

Digital Isolation and Depression Risk in Older Adults: An 8-Year Longitudinal Study Using the NHATS Database

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Abstract

Background: The rapid advancement of digital technologies has profoundly transformed communication practices. However, this technological revolution has also led to "digital isolation," a form of social disconnection caused by limited or absent engagement with digital communication tools, including smartphones, computers, email, and the internet. This issue is particularly concerning for older adults, as it may increase their likelihood of developing mental health disorders, with depression being a primary concern. Although digital isolation has been studied less frequently than traditional social isolation, it may be a significant contributor to both the initiation and progression of depression in this population.

Objective: This investigation seeks to assess longitudinal relationships between multidimensional digital disengagement (encompassing four dimensions: mobile device utilization, computer interaction, electronic correspondence, and web-based engagement) and incident depression among older adults, utilizing longitudinal data from the nationally representative National Health and Aging Trends Study (NHATS).

Methods: The analysis was conducted based on the NHATS dataset, a nationally representative longitudinal survey employing multistage sampling to represent community-dwelling Medicare beneficiaries aged 65 and older in the US. We analyzed data from 2011 (Round 1) to 2018 (Round 8), including 8,199 participants in the discovery and validation cohorts. Digital isolation was measured using self-reported data on smart phones, computers, email, and internet platforms, with each categorized as isolated (1) or not isolated (0). Weighted Cox regression models with proportional hazards assumptions were employed to quantify longitudinal associations between digital disengagement and incident depression, incorporating multivariable adjustment for sociodemographic characteristics (age, sex, race or ethnicity), socioeconomic indicators (education level, family income, marital status), and clinical profiles (tobacco use history, multimorbidity burden). Time-to-event analyses were visualized through Kaplan-Meier estimators, complemented by prespecified subgroup analyses evaluating effect modification patterns through interaction term testing.

Results: Integrated analysis of combined cohorts demonstrated a robust longitudinal association between digital disengagement levels and depression incidence (crude model: HR=1.75, 95%CI 1.60-1.92; fully adjusted model: HR=1.35, 95%CI 1.18-1.55; both $P<0.001$). Participants exhibiting elevated disengagement showed 1.75-fold greater hazard of developing depression compared to those with minimal disengagement, demonstrating a dose-response gradient that persisted after comprehensive covariate adjustment. Specific aspects of digital isolation, including computer, email, and internet use, were significantly linked to depression risk, whereas mobile phone isolation had a weaker association.

Conclusions: The study reveals a robust correlation between increased digital isolation and a higher likelihood of depression in the elderly population. These results underscore the importance of implementing tailored public health strategies to address digital isolation, especially for older adults. To minimize its detrimental effects on mental health, policy makers should encourage digital literacy programs and strengthen mental health services.

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Digital Isolation and Depression Risk in Older Adults: An 8-Year Longitudinal Study Using the NHATS Database

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Abstract

Background

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adults, as it may increase their likelihood of developing mental health disorders, with depression being a primary concern. Although digital isolation has been studied less frequently than traditional social isolation, it may be a significant contributor to both the initiation and progression of depression in this population.

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The analysis was conducted based on the NHATS dataset, a nationally representative longitudinal survey employing multistage sampling to represent community-dwelling Medicare beneficiaries aged 65 and older in the US. We analyzed data from 2011 (Round 1) to 2018 (Round 8), including 8,199 participants in the discovery and validation cohorts. Digital isolation was measured using self-reported data on smart phones, computers, email, and internet platforms, with each categorized as isolated (1) or not isolated (0). Weighted Cox regression models with proportional hazards assumptions were employed to quantify longitudinal associations between digital disengagement and incident depression, incorporating multivariable adjustment for sociodemographic characteristics (age, sex, race or ethnicity), socioeconomic indicators (education level, family income, marital status), and clinical profiles (tobacco use history, multimorbidity burden). Time-to-event analyses were visualized through Kaplan-Meier estimators, complemented by prespecified subgroup analyses evaluating effect modification patterns through interaction term testing.

Results

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covariate adjustment. Specific aspects of digital isolation, including computer, email, and internet use, were significantly linked to depression risk, whereas mobile phone isolation had a weaker association.

Conclusions

The study reveals a robust correlation between increased digital isolation and a higher likelihood of depression in the elderly population. These results underscore the importance of implementing tailored public health strategies to address digital isolation, especially for older adults. To minimize its detrimental effects on mental health, policy makers should encourage digital literacy programs and strengthen mental health services.

Keywords: digital isolation; depression; older adults; longitudinal cohort study; NHATS; mental health; social isolation; technology use; risk factors; public health interventions

Introduction

In today's digital landscape, the rapid advancement of information technology has profoundly transformed human lifestyles. The growing prominence of digital technologies has resulted in an increased dependence on electronic devices for communication and social bonding, giving rise to a phenomenon known as "digital isolation." This term denotes the social disconnect that occurs when individuals either lack access to or choose not to engage with contemporary communication tools, such as smartphones, computers, email, and the internet [1, 2]. Despite their intent to foster human interaction, these technologies can paradoxically contribute to heightened feelings of loneliness and social isolation when misused or absent. Of significant concern is the negative effect this can have on mental health, particularly in relation to depression [3, 4].

Depression, a widespread global mental health disorder, significantly impairs quality of life and social functionality. Depression, affecting roughly 280 million individuals, or 3.8% of the global population, is a significant mental health concern, as reported by the World Health Organization. Women are disproportionately affected compared to men, and its prevalence increases notably in older adults, where it ranks high as a cause of disability and suicide [5-7]. Not merely a psychological issue, depression is intricately connected to physical health problems like cardiovascular disease and diabetes, contributing to a heightened mortality rate. Consequently, recognizing the risk factors for depression and developing efficient preventive and treatment approaches are of utmost importance for public health [8-10].

Social isolation has been widely acknowledged in the existing literature as a significant risk factor for the development of depression [11]. The term typically refers to a situation where an individual has limited access to social networks or face-to-face interactions[12]. However, in the digital age, social isolation has evolved into "digital isolation." Digital technologies provide numerous avenues for social engagement, but their usage patterns can profoundly affect mental health [13]. For instance, excessive reliance on social media may heighten social isolation, whereas rejecting these technologies can result in traditional social isolation [14, 15].

Studies have begun exploring the negative impacts of specific digital behaviors on the relationship between digital isolation and depression. For example, a study reported a significant link between excessive smartphone use and heightened depressive symptoms in young people [16]. However, research on how various forms of digital isolation influence depression risk remains limited. Additionally, existing studies often ignore the combined effects of multiple forms of digital isolation, lacking comprehensive analysis of their collective impact [17].

This investigation seeks to delineate domain-specific mechanisms linking multidimensional digital disengagement (operationalized as deficiencies in mobile connectivity, computer literacy barriers, electronic communication lapses, and internet engagement deficits) to incident depressive disorders in older adults, bridging a critical knowledge gap through rigorous longitudinal analysis of understudied socio-technological risk pathways. Using data from a large-scale retrospective cohort study, we aim to uncover associations between telephone, computer, email, and online isolation and depression risk. The study will also investigate the combined effects of these forms of isolation to inform digital health intervention strategies. The findings will offer new insights into how digital isolation affects mental health, guiding the creation of evidence-based public health policies to prevent and mitigate depression.

Methods

Study Population

The National Health and Aging Trends Study (NHATS) formed our analytical sample, a longitudinal survey that utilizes a multistage probability sampling technique to mirror the US population of community-living Medicare beneficiaries aged 65 years and above. Designed to examine the health and aging dynamics of older Americans, NHATS initially draws samples from the Medicare enrollee list, deliberately over-representing individuals aged 85 and above to guarantee sufficient representation of the senior age brackets.

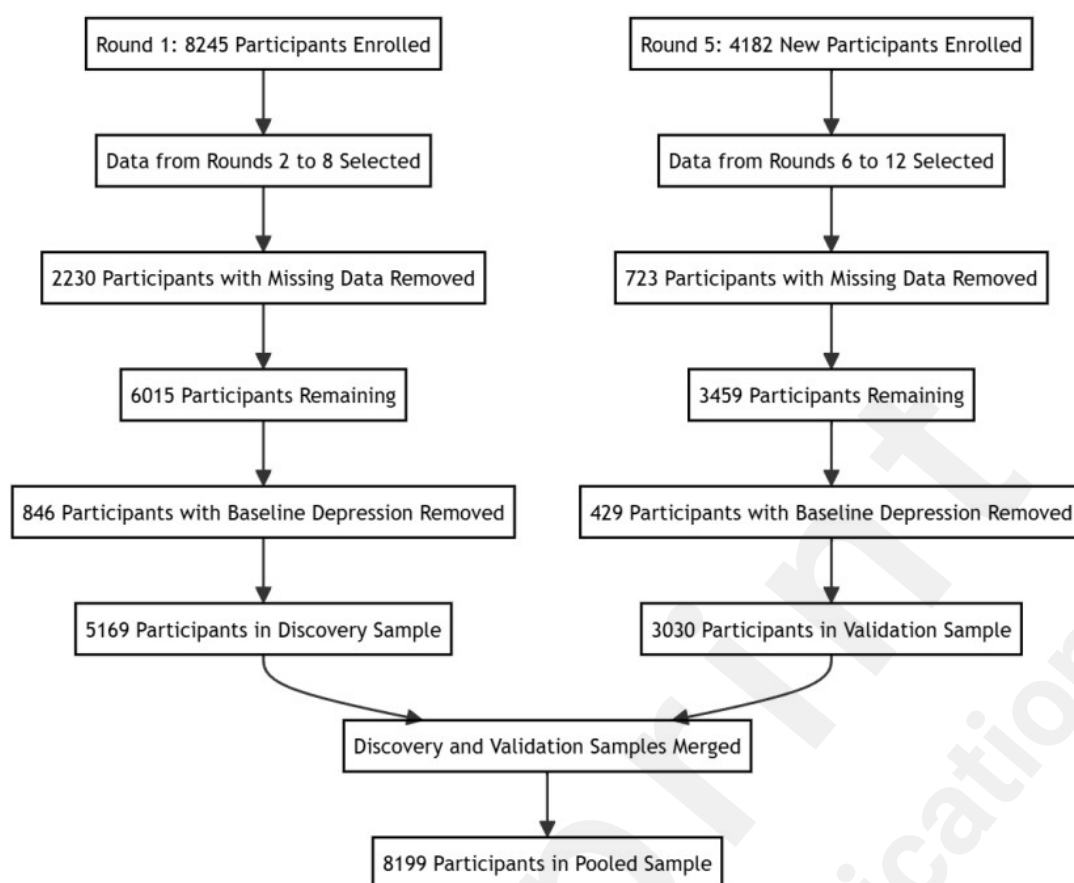
We analyzed data collected from NHATS starting in 2011 (Round 1). For the discovery cohort,

we utilized data from Round 1 (2011) to Round 8 (2018), encompassing seven waves of follow-up. The initial wave enrolled 8,245 participants. To ensure analytical precision, we excluded 2,230 participants lacking crucial information on key variables such as digital isolation and depressive symptoms, which were central to our research question. Additionally, we excluded 846 participants with a baseline diagnosis of depression to focus on the de novo development of depression. This resulted in a discovery cohort of 5,169 participants.

For external validation, we established an independent verification cohort comprising 4,182 newly enrolled participants during Wave 5 (2015) of NHATS data collection, ensuring temporal and spatial independence from the discovery sample. For these participants, we utilized data from Round 5 to Round 12 (2015–2022), also spanning seven waves of follow-up. The validation cohort was formed by excluding 723 individuals who had missing data on crucial variables and an additional 429 participants who were diagnosed with depression at the baseline assessment. Consequently, a total of 3,030 participants constituted the final validation cohort.

In the final analysis, we combined the discovery and validation cohorts, yielding a total sample of 8,199 participants. Merging these cohorts enhanced the robustness and generalizability of our findings. A flowchart delineating the participant selection process is presented in Figure 1.

Figure 1. Flowchart of participant selection and data integration process for discovery, validation, and pooled samples



Digital Isolation

In this study, digital isolation is defined as an individual's limitation or lack of engagement with modern digital technologies and communication tools [18, 19]. We quantified digital isolation using the technology environment section of NHATS, evaluating four key domains: Mobile device utilization, Computer interaction proficiency, Digital messaging patterns, Web-based engagement [20, 21]. For each domain, a binary variable was constructed: if a participant reported non-use or infrequent use of the respective technology, the isolation variable for that domain was coded as 1; otherwise, it was coded as 0. Specifically, mobile phone isolation was determined by whether the participant possessed a functional mobile phone; computer isolation was based on whether they used a computer at home or elsewhere; electronic communication isolation was assessed by their use of email or text messaging in the preceding month; and internet activity isolation was evaluated based on internet usage within the past month. An index for digital isolation was constructed by aggregating the scores of the four binary variables, which yielded a range from 0 to 4. In this context, a higher score reflects a higher level of digital isolation [22]. In our threshold-based classification schema, participants were categorized as demonstrating either minimal digital disengagement (aggregate score ≤ 2) or substantial digital disengagement (cumulative metric ≥ 3), based on validated

cut-points derived from previous techno-gerontology studies. This multidimensional measure of digital isolation accounts for both device ownership and actual usage patterns, providing a comprehensive assessment of participants' engagement in the modern digital environment. The adopted approach enables a detailed examination of the intricate connection between digital isolation and its impact on health outcomes.

Depression

The National Health and Aging Trends Study (NHATS) employed the Patient Health Questionnaire-2 (PHQ-2) to evaluate depressive symptoms. This concise screening instrument consists of two questions that assess the frequency of such symptoms experienced over the previous month: (a) a lack of interest or enjoyment in activities, and (b) persistent feelings of sadness, hopelessness, or depression. Respondents can choose from a scale of "not at all" (assigned 1 point) to "nearly every day" (4 points), resulting in a total PHQ-2 score between 2 and 8. Higher scores on this scale indicate more severe depressive symptoms. Notably, NHATS applies a one-month reference period for the PHQ-2, differing from the standard two-week timeframe, to align with the reference periods used for other functional measures, such as self-care and mobility assessments [23]. Based on the foundational work of Kroenke et al., we used a threshold of 3 points or more to define clinically significant depressive symptoms [24, 25].

Covariates

Our analytical approach comprehensively adjusted for potential confounders spanning sociodemographic determinants, socioeconomic gradients, behavioral risk profiles, and clinical comorbidities. The analysis focused on several variables known from previous research to be linked with depression and mental health. These variables comprised age, categorized as ≤ 75 years and > 75 years; gender, distinguished as male and female; race/ethnicity, comparing non-Hispanic whites with other groups; marital status, with comparisons made between married individuals and others; educational attainment, contrasted as less than high school versus high school or above; income level, separated into $< 50,000$; smoking status, classified as non-smokers and smokers; presence or absence of sleep disorders; dementia status; anxiety presence or absence; and chronic disease burden, defined as having fewer than 3 or 3 or more conditions.

Age, gender, and race/ethnicity may affect individuals' use and adaptation to digital technologies, influencing their social interaction patterns and mental well-being [26-28]. Marital status, education level, and income level were included as proxies for socioeconomic status, a well-

documented determinant of mental health outcomes [29-31]. Additionally, health behaviors and medical history, such as smoking status, sleep disorders, dementia, and anxiety, have shown strong associations with the risk of depression in the existing literature [32].

Statistical Analysis

We employed survey-weighted analytical methods to address the intricate design of the NHATS dataset. These approaches incorporated adjustments for varying selection probabilities, strategies to minimize non-response bias, and targeted over-sampling of the octogenarian population segments. This weighting strategy enabled generation of nationally representative estimates for community-dwelling older Americans. Weighted means with standard errors (SE) were employed to describe continuous measures, while categorical variables were depicted as adjusted proportions accompanied by 95% confidence intervals. Intergroup comparisons employed Chi-square test. Survival analyses utilized inverse probability-weighted Cox proportional hazards models, with hierarchical adjustment for: (a) sociodemographic factors (age, sex, race/ethnicity, education); (b) health behaviors (tobacco exposure, sleep dysfunction); and (c) clinical profiles (multimorbidity burden, dementia status, anxiety comorbidity). To clarify the independent effects of digital isolation components (e.g., phone, computer, email, and online isolation) on depression risk, additional analyses estimated hazard ratios (HRs) for each component.

Kaplan-Meier (KM) survival and stratified analyses were conducted after combining the discovery and validation cohorts. KM curves visualized depression incidence differences between low- and high-isolation groups, with log-rank tests evaluating their statistical significance. In stratified analyses, the low-isolation group served as the reference, and associations between digital isolation and depression incidence were examined across subgroups based on age (<75 vs. ≥75 years), gender, race/ethnicity, smoking status, sleep disorders, marital status, and chronic disease burden (<3 vs. ≥3). Meta-regression analysis assessed heterogeneity across subgroups. To examine potential non-linear associations between digital isolation scores and depression risk, we employed restricted cubic splines (RCS) in our analysis. Cox regression models with three knots were fitted to assess non-linear trends in digital isolation scores (0–4). Risk curves visualized the progressive impact of higher digital isolation scores on depression risk.

To assess the robustness of the findings, sensitivity analyses were conducted. Digital isolation scores were reclassified into three levels: no isolation (0 points), moderate isolation (1–2 points), and high isolation (3–4 points). Cox models were refitted using this classification across discovery, validation, and pooled cohorts to evaluate result consistency under different strategies. Statistical

analyses were conducted with a significance level set at $P < 0.05$ for two-tailed tests. The R software, version 4.4.0, was employed for all the statistical computations.

Ethical Consideration

The ethical review board at The Central Hospital of Wuhan, which is affiliated with Tongji Medical College and Huazhong University of Science and Technology, granted approval for this research protocol.

Results

Baseline Characteristics of Participants

Table 1 presented the baseline sociodemographic and clinical profiles stratified by analytical cohort (discovery: $N=5,169$; validation: $N=3,030$; pooled: $N=8,199$). The participant pool comprised 44.72% males and 55.28% females. In terms of age, the majority, 68.39%, were 75 years or younger, while the remaining 31.61% were older than 75 years. The majority (70.39%) identified as non-Hispanic White. Educational attainment indicated that 80.12% of participants had completed at least high school, while 17.89% had not. Income data revealed that 35.63% of participants had an annual income below \$50,000, whereas 21.20% reported an income above this threshold. Lifestyle analysis showed that 48.31% were non-smokers, and 51.59% were smokers. Health assessments found that 80.89% of participants did not report sleep disorders, 97.46% were dementia-free, and 93.19% showed no symptoms of anxiety. Regarding chronic disease burden, 78.86% of participants had fewer than three chronic conditions, while 21.14% had three or more. For digital isolation, 69.01% of participants were categorized as low isolation, and 30.99% as high isolation. Among specific components, 8.59% experienced phone isolation, 30.00% computer isolation, 52.14% email isolation, and 51.09% online isolation. Chi-square tests identified significant group differences in categorical variables, including gender, age group, education, income, smoking status, sleep disorders, dementia, anxiety symptoms, chronic disease burden, and components of digital isolation.

Table 1. Baseline characteristics of participants.

^a Variables	Discovery group (N=5,169)	Validation group (N = 3,030)	Pooled group (N = 8,199)
Sex n (%)			
Male	2,303 (44.55)	1,364 (45.02)	3,667 (44.72)
Female	2,866 (55.45)	1,666 (54.98)	4,532 (55.28)
Age Group, n (%) **			
≤75 years	3,440 (66.55)	2,167 (71.52)	5,607 (68.39)
>75 years	1,729 (33.45)	863 (28.48)	2,592 (31.61)
Race/Ethnicity, n (%) **			
White, non-Hispanic	3,699 (71.56)	2,072 (68.38)	5,771 (70.39)
^b Other	1,413 (27.34)	841 (27.76)	2,254 (27.49)
Marital Status, n (%) **			
Married	2,836 (54.87)	1,609 (53.10)	4,445 (54.21)
Other	2,327 (45.02)	1,417 (46.77)	3,744 (45.66)
Education, n (%) **			
Low (< High School)	997 (19.29)	470 (15.51)	1,467 (17.89)
High (≥ High School)	4,118 (79.67)	2,451 (80.89)	6,569 (80.12)
Income, n (%) **			
Low (< 50,000)	1,919 (37.13)	1,002 (33.07)	2,921 (35.63)

High ($\geq 50,000$)	1,019 (19.71)	719 (23.73)	1,738 (21.20)
Smoking Status, n (%) **			
Non-smoker	2,453 (47.46)	1,508 (49.77)	3,961 (48.31)
Smoker	2,713 (52.49)	1,517 (50.07)	4,230 (51.59)
Sleep Disorder, n (%) **			
No	4,184 (80.94)	2,448 (80.79)	6,632 (80.89)
Yes	975 (18.86)	579 (19.11)	1,554 (18.95)
Dementia, n (%) *			
No	5,033 (97.37)	2,958 (97.62)	7,991 (97.46)
Yes	134 (2.59)	70 (2.31)	204 (2.49)
Anxiety, n (%) **			
No	4,808 (93.02)	2,833 (93.50)	7,641 (93.19)
Yes	361 (6.98)	197 (6.50)	558 (6.81)
Chronic Disease, n (%) **			
Less than 3 diseases	4,060 (78.55)	2,406 (79.41)	6,466 (78.86)
3 or more diseases	1,109 (21.45)	624 (20.59)	1,733 (21.14)
Digital Isolation Group, n (%) **			
Low Isolation	3,408 (65.93)	2,250 (74.26)	5,658 (69.01)
High Isolation	1,761 (34.07)	780 (25.74)	2,541 (30.99)
Items of Digital Isolation, n (%)			
Phone Isolation *	533 (10.31)	171 (5.64)	704 (8.59)
Computer Isolation **	1,579 (30.55)	881 (29.08)	2,460 (30.00)

Email Isolation **	2,973 (57.52)	1,302 (42.97)	4,275 (52.14)
Online Isolation **	2,856 (55.25)	1,333 (43.99)	4,189 (51.09)

^aWe conducted chi-square tests for all categorical variables to assess the association between each variable and the occurrence of depression. Variables with P-values less than 0.05 in the chi-square tests are marked with *, indicating statistically significant differences. Variables with P-values less than 0.001 are marked with **, indicating stronger statistical significance.

^bThe "Other" category in the race/ethnicity classification includes Black/African American, American Indian, Alaska Native, Asian, Native Hawaiian, Pacific Islander, and other unspecified races or ethnicities.

^cThe assessment of chronic disease burden is based on the cumulative number of the following conditions: heart disease, hypertension, arthritis, osteoporosis, diabetes, lung disease, stroke, dementia or Alzheimer's disease, cancer, and others.

Association Between Digital Isolation and Depression

Table 2 demonstrates a significant correlation between heightened digital isolation and a greater likelihood of depression. The Cox proportional hazards analysis indicated that participants in the high-isolation category had a notably higher risk of depression compared to those in the low-isolation category. In the discovery cohort, the unadjusted hazard ratio (HR) for the high-isolation group was 1.73 (95% CI: 1.54–1.94, $P < 0.001$), which reduced to an adjusted HR of 1.33 (95% CI: 1.12–1.57, $P = 0.001$) upon controlling for potential confounders. The validation cohort displayed comparable results, with an unadjusted HR of 1.81 (95% CI: 1.55–2.12, $P < 0.001$) and an adjusted HR of 1.37 (95% CI: 1.07–1.75, $P = 0.012$). When analyzing the combined sample, the unadjusted HR was 1.75 (95% CI: 1.60–1.92, $P < 0.001$), and the adjusted HR was 1.35 (95% CI: 1.18–1.55, $P < 0.001$). Figure 2 visually supports these findings, depicting a significantly higher cumulative incidence of depression in the high-isolation group throughout the follow-up period. Figure 3 further solidifies this association across diverse subgroups, highlighting particularly elevated risks among women, individuals aged 75 and above, those with less education, and participants with a higher burden of chronic illnesses. These disparities imply that while the effect of digital isolation may vary by individual characteristics,

it consistently acts as a substantial risk factor for depression. Collectively, the data from Table 2, Figure 2, and Figure 3 strongly suggest that increased digital isolation is significantly linked to a higher risk of depression, a relationship that persists even after accounting for multiple potential confounding factors. This underscores the necessity of incorporating digital isolation reduction strategies into public health initiatives to mitigate the burden of depression.

Table 2. The observed link between digital isolation and the likelihood of depression

Samples	Event/Total number (%)	Model 1 HR (95% CI) ^{a,c}	P-Value	Model 2 HR (95% CI) ^{b,c}	P-Value
Discovery					
Low Isolation (Ref)	3,408/5,169 (65.93)	1 (Ref)		1 (Ref)	
High Isolation	1,761/5,169 (34.07)	1.73 (1.54, 1.94)	<0.001	1.33 (1.12, 1.57)	0.001
Validation					
Low Isolation (Ref)	2,250/3,030 (74.26)	1 (Ref)		1 (Ref)	
High Isolation	780/3,030 (25.74)	1.81 (1.55, 2.12)	<0.001	1.37 (1.07, 1.75)	0.012
Pooled					
Low Isolation (Ref)	5,658/8,199 (69.01)	1 (Ref)		1 (Ref)	
High Isolation	2,541/8,199 (30.99)	1.75 (1.60, 1.92)	<0.001	1.35 (1.18, 1.55)	<0.001

^a**Model 1:** Unadjusted Cox proportional hazards model.

^b**Model 2:** Cox proportional hazards model adjusted for age, gender, race, education, income, marital status, sleep disorder, smoking status, dementia, anxiety, and chronic disease.

^c**Abbreviation:** HR, Hazard Ratio; CI, Confidence Interval.

Figure 2. KM curves depicting the identified association between digital isolation and the risk of depression. Panels A,B and C

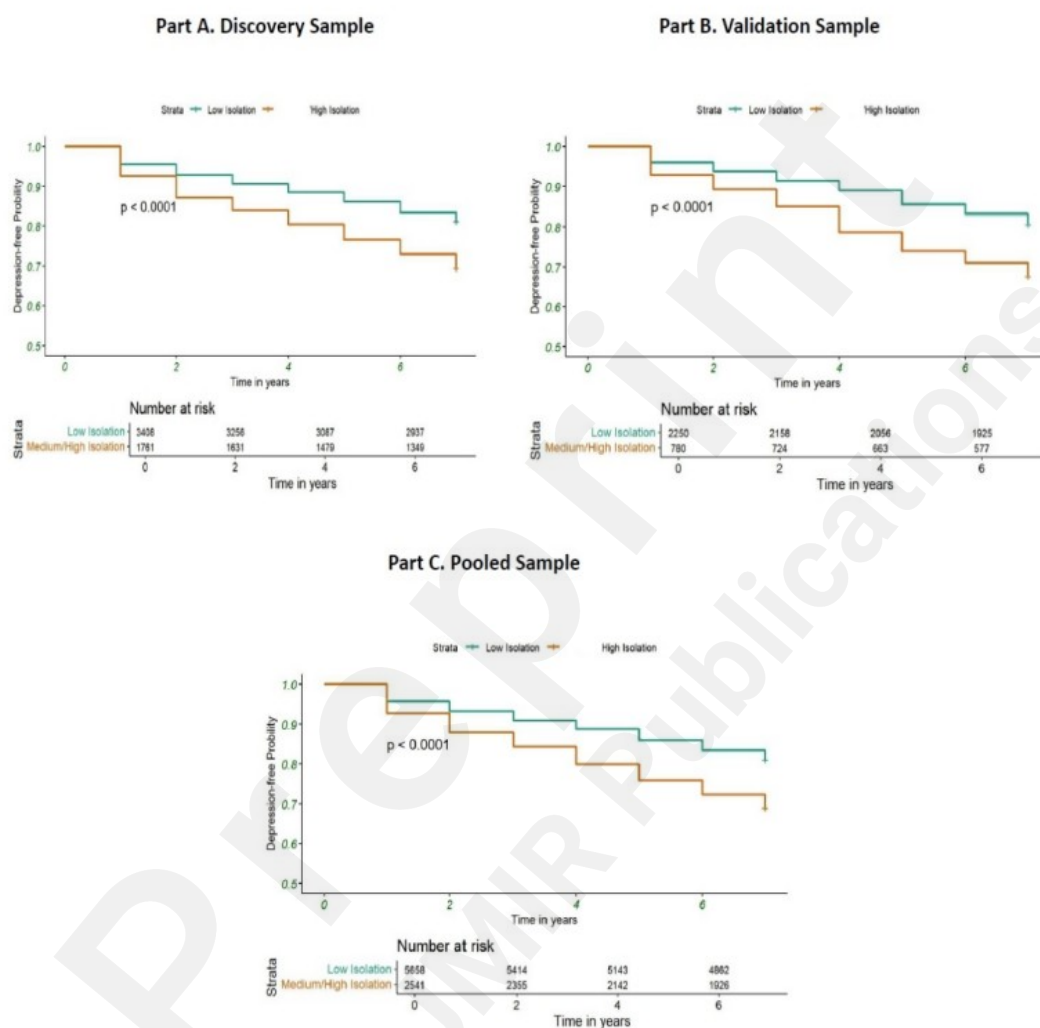
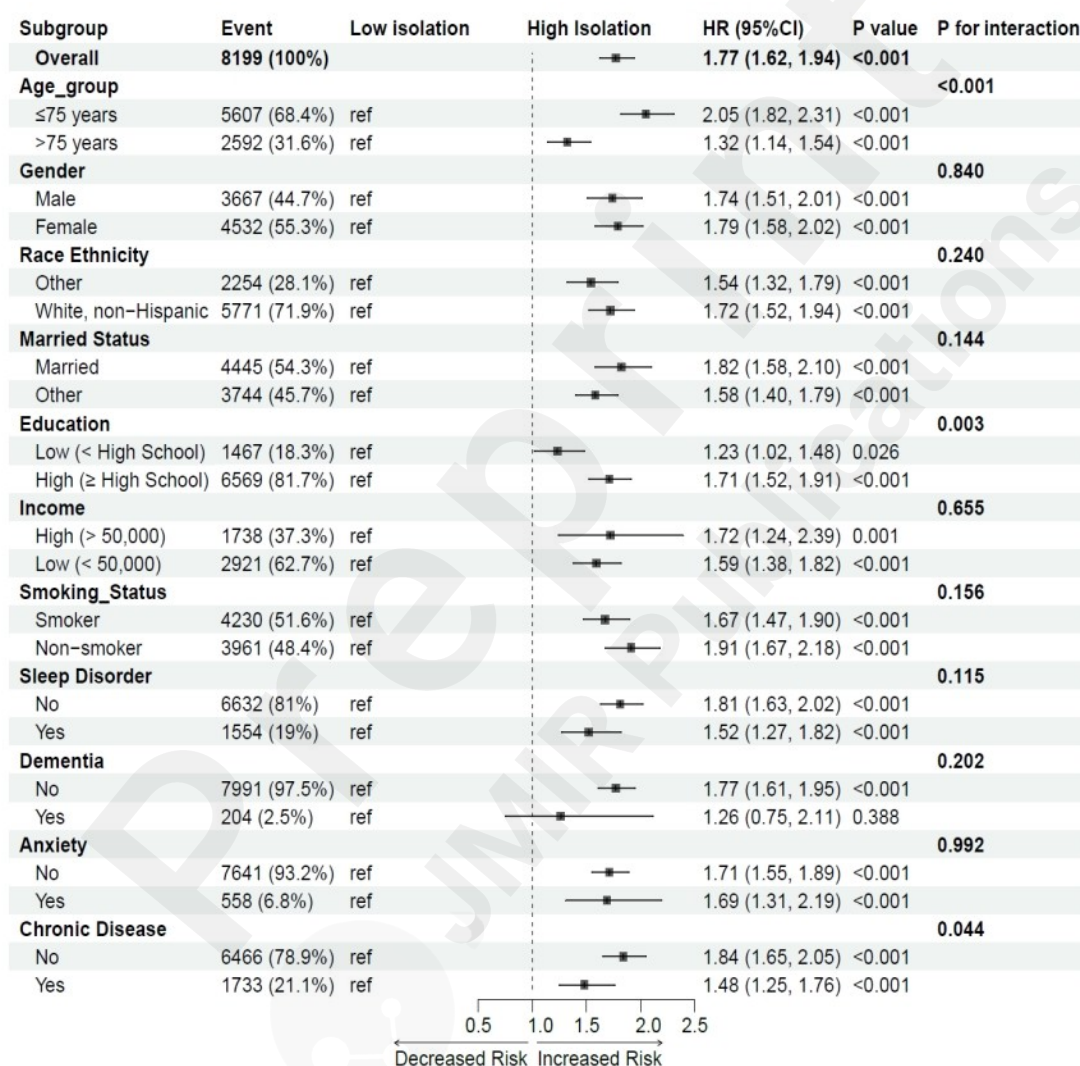


Figure 3. The relationship between digital isolation and depression across

subgroups. reference group was defined as the low-isolation group. All models incorporated adjustments for age, sex, race/ethnicity, educational attainment, income, marital status, smoking status, sleep disorders, dementia, anxiety, and chronic diseases. The P-int value reflected subgroup heterogeneity, as assessed through metaregression analysis.



Association Between Different Items of Digital Isolation and Depression

An overview of the correlation between the various components of digital isolation and the likelihood of depression is provided in Table 3. Adjusted Cox

models revealed significant associations for computer isolation, email isolation, and online isolation, but not for phone isolation. In the pooled sample, adjusted HRs were 1.23 (95% CI: 1.08–1.41, $P = 0.003$) for computer isolation, 1.52 (95% CI: 1.32–1.75, $P < 0.001$) for email isolation, and 1.32 (95% CI: 1.15–1.52, $P < 0.001$) for online isolation. In contrast, the adjusted HR for phone isolation was 1.19 (95% CI: 0.98–1.44, $P = 0.077$), which was not statistically significant. These findings suggest a stronger link between reduced digital communication or online activity and depression risk.

Table 3. Association between different items of digital isolation and depression

Sample/Variables	Model 1 HR (95% CI) ^{a,c}	P-Value	Model 2 HR (95% CI) ^{b,c}	P-Value
Discovery Sample				
Phone Isolation	1.29 (1.09, 1.54)	0.004	1.18 (0.94, 1.47)	0.153
Computer Isolation	1.55 (1.38, 1.75)	<0.001	1.19 (1.01, 1.40)	0.043
Email Isolation	1.81 (1.60, 2.05)	<0.001	1.48 (1.24, 1.77)	<0.001
Online Isolation	1.76 (1.56, 1.99)	<0.001	1.35 (1.13, 1.61)	0.001
Validation Sample				
Phone Isolation	1.34 (1.00, 1.79)	0.054	1.24 (0.85, 1.83)	0.268
Computer Isolation	1.74 (1.49, 2.02)	<0.001	1.28 (1.02, 1.61)	0.034
Email Isolation	1.99 (1.71, 2.31)	<0.001	1.59 (1.25, 2.02)	<0.001
Online Isolation	1.86 (1.60, 2.17)	<0.001	1.26 (0.99, 1.60)	0.058
Pooled Sample				
Phone Isolation	1.30 (1.12, 1.51)	<0.001	1.19 (0.98, 1.44)	0.077
Computer Isolation	1.62 (1.47, 1.78)	<0.001	1.23 (1.08, 1.41)	0.003
Email Isolation	1.86 (1.69, 2.04)	<0.001	1.52 (1.32, 1.75)	<0.001
Online Isolation	1.79 (1.63, 1.97)	<0.001	1.32 (1.15, 1.52)	<0.001

^a**Model 1:** Unadjusted Cox proportional hazards model.

^b**Model 2:** Cox proportional hazards model adjusted for age, gender, race, baseline disease, depression, anxiety, smoking status, and sleep difficulty.

All variables compare "Not using" vs. "Using."

^cAbbreviations: HR, Hazard Ratio; CI, Confidence Interval.

Non-linear Relationship Between Digital Isolation and Depression Risk

Figure S1 presents results from RCS analyses examining non-linear relationships between digital isolation scores (0–4) and depression risk. Across all cohorts—discovery, validation, and pooled—a consistent non-linear trend was observed, with depression risk increasing progressively with higher digital isolation scores. This trend reinforces the role of digital isolation as a significant contributor to depression risk.

Sensitivity Analysis

Sensitivity analyses confirmed the robustness of the main findings. Using a multi-level categorization of digital isolation (no isolation, moderate isolation, high isolation; Table S1, Figure S2), the results were consistent across discovery, validation, and pooled samples. The adjusted hazard ratios (HRs) in the combined analysis revealed a significant association between isolation and adverse outcomes. Specifically, moderate isolation was associated with an HR of 1.63 (95% CI: 1.44–1.84, $P < 0.001$), whereas high isolation carried an even higher HR of 2.23 (95% CI: 1.99–2.51, $P < 0.001$), both in comparison to the absence of isolation. Kaplan-Meier survival curves further supported these findings, showing significantly higher depression incidence over time in the high isolation group. The sensitivity analyses emphasized the strong and consistent link between digital isolation and depression risk, thereby underscoring the reliability of the findings across different analytical methods and stratifications.

Discussion

Principal Results

The study demonstrates a strong correlation between digital isolation and the increased likelihood of developing depression. Employing Cox proportional hazards models, researchers observed that individuals in the high-isolation category exhibited a significantly elevated risk of depression compared to those in the low-isolation

group, specifically in terms of computer isolation, email isolation, and online isolation. Additionally, the analysis using Kaplan-Meier survival curves confirmed these findings, revealing a notably higher cumulative incidence of depression over time within the high-isolation group. These outcomes emphasize digital isolation as a crucial risk factor for depression.

This study's results support existing research that demonstrates a connection between digital isolation and negative mental health consequences. Notably, prior investigations have consistently found that social isolation and restricted access to digital resources are strongly linked to increased rates of depression [13, 33, 34]. Our study builds on these findings, highlighting the pronounced effects of computer, email, and online isolation. Notably, in contrast to some earlier research, we observed that the impact of mobile phone isolation was relatively limited. This may be due to the ubiquity and user-friendliness of mobile phones, which could mitigate significant social isolation [35, 36].

The relationship between digital isolation and depression may operate through several psychosocial mechanisms. First, digital isolation can foster social isolation by reducing interpersonal interactions and social support, thereby increasing vulnerability to depression [37]. Second, restricted access to online information may limit awareness and use of mental health resources, exacerbating depressive symptoms [38]. In particular, computer and online isolation may more severely restrict access to information and social networks, potentially explaining their stronger associations with depression observed in this study. Subgroup analysis further revealed that women, older adults, individuals with lower educational attainment, and those with multiple chronic conditions faced a higher risk of depression in the context of digital isolation. These groups may experience a greater need for social support and access to information, amplifying the adverse effects of digital isolation [13, 39, 40].

Strengths

One of the key strengths of our research lies in the adoption of a longitudinal cohort design. This approach permitted us to monitor participants' progress over an extended period, thereby enhancing our ability to establish a clearer causal link between digital isolation and depression. Additionally, we employed a large sample size and performed dual analysis using discovery and validation cohorts to ensure the robustness and reproducibility of our results. This design enhances the external validity of the study, augmenting the generalizability of the findings. We also adjusted for a variety of potential confounding factors, such as demographic characteristics, health status, and lifestyle factors, further enhancing the accuracy of the analysis. Further analysis revealed a non-linear association between digital isolation scores and depression risk. The restricted cubic splines analysis (Figure S1) showed a non-linear upward trend in depression risk as digital isolation scores increased, underscoring the complexity of how digital isolation affects mental health. These results support the conclusion that higher digital isolation levels substantially elevate depression risk. Sensitivity analyses (Table S1, Figure S2) confirmed the robustness of these findings, demonstrating consistent results across different grouping strategies. These additional analyses further strengthen the link between digital isolation and depression risk, thereby enhancing the credibility and reliability of the study's conclusions.

Limitations

Despite its contributions, the study possesses certain limitations. Primarily, the reliance on self-reported data could introduce information bias, as participants' recollection or disclosure of their digital usage habits and mental health status may not be entirely accurate, which in turn could affect the reliability of the study outcomes. It is crucial to consider these limitations when interpreting the findings and to explore more objective methods for data collection in future research to strengthen the study's public health relevance. Secondly, although we considered multiple forms of digital isolation, these definitions may not fully capture the complexity of digital isolation, and their applicability may vary across different cultural contexts[41, 42]. Additionally, while the longitudinal design mitigates the risk of confounding bias, the

possibility of reverse causality persists—depressive symptoms may lead individuals to reduce digital communication, thereby increasing the risk of digital isolation. To address this issue, future research could employ more refined time-series analyses or mediation models to further validate the causal effect of digital isolation on depression.

Our study underscores the significant impact of digital isolation on depression risk, particularly among older adults and other vulnerable populations. As digital technologies become increasingly integral to social interaction and information access, public health policies must address the adverse effects of digital isolation. Policymakers could prioritize digital literacy education, particularly for older adults, to improve their ability to engage with digital platforms, thereby reducing social isolation and lowering depression rates [43, 44]. Additionally, both governmental and non-governmental organizations should expand the availability of mental health resources to support those at risk of digital isolation [45].

Future Directions and Public Health Relevance

Although this study employs a longitudinal design to investigate the connection between digital isolation and depression, it is essential to conduct more research in order to establish definitive causal links. Refined time-series analyses and mediation models could help disentangle the influence of reverse causality. It is imperative for future research to broaden its scope and examine the potential impacts of digital isolation on various mental health aspects, including anxiety, social phobia, and cognitive decline, in order to establish if these conditions share comparable associations with digital isolation[46]. Moreover, studying the mental health implications of emerging digital platforms, such as social media, represents a promising avenue. Given the growing role of social media in daily life, understanding whether its use mitigates or exacerbates the negative effects of digital isolation will provide critical insights into the multifaceted impact of digital technologies on mental health in modern society [47, 48].

Conclusions

The study reveals a strong connection between digital isolation and the likelihood of depression, with specific emphasis on computer isolation, email detachment, and internet seclusion. Though mobile phone isolation seems to have a lesser effect, the overall outcomes emphasize the vital need to combat digital isolation in order to foster improved mental health. These findings hold substantial relevance for the development of public health policies and interventions, particularly targeting elderly individuals and other vulnerable groups, to alleviate digital isolation and its associated risks.

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Z.H. conceived and designed the study, conducted data analysis and interpretation, and drafted the manuscript. S.Y. contributed to study design and statistical analysis and assisted with study design, data analysis, and manuscript preparation. W.T. provided critical revisions and contributed to data interpretation. W.Z. supervised the entire project, provided critical revisions, and approved the final manuscript. All authors reviewed and approved the final manuscript for publication.

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Conflicts of Interest

The authors declare no conflict of interest.

Abbreviations

HR: Hazard Ratio

CI: Confidence Interval

NHATS: National Health and Aging Trends Study

PHQ-2: Patient Health Questionnaire-2

RCS: Restricted Cubic Splines

IRB: Institutional Review Board

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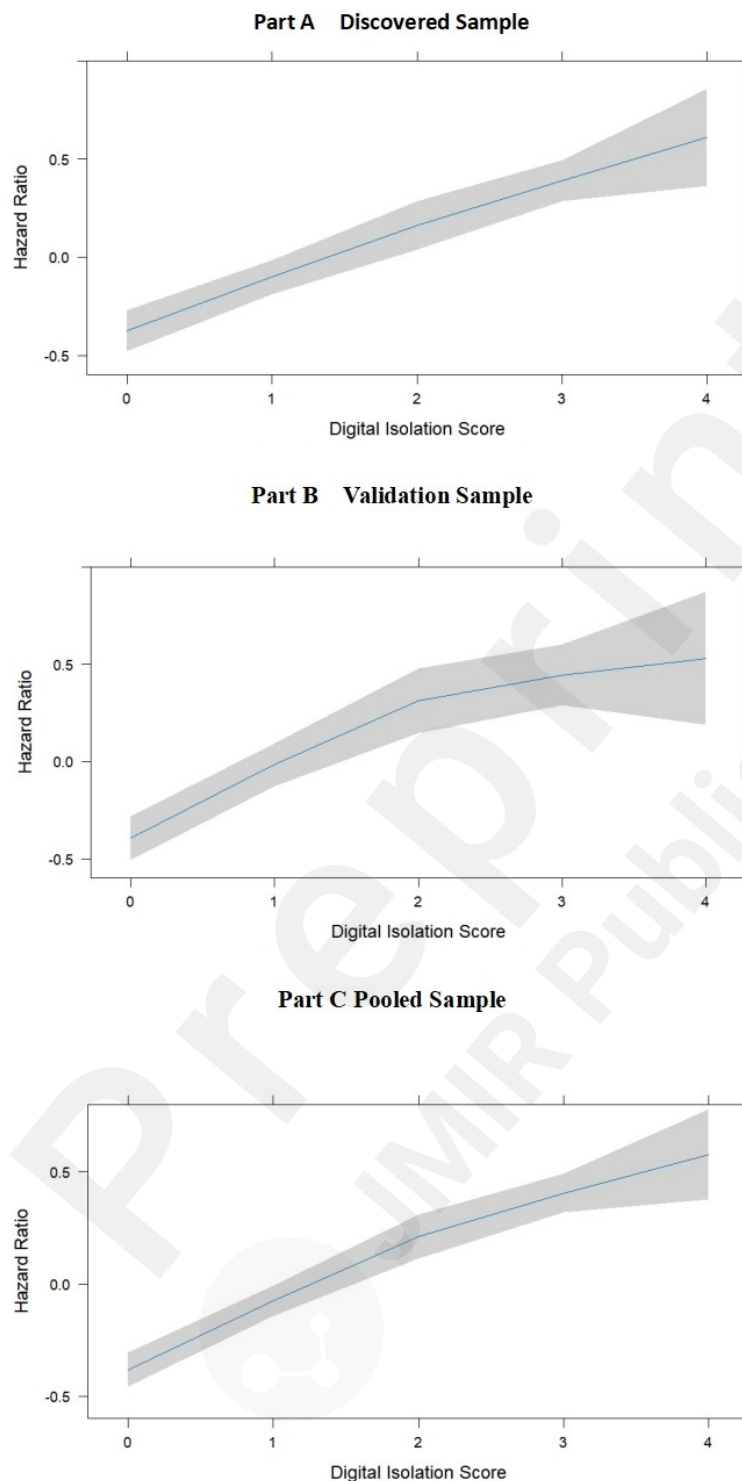
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Supplemental information

Figure S1: Non-linear association between digital isolation score and depression risk in discovery, validation, and pooled samples (restricted cubic splines analysis).



This figure depicts the non-linear relationship between digital isolation scores (0–4) and depression risk, analyzed using RCS across three cohorts. HRs are plotted on the y-axis, with the reference value set at 0 (no isolation). Shaded areas indicate 95% confidence intervals.

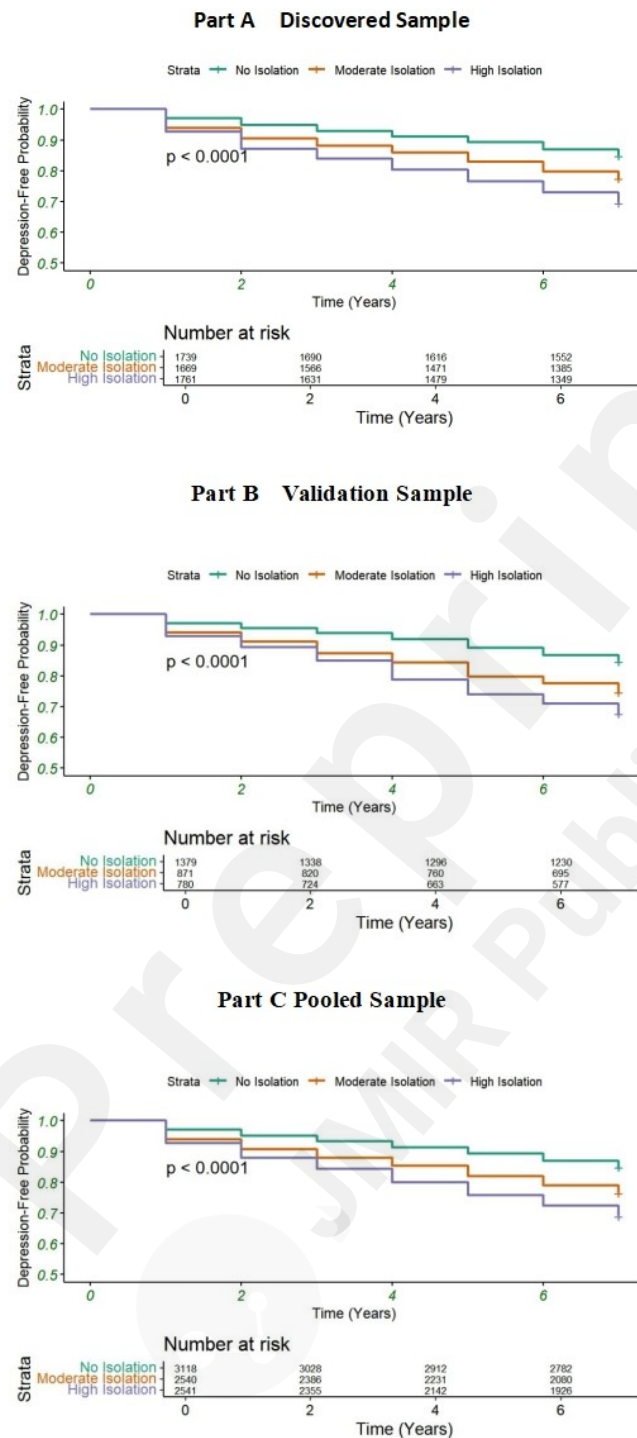
Part A: Discovery sample ($n = 5,169$), showing a steady increase in depression risk with higher digital isolation scores.

Part B: Validation sample ($n = 3,030$), revealing similar trends, albeit with wider confidence intervals due to the smaller sample size.

Part C: Pooled sample ($n = 8,199$), integrating discovery and validation data to provide robust estimates.

The analysis reveals a dose-response relationship, with depression risk progressively rising as digital isolation scores increase. These results support the hypothesis that digital isolation is a significant and incremental risk factor for depression. The RCS method enables flexible modeling of non-linear effects, offering detailed insights into the complex interplay between digital isolation and mental health outcomes.

Figure S2: Kaplan-Meier survival curves showing depression risk by digital isolation levels (sensitivity analysis).



This figure illustrates Kaplan-Meier survival curves for depression-free probability, stratified by digital isolation levels in the sensitivity analysis. Digital isolation was categorized into three

levels: No Isolation (0 points), Moderate Isolation (1–2 points), and High Isolation (3–4 points).

Survival probabilities for each group are plotted over time (years).

Part A: Discovery sample ($n = 5,169$).

Part B: Validation sample ($n = 3,030$).

Part C: Pooled sample ($n = 8,199$).

P-values from log-rank tests comparing survival distributions across the three groups are shown in each panel. The number of participants at risk at each time point is provided below the plots. The results consistently demonstrate a significant association between higher digital isolation levels and increased depression risk in all samples.

Table S1. Association between digital isolation and the risk of depression (sensitivity analysis).

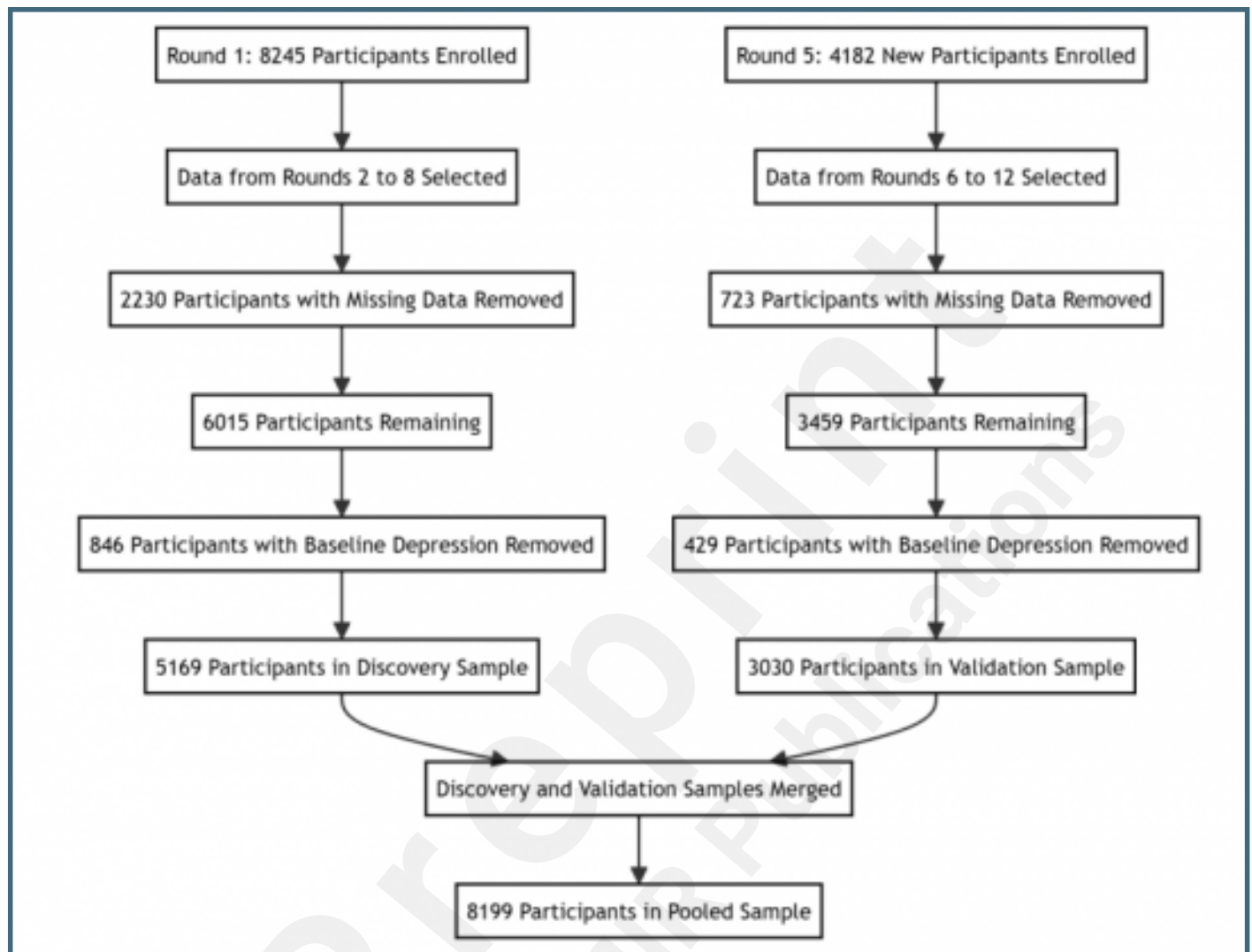
Sample/Variables	Event/N (%)	Model 1 HR (95% CI) ^{a,c}	P-Value	Model 2 HR (95% CI) ^{b,c}	P-Value
Discovery Sample					
No Isolation (Ref)	707/3118 (22.67)	1 (Ref)		1 (Ref)	
Moderate Isolation	242/1474 (16.42)	1.54 (1.33, 1.78)	<0.001	1.56 (1.33, 1.83)	<0.001
High Isolation	226/577 (39.17)	2.12 (1.88, 2.54)	<0.001	2.20 (1.89, 2.56)	<0.001
Validation Sample					
No Isolation (Ref)	423/1753 (24.13)	1 (Ref)		1 (Ref)	
Moderate Isolation	169/1173 (14.41)	1.76 (1.46, 2.14)	<0.001	1.76 (1.46, 2.13)	<0.001
High Isolation	92/104 (88.46)	2.31 (1.91, 2.80)	<0.001	2.31 (1.91, 2.80)	<0.001
Pooled Sample					
No Isolation (Ref)	1130/4871 (23.20)	1 (Ref)		1 (Ref)	
Moderate Isolation	411/2647 (15.53)	1.63 (1.44, 1.84)	<0.001	1.63 (1.44, 1.84)	<0.001
High Isolation	318/681 (46.69)	2.23 (1.99, 2.51)	<0.001	2.23 (1.99, 2.51)	<0.001



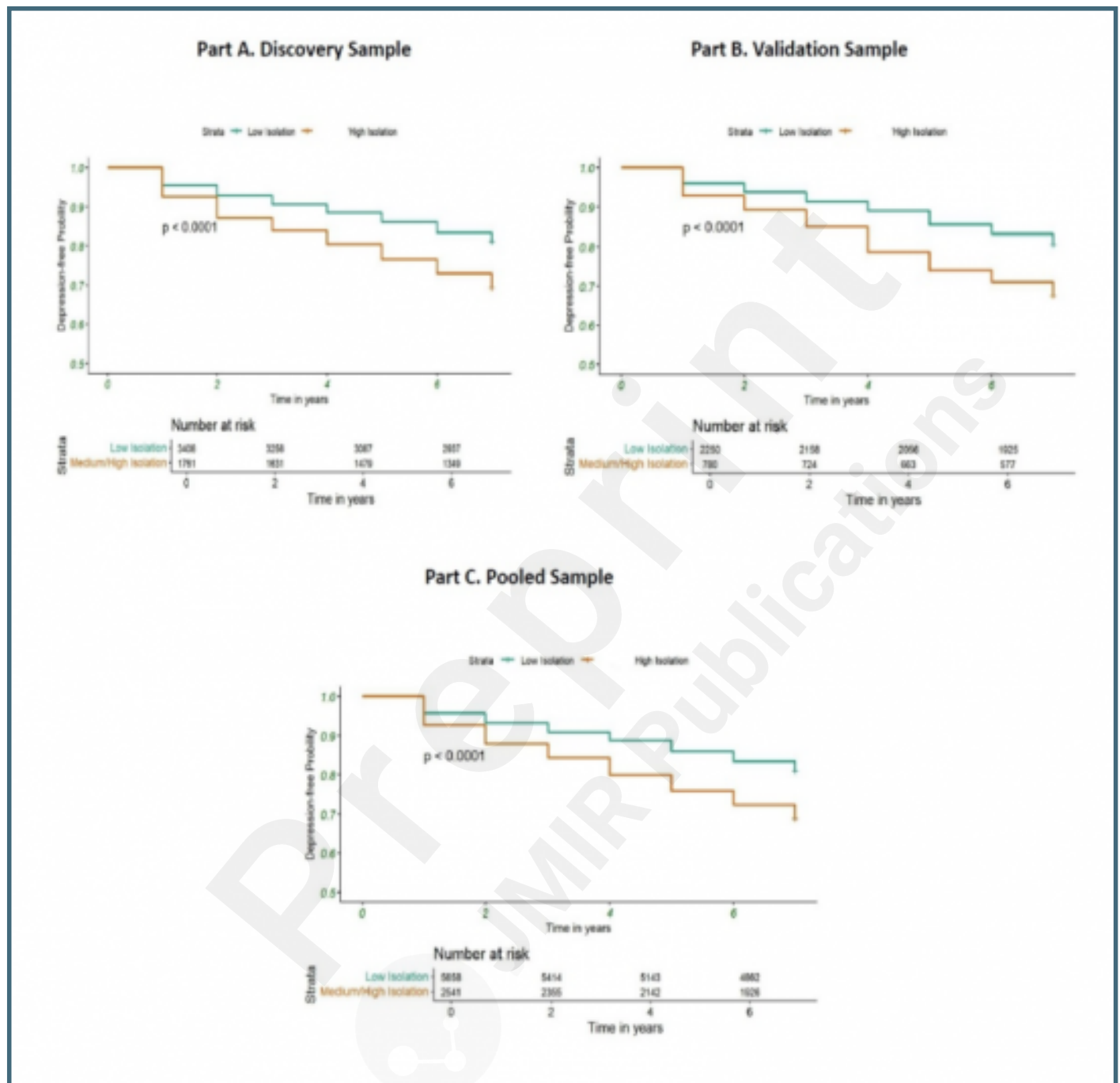
Supplementary Files

Figures

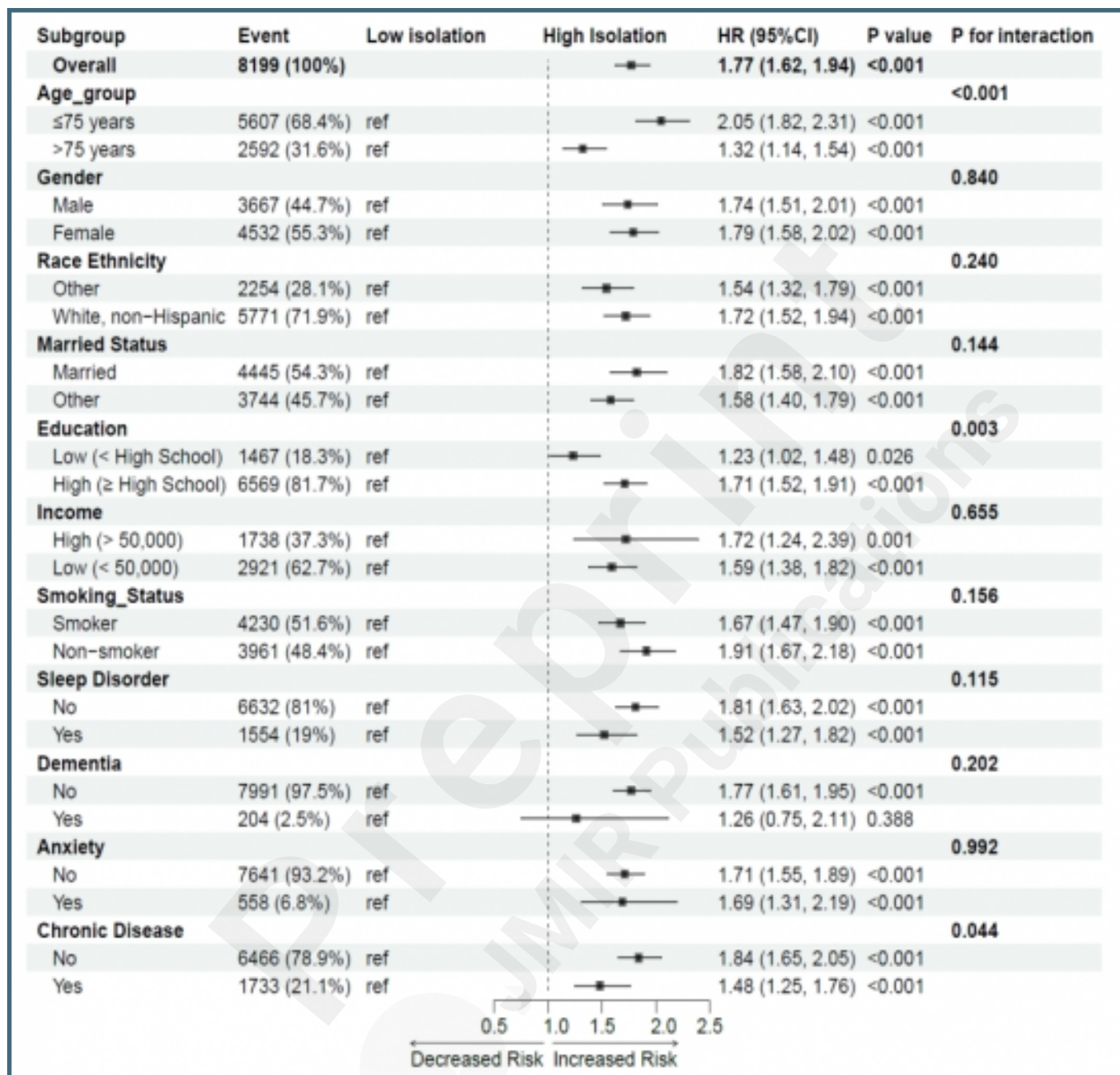
Flowchart of participant selection and data integration process for discovery, validation, and pooled samples.



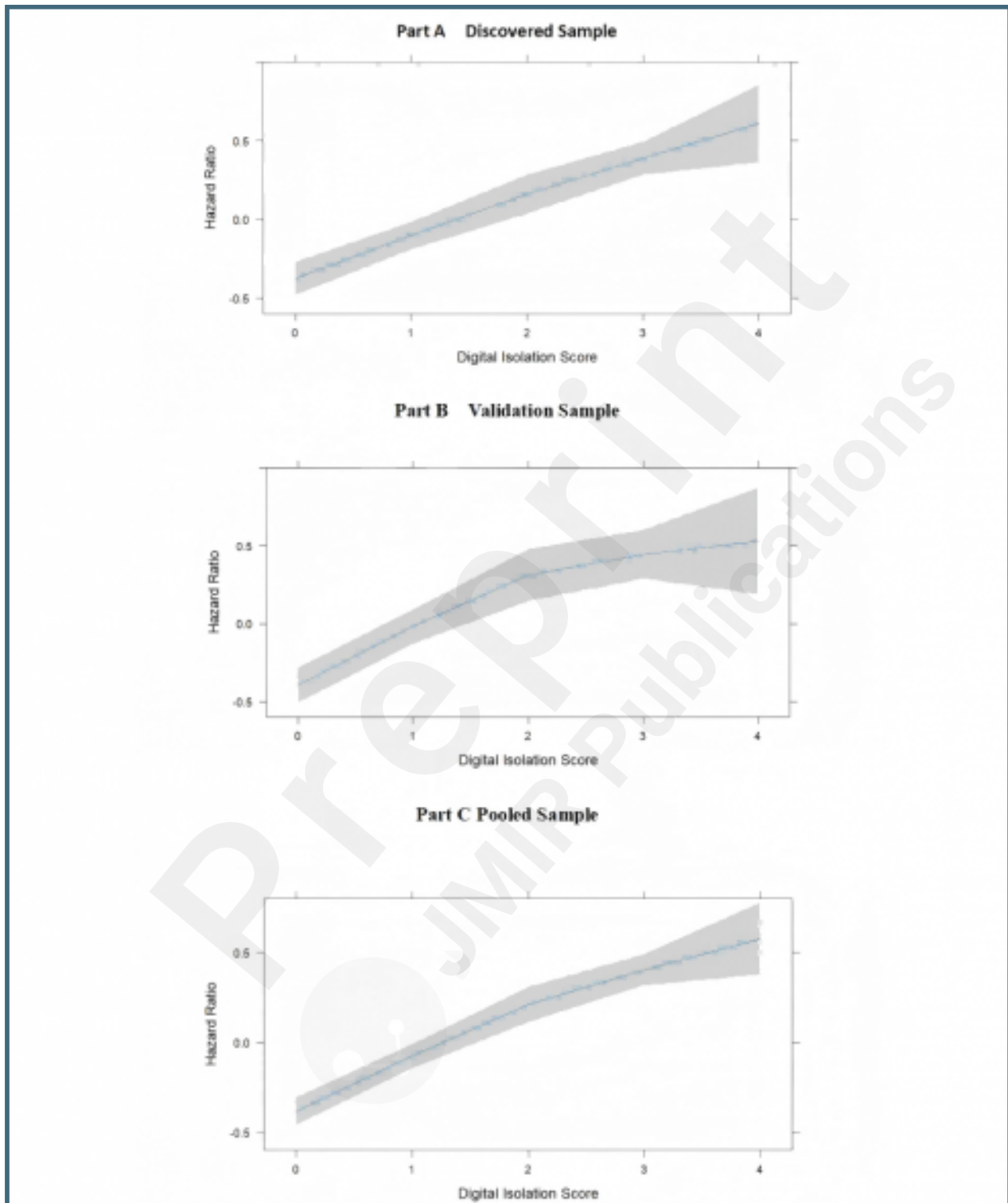
KM curves depicting the identified association between digital isolation and the risk of depression. Panels A,B and C.



The relationship between digital isolation and depression across subgroups.



Non-linear association between digital isolation score and depression risk in discovery, validation, and pooled samples (restricted cubic splines analysis).



Kaplan-Meier survival curves showing depression risk by digital isolation levels (sensitivity analysis).

