1); standard error computed by the delta method retaining $Cov(\beta_2, \beta_3)$. Individual controls: 5-category age, 3-category ISCED education, sex, 3-category urbanisation, 5-quintile income, continuous chronic-condition z-score, 3-category Oslo-3 social support scale. All three specifications additionally include the narrower PUI_platform index and the four regional covariates (log GDP per capita, employment rate 20–64, hospital beds per 100,000, physicians per 100,000). MH_CWC replaces PUI_digital with its country-mean-centered component while retaining the remaining covariates in their original form. Welfare-regime-stratified estimates are reported separately in Table 5, together with a specification-sensitivity check (regional-control block included vs omitted).*

First, the pooled cross-level interaction is negative and highly significant. In MH2, $\beta_3 = -0.281$ (OR = 0.755, 95 % CI [0.70, 0.81], $p < 0.001$). The associated digital-maturity slope differs sharply across individual type. For the non-vulnerable, $\beta_2 = +0.115$ ($p = 0.061$): predicted depression risk is modestly higher in higher-maturity regions, an association we interpret non-causally. Because the model includes country fixed effects, this positive slope is better treated as a residual regional association that may reflect confounding, measurement composition, or cross-cultural response-style heterogeneity not fully captured by country intercepts (King et al., 2004). For the vulnerable, $\beta_2 + \beta_3 = -0.167$ (SE = 0.063, $p = 0.008$): predicted risk is modestly lower in higher-maturity regions. The paper's principal empirical claim is not that either subgroup slope has a particular magnitude, but that the difference between them — captured by $\beta_3$ — is large and highly significant. In the pooled specification, composite digital ecosystem maturity has a more negative association with depression risk among digitally vulnerable respondents than among non-vulnerable respondents.

Second, the interaction dissolves under within-country centering. In MH_CWC, $\beta_3 = -0.055$ ($p = 0.725$) and $\beta_2 + \beta_3 = -0.062$ ($p = 0.543$). This indicates that the identifying variation for the pooled interaction is essentially between-country: within-country regional variation alone does not yield the differential association.

Third, welfare-regime stratification (Table 5) allows a descriptive decomposition of this between-country variation but does not identify a stable regime-specific parameter. The interaction coefficient $\beta_3$ is comparatively similar across the three regimes and across the regional-control specification, but the main digital-maturity slope $\beta_2$ changes appreciably in the Social-Democratic and Conservative-Corporatist strata when regional covariates are added or removed. The vulnerable-group slope $\beta_2 + \beta_3$ is therefore sensitive to the specification choice in these small strata. Given the small number of countries and regions in each regime (three, two, and eight countries respectively), the stratified results are treated as exploratory descriptive contrasts rather than as estimates of stable welfare-regime parameters. What the stratification does support is the more limited claim that the stratified point estimates vary descriptively across the regime groupings and across specifications, suggestive of cross-national heterogeneity whose location varies by specification — a further indication that the pooled pattern is a cross-national phenomenon rather than a within-country regional-infrastructure effect.

### 4.3 Reinterpreting the interaction: two marginal effects

The negative and significant interaction OR admits two distinct verbal readings that must be kept separate. The first — which we do not endorse — is that 'the effect of digital-ecosystem maturity on mental health reverses sign for the vulnerable'. The second — which the pooled MH2 estimate is compatible with — is that the point estimates of the two subgroup slopes have opposite signs, but only the vulnerable-group slope is statistically distinguishable from zero at conventional levels. Only the difference $\beta_3$ identifies a robust relative pattern. Specifically, $\beta_2 = +0.115$ ($p = 0.061$) is not significantly distinguishable from zero for the non-vulnerable, and $\beta_2 + \beta_3 = -0.167$ ($p = 0.008$) is negative and significant for the vulnerable. We do not interpret either subgroup slope causally. The quantity of empirical interest is the relative slope difference $\beta_3$, which indicates that the association between PUI_digital and depression risk is more negative among vulnerable respondents than among non-vulnerable respondents in the pooled specification.

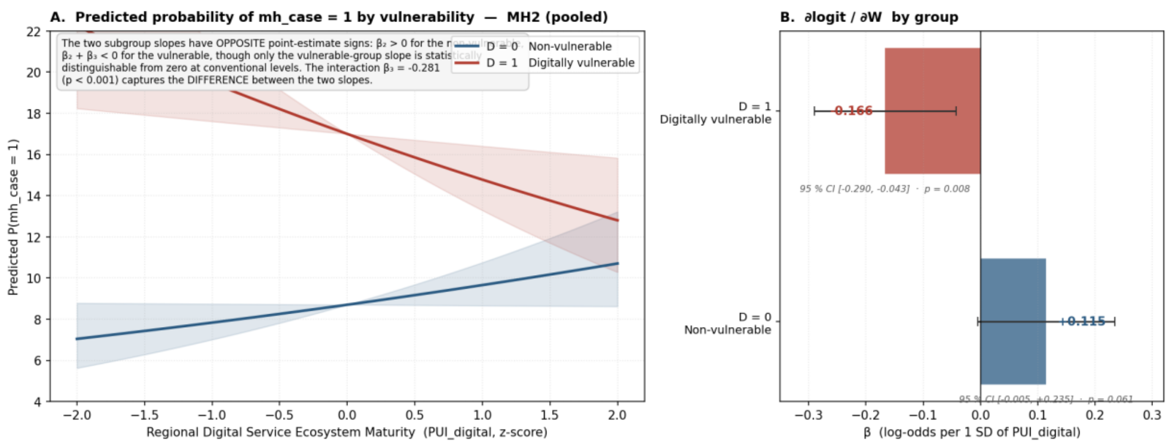


*Figure 3. Marginal effect of PUI_digital on P(mh_case = 1) by vulnerability status — pooled MH2. Panel A: predicted probability curves with 95 % CI bands. The D = 0 (non-vulnerable) curve slopes modestly upward with W ($\beta_2 = +0.115$, $p = 0.061$), while the D = 1 (vulnerable) curve slopes modestly downward ($\beta_2 + \beta_3 = -0.167$, $p = 0.008$); the two curves cross near $W \approx 0$. Panel B: log-odds slopes $\beta_2$ (D = 0) and $\beta_2 + \beta_3$ (D = 1) with 95 % CIs, showing that 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 $\beta_3 = -0.281$ ($p < 0.001$) — not either slope in isolation.*

Figure 3 visualises the pooled MH2 result. The digital-maturity slope on the outcome, $\partial \text{logit} / \partial W = \beta_2 + \beta_3 \cdot D$, is calculable at each level of D. For D = 0 this equals $\beta_2 = +0.115$ ($p = 0.061$), and for D = 1 it equals $\beta_2 + \beta_3 = -0.167$ ($p = 0.008$). The positive non-vulnerable slope should not be interpreted as a harmful effect of digital maturity. Because the model includes country fixed effects, this slope is better treated as a non-causal within-country regional association that may reflect residual regional confounding, measurement composition, or outcome-reporting heterogeneity not captured by country intercepts. The paper's identified quantity is the relative slope difference $\beta_3 = -0.281$ ($p < 0.001$). The curves in Figure 3 cross near W = 0, so the vulnerability–outcome gap shifts sign across the observed range of PUI_digital even as no single subgroup slope reverses sign along the way.

## 4.4 Dimensional decomposition

Because dig_demo is a union of age and education criteria, we decompose the interaction. The age-dimensional interactions yield a monotonic protective gradient: 35–49 OR = 0.86, 50–64 OR = 0.71, 65–74 OR = 0.57, and 75+ OR = 0.5374 ($p < 0.001$); a linear-trend test rejects the null ($\chi^2 = 18.47$, $p < 0.001$). The education dimension shows no analogous gradient: ISCED 3–4 OR = 1.07, ISCED 5–8 OR = 0.94, neither statistically distinguishable from unity. The absence of an analogous education gradient provides a useful internal contrast: a generic category-boundary artefact would produce a spurious gradient in both dimensions, whereas the observed pattern is age-specific.

This asymmetry between age and education is theoretically instructive rather than merely descriptive. A plausible interpretation is that elderly respondents may benefit from the ambient digital environment through pathways that do not require personal digital literacy — proxy digital navigators such as adult children and household caregivers (Correa et al., 2015; Hunsaker & Hargittai, 2018), structured elderly-care networks that mediate access to public services, and welfare-state routines that pre-configure benefit take-up on their behalf. Low-education working-age respondents may have less consistent access to comparable proxy-navigation or welfare-mediated support, although these mechanisms are not measured in EHIS 2019. Their digital exclusion tends to be persistent across the life course, in line with Friemel's (2016) documentation of the 'grown-old' digital divide, and the welfare-institutional systems that assist the elderly in navigating digital public services may not extend equivalently to working-age adults with limited formal education. This structural asymmetry — proxy-mediated access for the elderly versus unbridged institutional barriers for the low-educated — offers a plausible interpretation of why the pooled interaction appears age-specific. EHIS 2019 does not directly measure proxy navigation, household support, or welfare-mediated service completion, so this account should be treated as theoretically motivated rather than empirically identified. This asymmetry is central to the candidate mechanism developed later.

### 4.5 Candidate mediators and moderators

Two exploratory pathway checks return null results. Three-way interaction with the Oslo-3 social support scale yields $\chi^2(2) = 1.07$ ($p = 0.59$): social support does not moderate the interaction. Indirect mediation through unmet medical care yields an indirect effect $\approx -0.002$ (n.s.).

These exploratory checks do not support unmet medical care or general social support as the measured channels through which the pooled interaction operates. An administrative-friction or cognitive-load mechanism remains a plausible but untested alternative. The two null results should therefore be read as evidence that two commonly hypothesised pathways are not supported in EHIS 2019, rather than as identification of a specific surviving mechanism. What they leave in place is an identification question about where in the data the pooled interaction is actually estimated.

### 4.6 Within-between decomposition of the interaction

To make the identification structure of the pooled interaction more transparent, we re-estimate the model with PUI_digital explicitly decomposed into a within-country component and a between-country component in the Mundlak-style formulation W_j = W_within_j + W_between_c(j), where W_between_c is the country mean and W_within_j is the region-specific deviation from that mean. The model then admits two cross-level interactions, D × W_within and D × W_between, whose separate estimates locate where the pooled interaction is coming from. Table 4 reports the result.

*Table 4. Mundlak within-between decomposition of the cross-level interaction.*

| Term | β (log-OR) | SE | OR | p |
|---|---|---|---|---|
| **D × PUI_within (within-country component)** | -0.0576 | 0.1240 | 0.9440 | 0.642 |
| **D × PUI_between (between-country component)** | **-0.3038** | **0.0333** | **0.7380** | **< 0.001*** |

*Note. Logistic regression with individual controls and country fixed effects; cluster-robust SE at NUTS2. W_within is PUI_digital with the country mean subtracted; W_between is the country mean of PUI_digital. The model includes PUI_within, dig_demo, D × PUI_within, D × PUI_between, individual controls, regional covariates, and country fixed effects. The non-interacted PUI_between main effect is absorbed by country fixed effects and is therefore not separately estimated. Because the between-country interaction is identified from country means (J_country = 13), the p-value shown is based on cluster-robust SE at NUTS2 and should be read with country-level inference in mind; leave-one-country-out diagnostics are reported in Appendix A and yield qualitatively similar conclusions. The point estimate is large and stable across leave-one-country-out analyses, although higher-level inference remains limited by the 13-country sample; country-level wild cluster bootstrap results are available on request. N = 92,961, NUTS2 = 85, countries = 13. Significance: * p < 0.05, ** p < 0.01, *** p < 0.001.*

The decomposition yields a pronounced contrast between the within- and between-country components. The within-country component of the cross-level interaction 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 ecosystem maturity. The between-country component ($\beta = -0.304$, $p < 0.001$) is essentially identical in magnitude to the pooled interaction estimate from MH2, and accounts for almost the entirety of the pooled result. In the pooled Mundlak model, the larger number of regions and the explicit separation of within- and between-country components make the key interaction estimates less sensitive to the regional-control block than they are within the small welfare-regime strata. The between-country term identifies whether the individual vulnerability gap covaries with country-average digital ecosystem maturity — that is, whether countries with higher mean digital maturity exhibit a more negative vulnerability slope on average. This is a stronger identification statement than the CWC test alone: the pooled interaction is not merely 'reduced' by within-country identification, it is empirically concentrated in the between-country component. We treat this decomposition, rather than the CWC alternative estimation, as the primary within-between identification test.

### 4.7 Welfare-regime stratified analysis: specification sensitivity

The three welfare-regime strata contain only 18 NUTS2 regions in Social-Democratic (three countries), 20 regions in Conservative-Corporatist (two countries), and 47 regions in Post-communist (eight countries). In such small strata, the choice of whether to include the four regional covariates alongside country fixed effects has a material effect on estimated slopes. We therefore report two specifications for each regime: a fully adjusted model that retains the regional covariate block used in the pooled analysis, and a reduced model that retains country fixed effects but omits the regional covariates. The comparison is intended to assess specification sensitivity rather than to select a preferred estimate.

*Table 5. Welfare-regime specification-sensitivity analysis.*

| **Regime** | **Specification** | **$\beta_2$ (SE)** | **$\beta_3$ (SE)** | **p($\beta_3$)** | **$\beta_2+\beta_3$ [95 % CI]** | **p($\beta_2+\beta_3$)** | **N (regions)** |
|---|---|---|---|---|---|---|---|
| **Social-Democratic** | Full: FE + regional | -0.278 (0.141) | -0.246 (0.316) | 0.436 | -0.524 [-0.936, -0.112] | 0.013 | 19,070 (18) |
| | Reduced: FE only | +0.114 (0.202) | -0.223 (0.322) | 0.488 | -0.110 [-0.562, +0.342] | 0.634 | 19,070 (18) |
| **Conservative-Corporatist** | Full: FE + regional | +0.214 (0.149) | -0.561 (0.189) | 0.003 | -0.347 [-0.725, +0.031] | 0.072 | 22,249 (20) |
| | Reduced: FE only | +0.053 (0.180) | -0.565 (0.187) | 0.003 | -0.512 [-0.769, -0.255] | < 0.001 | 22,249 (20) |
| **Post-communist** | Full: FE + regional | +0.040 (0.092) | -0.158 (0.076) | 0.038 | -0.118 [-0.316, +0.081] | 0.245 | 51,642 (47) |
| | Reduced: FE only | +0.001 (0.077) | -0.158 (0.076) | 0.037 | -0.157 [-0.303, -0.011] | 0.035 | 51,642 (47) |

*Note. Each pair reports the stratum-specific logistic regression under two specifications. Full: individual controls + regional covariates (GDP per capita, employment rate, hospital beds, physicians) + country fixed effects. Reduced: individual controls + country fixed effects, regional covariates omitted. Cluster-robust SE at NUTS2 in both. The interaction $\beta_3$ is comparatively stable across specifications, but the main slope $\beta_2$ shifts appreciably in the Social-Democratic and Conservative-Corporatist strata, and the vulnerable-group slope $\beta_2 + \beta_3$ inherits this sensitivity. Because $\beta_2 + \beta_3$ combines the interaction with the reference-group W slope, a stable $\beta_3$ does not guarantee a stable vulnerable-group slope when $\beta_2$ is imprecisely estimated in a small stratum. The results are therefore treated as exploratory descriptive contrasts and are not used to identify a stable welfare-regime parameter. Country-specific estimates within the Conservative-Corporatist stratum, also reported under both specifications, are presented in Appendix Table A3.*

Two features of the sensitivity pattern are worth noting. First, the interaction term $\beta_3$ moves only modestly across the two specifications in every regime (Social-Democratic: −0.246 vs −0.223; Conservative-Corporatist: −0.561 vs −0.565; Post-communist: −0.158 vs −0.158). The instability is therefore not in the estimated interaction itself but in the reference-group W slope $\beta_2$, which flips sign in the Social-Democratic stratum (−0.278 with regional controls vs +0.114 without) and shrinks substantially in the Conservative-

Corporatist stratum (+0.214 vs +0.053). This sensitivity is substantively important because $\beta_2 + \beta_3$ combines the interaction term with the reference-group slope.

Second, 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. Detailed country-specific results under both specifications are reported in Appendix Table A3. Given the sensitivity to specification and the small number of countries in each stratum, the stratified results do not identify a stable Social-Democratic, Conservative-Corporatist, or Post-communist welfare-regime parameter. Whether particular welfare or administrative institutions condition the digital-maturity association requires a larger country sample and directly measured institutional covariates.

### 4.8 Construct-validity check: PUI_platform (narrower platform-transaction index)

The seven Eurostat ICT indicators aggregated into PUI_digital mix infrastructural supply, usage behaviour, and skills at the NUTS2 scale. This is a construct-validity concern, not a peripheral robustness worry: if the observed interaction reflected the platform-service component of regional digital maturity, it should reproduce under a narrower platform-transaction construct. We therefore re-estimate the pooled MH2 specification substituting a narrower platform-transaction index PUI_platform, constructed as the first principal component of three service-platform variables — e-government interaction, e-commerce, and e-banking — that more narrowly track digital service channels than PUI_digital does. Because the available NUTS2 platform indicators still partly measure uptake rather than pure supply-side availability, this check should not be read as a definitive supply-side infrastructure-provision test. It is instead a narrower platform-transaction construct-validity check. The result is a null interaction: $\beta_3 = +0.011$ (SE = 0.054, $p = 0.84$), with a vulnerable-group marginal effect $\beta_2 + \beta_3 = -0.004$ ($p = 0.91$). The narrower index eliminates the interaction that PUI_digital returned.

This is a substantive finding, not merely a diagnostic one. Under the narrower platform-transaction reading — the reading that would come closest to justifying the label 'digital infrastructure' — the interaction disappears. The pooled result therefore is not identified by infrastructure provision alone, but by the combined digital-ecosystem index that mixes infrastructural, usage, and skills components. Two interpretations follow directly. First, the appropriate name for what PUI_digital measures is a composite digital ecosystem or digital-service readiness construct, and specifically not a supply-side infrastructure-provision construct in the narrow sense. Second, the pooled association between PUI_digital and vulnerable-group outcomes cannot be interpreted as evidence of an infrastructure-provision effect. On both counts, the substantive target of the analysis is a composite digital-service ecosystem association rather than an infrastructure-provision effect.

# 5 Discussion

## 5.1 Decomposing an apparent protective effect

At first glance, composite digital maturity appears to attenuate the excess mental-health risk associated with digital vulnerability in the pooled 2019 EU cross-section. Read on its own, the pooled interaction of dig_demo × PUI_digital lends itself to a natural regional-infrastructure interpretation: places with higher digital maturity protect their more digitally exposed residents. The three diagnostic analyses reported above do not sustain this reading.

The Mundlak decomposition fundamentally qualifies the pooled result. The interaction is not estimated from within-country regional variation but from between-country differences. Comparing NUTS2 regions to one another inside the same country produces no differential association between individual vulnerability and regional digital ecosystem maturity. A reader interested in whether a more digitally mature region within a given country differentially protects vulnerable residents finds no evidence in our data. The regional-infrastructure framing that would justify such an inference is empirically vacated by the within-country component's null estimate.

Two further tests deepen this constraint on the pooled interpretation. The construct-validity check using PUI_platform shows that the pooled interaction does not reproduce under a narrower platform-transaction measurement of the digital-infrastructure construct. Whatever the pooled model is capturing, it is not a narrowly infrastructural provision effect. The welfare-regime stratification does not identify a stable ordering of welfare regimes. Although the interaction term itself is comparatively similar across alternative specifications, regime-specific vulnerable-group slopes depend materially on the regional-control block, particularly in the small Social-Democratic and Conservative-Corporatist strata. Country-specific patterns within the two-country Conservative-Corporatist stratum are likewise specification-sensitive and do not support a mechanism replicated across Austria and Belgium. Taken together with the Mundlak and construct-validity results, the picture is not one of infrastructure–welfare complementarity as a substantiated mechanism, but of an apparent protective effect that decomposes into cross-national ecosystem, uptake, and institutional differences whose specific causal components our data cannot separate.

The paper's main empirical contribution should therefore be read as a decomposition rather than a discovery. We do not show that regional digital infrastructure protects vulnerable individuals. We show that apparent digital-protection effects on the mental health of vulnerable Europeans are highly sensitive to measurement level, index composition, and cross-national institutional context, and that once these sensitivities are accounted for, the case for a regional-infrastructure reading is weak.

## 5.2 Interpreting the between-country ecosystem pattern

The stratified analysis does not support a stable ordering of welfare regimes. Although the interaction term itself is comparatively similar across alternative specifications, regime-specific vulnerable-group slopes depend materially on the regional-control block. Welfare-regime categories therefore serve only as descriptive institutional contexts in the present analysis. Determining whether particular welfare or administrative institutions condition the digital-maturity association requires a larger country sample and directly measured institutional covariates.

A plausible mechanism to which this pattern could be attributed differs from what the rejected mediators would have suggested. The null results on the Oslo-3 social support scale and on unmet medical care do not identify a surviving mechanism. They only indicate that these two measured pathways — social support and unmet medical care — are not supported in EHIS 2019. An administrative-friction or cognitive-load pathway remains a theoretically plausible interpretation for future research, but it is not directly tested here. Presented as a hypothesis rather than as an identified mechanism, this pathway would run through the everyday reduction of cognitive load, administrative friction, and low-grade chronic stress associated with navigating essential public and transactional services. Under this hypothesis, vulnerable individuals in mature digital-service ecosystems with functioning welfare intermediation would be expected to expend less cognitive and emotional bandwidth on tasks such as tax filing, medical appointment booking, benefit application, prescription renewal, and utility account management. This reduction in ambient administrative and cognitive load — rather than a specific clinical encounter or a specific relational-support activation — is the candidate channel that remains theoretically consistent with Robeyns's (2017) capability-substituting mode.

Understood in this way, the reading extends the social-infrastructure argument of Klinenberg (2018) and Latham and Layton (2019) from the physical spaces (libraries, community centres, well-maintained public facilities) that ground their accounts into the digital-service layer that increasingly mediates everyday transactional life in Europe. It also clarifies the age-versus-education asymmetry documented in the Results: elderly respondents may be more likely to draw on proxy digital navigators (Correa et al., 2015; Hunsaker & Hargittai, 2018) and welfare-state routines that transmit the ambient-load reduction to them, whereas low-education working-age adults may face persistent digital-literacy barriers (Friemel, 2016) with no comparable institutional circuitry that would translate infrastructural availability into administrative-load reduction on their behalf.

The third-story reading is not observationally equivalent to either of the two originally posited. It generates three distinct empirical predictions in richer data. First, richer panel data could test whether within-region changes in digital maturity interact with independently measured welfare-institutional capacity to predict differential outcomes: neither alone should suffice. Second, quasi-experimental infrastructure rollouts in high- and low-welfare-capacity contexts could test whether comparable investments yield different vulnerable-group outcomes across institutional settings. Third, direct measures of everyday administrative and cognitive load — service completion time, form-abandonment rate, ambient chronic-stress biomarkers — could be tested as candidate mediators of the interaction where more distal mediators (social support, unmet medical care) do not. None of these three tests is possible with EHIS 2019 alone.

### 5.3 Institutional splintering as interpretive resource

Graham and Marvin's (2001) argument in Splintering Urbanism — that the twentieth-century modernist infrastructural ideal has been institutionally unbundled into differentiated service tiers — remains a useful interpretive resource for future research. The specification-sensitive stratified estimates do not, however, permit the present study to map institutional unbundling onto particular welfare-regime categories. The results are compatible with cross-national institutional heterogeneity, but they do not identify whether Social-Democratic, Conservative-Corporatist, or Post-communist institutions systematically strengthen or weaken the association between composite digital-service maturity and vulnerable-group depression risk. Adjudicating the institutional-unbundling reading against alternatives requires a larger country sample and directly measured indicators of welfare-institutional capacity.

### 5.4 Situating findings within the empirical literature

Our finding stands in productive tension with prior empirical work on digital divide and mental health. The dominant strand — Crawford and Serhal (2020) on digital health equity, Spanakis et al. (2021) on severe mental illness during COVID-19 — documents that individual digital disadvantage reinforces individual health disadvantage. Our pooled result does not contradict this literature; it operates at a different scale. What we add is the regional-scale observation that the aggregate pattern of individual disadvantage is strongly conditioned by cross-national digital-service and institutional context. This qualifies the individual-scale claim by locating the pooled association primarily in cross-national rather than within-country regional variation.

## 6 Conclusion and Policy Implications

Does regional digital service maturity differentially protect digitally vulnerable individuals from elevated depression risk? The empirical evidence only partially supports the expectation that it does. While pooled models show a negative interaction between vulnerability and composite digital maturity, Mundlak decomposition demonstrates that this pattern is almost entirely attributable to between-country differences rather than within-country regional variation. A narrower platform-transaction index eliminates the interaction, and welfare-regime-stratified estimates are sensitive to the inclusion of regional covariates and do not identify a stable regime-specific parameter. These findings caution against interpreting the pooled interaction as a regional infrastructure effect. Rather, the results suggest that apparent digital protection for vulnerable groups reflects broader cross-national digital-service ecosystems, population capabilities, and institutional contexts.

The findings do not support a simple infrastructure-investment interpretation. A narrower platform-transaction construct does not reproduce the protective interaction, and within-country regional variation in digital maturity does not moderate vulnerability risk. Policy evaluation should therefore distinguish infrastructure provision from service uptake, population capabilities, and institutional accessibility, rather than assume that infrastructure investment alone will reproduce the pooled association. The message we defend is not that digital infrastructure investment can be expected to reduce vulnerable populations' depression risk; it is that a simple infrastructure-provision interpretation is insufficient to account for the pooled association, and that these distinctions deserve central attention in policy evaluation.

The paper's contribution is therefore best understood as a decomposition rather than a discovery. For subsequent work, priority designs are: (i) an EHIS panel analysis exploiting within-region temporal variation in specific infrastructure rollouts (national broadband initiatives, e-government platform launches); (ii) natural-experimental variation in infrastructure holding welfare-institutional context approximately fixed; (iii) three-level (individual → NUTS2 → country) models with country-level welfare-capacity covariates coded per Esping-Andersen (1990), Ferrera (1996), and Fenger (2007) that could adjudicate between the mechanisms our decomposition cannot separate; and (iv) NUTS3 replication where sample size permits, to test sensitivity to the modifiable areal unit problem (Openshaw, 1984). We treat the decomposition presented in this paper as motivating rather than resolving the identification questions that a regional-infrastructure interpretation of digital-service-maturity effects raises.

# Appendix A · Robustness of the Mundlak decomposition

This appendix reports two robustness checks on the between-country component of the cross-level interaction (D × PUI_between, Table 4) and one country-specific sensitivity analysis for the Conservative-Corporatist stratum. Table A1 shows leave-one-country-out estimates: dropping each of the 13 countries in turn and re-estimating the Mundlak decomposition. Table A2 compares the primary p90 outcome with one alternative clinical-cutoff operationalisation (PHQ-8 ≥ 10) of the depression outcome. Table A3 reports Austria and Belgium country-specific interaction estimates under both the fully adjusted and reduced specifications defined in §4.7.

*Table A1. Leave-one-country-out estimates of D × PUI_between (Mundlak decomposition).*

| **Country dropped** | **β_between** | **SE** | **p** | **N** |
|---|---|---|---|---|
| **AT (Austria)** | -0.3055 | 0.0335 | < 0.001 | 77,500 |
| **BE (Belgium)** | -0.2902 | 0.0342 | < 0.001 | 86,173 |
| **BG (Bulgaria)** | -0.2992 | 0.0446 | < 0.001 | 86,040 |
| **CZ (Czechia)** | -0.3017 | 0.0326 | < 0.001 | 85,270 |
| **DK (Denmark)** | -0.2957 | 0.0361 | < 0.001 | 87,974 |
| **FI (Finland)** | -0.3065 | 0.0332 | < 0.001 | 87,950 |
| **HR (Croatia)** | -0.3046 | 0.0339 | < 0.001 | 92,201 |
| **HU (Hungary)** | -0.3000 | 0.0334 | < 0.001 | 87,739 |
| **LT (Lithuania)** | -0.3106 | 0.0350 | < 0.001 | 88,750 |
| **PL (Poland)** | -0.2935 | 0.0321 | < 0.001 | 81,149 |
| **SE (Sweden)** | -0.3115 | 0.0404 | < 0.001 | 83,889 |
| **SI (Slovenia)** | -0.3437 | 0.0301 | < 0.001 | 83,437 |
| **SK (Slovakia)** | -0.2973 | 0.0335 | < 0.001 | 87,460 |
| **BASELINE (all 13 countries)** | **-0.3038** | **0.0333** | **< 0.001** | **92,961** |

*Note. Each row re-estimates the Mundlak decomposition (mh_case ~ dig_demo × PUI_within + dig_demo × PUI_between + individual controls + country FE) after dropping the indicated country. Cluster-robust SE at NUTS2. All 13 leave-one-country-out estimates remain negative and significant at p < 0.001, in a range from -0.290 (drop BE) to -0.344 (drop SI). The between-country result is not driven by any single country in the sample. Leave-one-country-out stability rules out dependence on any single country but does not overcome the limited number of independent country-level units.*

*Table A2. Pooled interaction and Mundlak decomposition across outcome operationalisations.*

| Outcome | pooled $\beta_3$ | p | D × PUI_within | p | D × PUI_between | p |
|---|---|---|---|---|---|---|
| **PHQ-8 ≥ p90 (primary)** | -0.2812 | < 0.001 | -0.0576 | 0.642 | -0.3038 | < 0.001 |
| **PHQ-8 ≥ 10 (clinical)** | -0.2912 | < 0.001 | +0.0176 | 0.887 | -0.3207 | < 0.001 |

*Note. Each row re-estimates the pooled interaction model (mh_case ~ dig_demo × PUI_digital + controls + country FE) and the Mundlak decomposition (dig_demo × PUI_within + dig_demo × PUI_between + controls + country FE), using the indicated outcome operationalisation as the binary dependent variable. The clinical cutoff PHQ-8 ≥ 10 is provided as one alternative operationalisation to the primary p90 threshold. The within-country component is null and the between-country component is significant under both operationalisations, confirming that the paper's decomposition claim is not an artefact of the primary p90 cutoff.*

*Table A3. Country-specific cross-level interaction estimates within the Conservative-Corporatist stratum, under both specifications.*

| Country | Specification | $\beta_3$ | p($\beta_3$) | $\beta_2$+$\beta_3$ | p($\beta_2$+$\beta_3$) | N (regions) |
|---|---|---|---|---|---|---|
| **Austria** | Full: FE + regional | -0.3879 | 0.219 | -0.0896 | 0.662 | 15,461 (9) |
| | Reduced: FE only | -0.4227 | 0.196 | -0.1928 | 0.048 | 15,461 (9) |
| **Belgium** | Full: FE + regional | +0.1025 | 0.546 | -0.5438 | 0.047 | 6,788 (11) |
| | Reduced: FE only | +0.0214 | 0.911 | -0.3333 | 0.044 | 6,788 (11) |

*Note. Standalone logistic regressions fit separately within Austria and Belgium; no country fixed effects (single-country samples). Individual controls as in the pooled MH2 model. Cluster-robust SE at NUTS2. Under the reduced specification, vulnerable-group slopes are negative and statistically significant in both countries, whereas under the full specification only the Belgian slope remains statistically distinguishable from zero. Country-specific interaction terms $\beta_3$ remain individually non-significant in both countries under either specification. The results therefore do not identify a stable country-specific interaction pattern and should not be used to identify a country-level mechanism.*

## References


Andreotti, A., Mingione, E., & Polizzi, E. (2012). Local welfare systems: A challenge for social cohesion. Urban Studies, 49(9), 1925–1940.

Correa, T., Straubhaar, J. D., Chen, W., & Spence, J. (2015). Brokering new technologies: The role of children in their parents' usage of the internet. New Media & Society, 17(4), 483–500.

Crawford, A., & Serhal, E. (2020). Digital health equity and COVID-19: The innovation curve cannot reinforce the social gradient of health. Journal of Medical Internet Research, 22(6), e19361.

Enders, C. K., & Tofighi, D. (2007). Centering predictor variables in cross-sectional multilevel models: A new look at an old issue. Psychological Methods, 12(2), 121–138.

Esping-Andersen, G. (1990). The Three Worlds of Welfare Capitalism. Princeton University Press.

Fenger, H. J. M. (2007). Welfare regimes in Central and Eastern Europe: Incorporating post-communist countries in a welfare regime typology. Policy Studies Journal, 35(1), 1–30.

Ferrera, M. (1996). The 'Southern Model' of Welfare in Social Europe. Journal of European Social Policy, 6(1), 17–37.

Festinger, L. (1954). A theory of social comparison processes. Human Relations, 7(2), 117–140.

Friemel, T. N. (2016). The digital divide has grown old: Determinants of a digital divide among seniors. New Media & Society, 18(2), 313–331.

Graham, S., & Marvin, S. (2001). Splintering Urbanism: Networked Infrastructures, Technological Mobilities and the Urban Condition. Routledge.

Helsper, E. J. (2012). A corresponding fields model for the links between social and digital exclusion. Communication Theory, 22(4), 403–426.

Hunsaker, A., & Hargittai, E. (2018). A review of internet use among older adults. New Media & Society, 20(10), 3937–3954.

Jürges, H. (2007). True health vs response styles: Exploring cross-country differences in self-reported health. Health Economics, 16(2), 163–178.

Kazepov, Y. (Ed.). (2010). Rescaling Social Policies: Towards Multilevel Governance in Europe. Ashgate.

King, G., Murray, C. J. L., Salomon, J. A., & Tandon, A. (2004). Enhancing the validity and cross-cultural comparability of measurement in survey research. American Political Science Review, 98(1), 191–207.

Klinenberg, E. (2018). Palaces for the People. Crown.

Kroenke, K., Strine, T. W., Spitzer, R. L., Williams, J. B. W., Berry, J. T., & Mokdad, A. H. (2009). The PHQ-8 as a measure of current depression in the general population. Journal of Affective Disorders, 114(1–3), 163–173.

Latham, A., & Layton, J. (2019). Social infrastructure and the public life of cities. Geography Compass, 13(7), e12444.

OECD/European Union. (2022). Health at a Glance: Europe 2022. OECD Publishing.

Openshaw, S. (1984). The Modifiable Areal Unit Problem. CATMOG 38. Geo Books.

Robeyns, I. (2017). Wellbeing, Freedom and Social Justice: The Capability Approach Re-Examined. Open Book Publishers.

Runciman, W. G. (1966). Relative Deprivation and Social Justice. University of California Press.

Salomon, J. A., Tandon, A., & Murray, C. J. L. (2004). Comparability of self-rated health: Cross-sectional multi-country survey using anchoring vignettes. BMJ, 328(7434), 258.

Scheerder, A., van Deursen, A., & van Dijk, J. (2017). Determinants of Internet skills, uses and outcomes: A systematic review of the second- and third-level digital divide. Telematics and Informatics, 34(8), 1607–1624.

Sen, A. (1992). Inequality Reexamined. Oxford University Press.

Sen, A. (1999). Development as Freedom. Knopf.

Spanakis, P., Peckham, E., Mathers, A., Shiers, D., & Gilbody, S. (2021). The digital divide: Amplifying health inequalities for people with severe mental illness. British Journal of Psychiatry, 219(4), 529–531.

van Dijk, J. (2020). The Digital Divide. Polity Press.