

Association Between Digital Isolation and Sleep Disorders in Older Adults: A Cross-Sectional and Longitudinal Study Using NHATS Data

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Submitted to: Journal of Medical Internet Research
on: April 01, 2025

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Abstract

Background: As digital technology becomes increasingly embedded in daily life, digital isolation among older adults has become more pronounced. This isolation may restrict access to health information and social support, potentially leading to poorer sleep quality. However, most existing studies on digital isolation and sleep disorders are cross-sectional, lacking longitudinal evidence to establish causality.

Objective: This study aimed to investigate the association between digital isolation and sleep disorders in older adults using both cross-sectional and longitudinal designs, and to assess the impact of specific components of digital isolation on the risk of sleep disorders.

Methods: We analyzed data from the National Health and Aging Trends Study (NHATS) collected from 2011 to 2022, including a discovery sample of 5,989 older adults and a validation sample of 3,443. Digital isolation was measured by the use of mobile phones, computers, email, and the internet, while sleep disorders were identified based on difficulties initiating or maintaining sleep and the use of sleep medication. Multivariable logistic regression and Cox proportional hazards models were employed for cross-sectional and longitudinal analyses, respectively.

Results: Cross-sectional analyses revealed a higher prevalence of sleep disorders among those with high digital isolation (discovery: 67.03% vs. 59.06%, OR = 1.23, $P < 0.001$; validation: 70.10% vs. 61.38%, OR = 1.22, $P = 0.033$). In longitudinal analyses, high digital isolation was associated with an increased risk of sleep disorders in the discovery (HR = 1.21, $P = 0.006$) and pooled samples (HR = 1.17, $P = 0.005$), but the association was not statistically significant in the validation sample after adjustment (HR = 1.11, $P = 0.298$).

Conclusions: Digital isolation is significantly associated with sleep disorders among older adults, particularly in cross-sectional analyses, while longitudinal findings provide partial support for this association. The non-significant result observed in the validation sample may reflect sample heterogeneity, and suggests that mental health may mediate this relationship. Future interventions should address mental health to help mitigate the negative impact of digital isolation on sleep.

(JMIR Preprints 01/04/2025:75328)

DOI: <https://doi.org/10.2196/preprints.75328>

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Original Manuscript

Association Between Digital Isolation and Sleep Disorders in Older Adults: A Cross-Sectional and Longitudinal Study Using NHATS Data

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Abstract

Background: As digital technology becomes increasingly embedded in daily life, digital isolation among older adults has become more pronounced. This isolation may restrict access to health information and social support, potentially leading to poorer sleep quality. However, most existing studies on digital isolation and sleep disorders are cross-sectional, lacking longitudinal evidence to

establish causality.

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Conclusions: Digital isolation is significantly associated with sleep disorders among older adults, particularly in cross-sectional analyses, while longitudinal findings provide partial support for this association. The non-significant result observed in the validation sample may reflect sample heterogeneity, and suggests that mental health may mediate this relationship. Future interventions should address mental health to help mitigate the negative impact of digital isolation on sleep.

Keywords: digital isolation; sleep disorders; older adults; cross-sectional study; longitudinal study; mental health

Introduction

Technology has advanced significantly and is now integrated into nearly every aspect of daily life, including information retrieval, social communication, and entertainment [1]. Devices such as smartphones, the internet, and computers have greatly facilitated social connectivity. However, not everyone has embraced this digital transformation. A significant portion of the population, particularly older adults, remains excluded—a phenomenon referred to as "digital isolation" [2-4]. Digital isolation refers to the inability or unwillingness to use digital technologies such as the internet or electronic devices, often due to lack of access, skills, or interest [5]. This issue is particularly pronounced among older adults. Barriers include financial constraints, limited digital literacy, or lack of prior exposure to such technologies. In some cases, physical or cognitive health issues—such as motor impairments or memory decline—further hinder technology adoption [6]. The implications of this digital divide extend beyond mere entertainment. It can restrict access to essential information and services, increase social isolation, and negatively impact mental health. Studies indicate that digitally isolated older adults are more prone to loneliness, which may contribute to depression [7-10]. The implications of this digital divide extend beyond mere

entertainment. It can restrict access to essential information and services, increase social isolation, and negatively impact mental health. Studies indicate that digitally isolated older adults are more prone to loneliness, which may contribute to depression or anxiety [11, 12]. However, the relationship between digital isolation and sleep remains under-explored, with limited research available on the topic.

Sleep disturbances are prevalent among older adults and tend to increase with age. More than half report difficulties initiating or maintaining sleep, or experiencing early morning awakenings [13, 14]. Poor sleep is associated with serious health outcomes, including cardiovascular disease, diabetes, cognitive decline, and impaired immune function [15-19]. Therefore, identifying the determinants of sleep quality in older adults is crucial for promoting healthy aging.

Digital isolation may be a contributing factor to sleep disturbances, potentially through several mechanisms. For instance, limited internet access may reduce exposure to sleep hygiene information or behavioral recommendations [20, 21]. Furthermore, various digital tools—such as meditation apps, soothing music, and sleep tracking technologies—may enhance sleep quality. These tools can be beneficial; however, individuals experiencing digital isolation are unlikely to access them [22]. Additionally, digital technologies facilitate social connections (e.g., video calls with family), which may reduce loneliness and improve sleep outcomes. However, existing research predominantly focuses on excessive technology use. Most studies examine the adverse effects of excessive screen time—such as prolonged social media use—on sleep, particularly among adolescents and young adults [23-26]. In contrast, the impact of digital isolation on sleep in older adults remains largely unexplored. Existing studies are primarily cross-sectional, providing only a snapshot at a single time point. Without longitudinal data, it is difficult to establish causal relationships between digital isolation and sleep disturbances. Therefore, further longitudinal research is required to comprehensively understand this relationship.

Given these research gaps, this study aims to explore the association between digital isolation and the risk of sleep disorders in older adults. We employ both cross-sectional and longitudinal study designs to provide more comprehensive and in-depth evidence. We hypothesize that higher levels of digital isolation will be associated with an increased risk of sleep disorders among older adults. The objectives of this study are to evaluate the cross-sectional association between the degree of digital isolation and the prevalence of sleep disorders in older adults, and to assess whether digital isolation increases the risk of developing sleep disorders in the future through longitudinal analysis. Additionally, we will analyze the effects of different components of digital isolation (e.g., use of

phone, computer, email, and the internet) on the risk of sleep disorders.

This study holds significant theoretical and practical implications. Theoretically, it will enrich the scientific understanding of the relationship between digital isolation and sleep health, deepening our understanding of the determinants affecting the health of aging population. Practically, the findings can provide evidence for public health policymakers and healthcare providers, emphasizing the importance of promoting digital inclusion among older adults. By raising awareness of the issue of digital isolation in older adults within families, communities, and society, and by mobilizing resources to help them integrate into the digital world, we can expect to improve the sleep health and overall quality of life of older adults.

Methods

Study Population

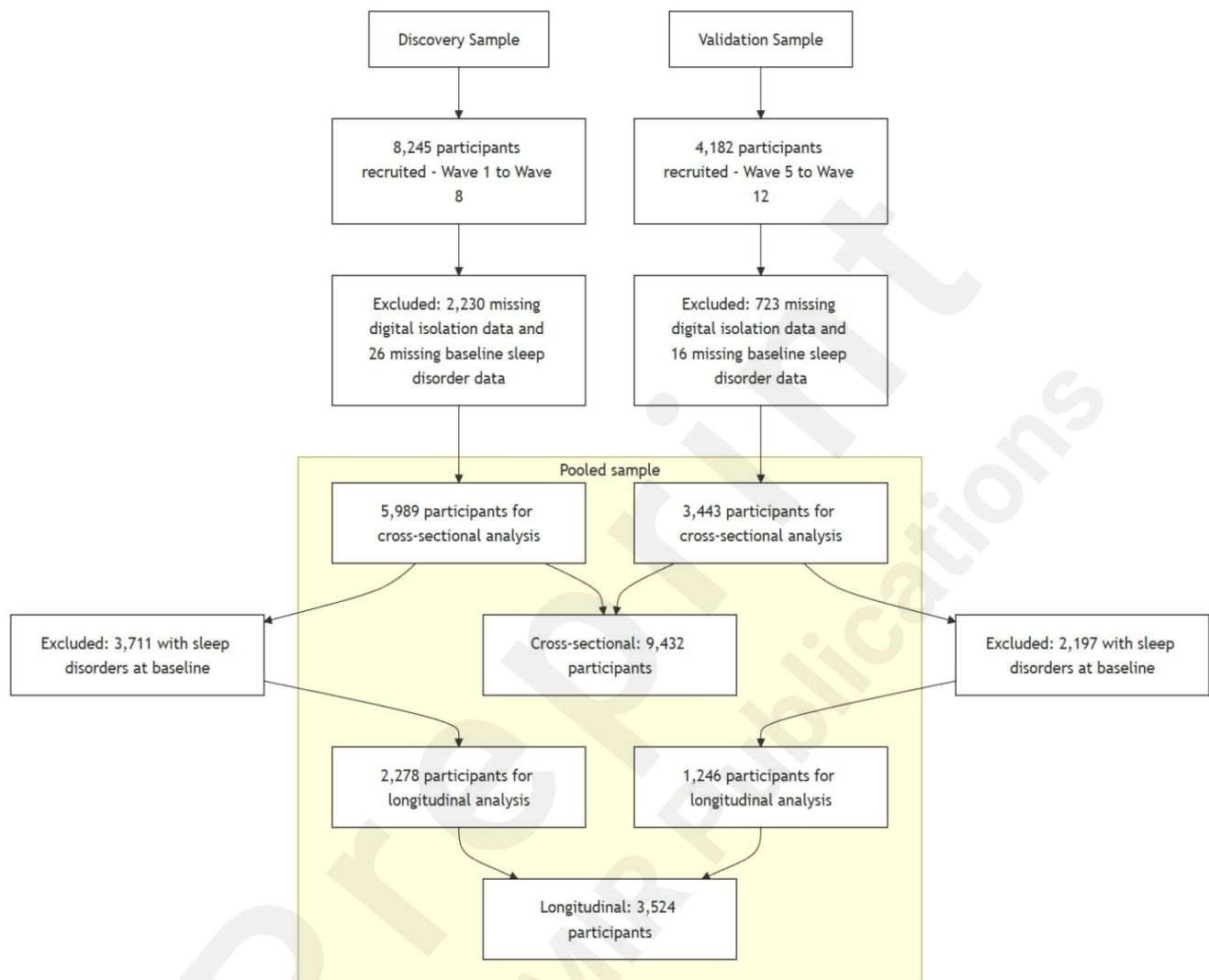
We analyzed data from the National Health and Aging Trends Study (NHATS), which has been collecting data since Wave 1 in 2011. For the discovery sample, we utilized data from Wave 1 (2011) through Wave 8 (2018), encompassing a total of seven waves of follow-up. In Wave 1, 8,245 participants were initially recruited into the study. To ensure analytical accuracy, we first excluded 2,230 participants lacking key data (missing data related to digital isolation) and further excluded 26 participants missing baseline sleep disorder data. This resulted in 5,989 participants included in the cross-sectional analysis of the discovery sample. To examine the longitudinal association between digital isolation and sleep disorders, we excluded 3,711 participants with confirmed sleep disorders at baseline. As a result, 2,278 participants were included in the longitudinal analysis of the discovery sample.

To validate our findings, we utilized an independent validation sample comprising 4,182 participants newly recruited in Wave 5 (2015) of NHATS. For these participants, data from Wave 5 to Wave 12 (2015–2022) were used, encompassing seven waves of follow-up. In the validation sample, 723 participants lacking digital isolation-related information and 16 with missing baseline sleep disorder data were excluded. Thus, 3,443 participants remained for the cross-sectional analysis in the validation sample. Similarly, for longitudinal analysis, 2,197 participants with baseline sleep disorders were excluded, resulting in 1,246 participants in the longitudinal validation cohort.

In the final analysis, the discovery and validation samples were combined, yielding a total of 9,432 participants for the cross-sectional study. After excluding baseline cases of sleep disorders, 3,524 participants were included in the longitudinal cohort. Combining the discovery and validation samples enhanced the reliability and generalizability of the findings. A flowchart illustrating

participant inclusion is presented in Figure 1.

Figure 1. Study flowchart: derivation and Selection of the final analytical sample



Definition of Digital Isolation

In this study, digital isolation was defined based on participants' engagement with modern communication technologies and internet use. First, mobile phone ownership and usage were assessed; participants who did not own a mobile phone were classified as digitally isolated in this domain. Second, participants were asked whether they had a functioning computer at home, including a desktop or laptop. Those who did not own or were unable to use a computer were considered digitally isolated in terms of computer usage. Third, for electronic communication, participants were asked whether they had sent messages via email or text in the past month. Participants who had not engaged in these forms of communication were classified as isolated in terms of email and text messaging. Finally, participants were asked whether they had engaged in any

other online activities (excluding email or text) in the past month. Those who had not participated in these activities were classified as digitally isolated in terms of general internet use.

Based on participants' responses, a score was assigned to reflect engagement across four digital domains. Scores were summed to generate a composite digital isolation score ranging from 0 to 4, with higher scores indicating greater digital isolation. For subsequent analysis, participants scoring ≤ 2 were assigned to the low isolation group, while those scoring ≥ 3 were placed in the high isolation group. This classification effectively distinguished participants based on their digital technology access and usage, forming the basis for subsequent statistical analyses [27].

Sleep Disorders

This study aimed to assess sleep disorders based on participants' sleep patterns during the past month. Three key indicators were used to identify potential sleep disorders. First, participants were asked whether they frequently took more than 30 minutes to fall asleep. Those who reported this occurring every night, most nights, or some nights were classified as having difficulty initiating sleep. Second, participants were asked whether they had difficulty returning to sleep after nocturnal awakenings. Those who experienced this every night, most nights, or sometimes were considered to have difficulty maintaining sleep. Lastly, the study assessed whether respondents needed to use medication to help them sleep. Those who reported taking medication every night, almost every night, or on some nights were also classified as having a sleep disorder.

Based on these three questions, respondents were considered to have a sleep disorder if they experienced issues in any of the three areas and were assigned a value of 1 in the composite sleep disorder variable. If no issues were reported in these areas, they were assigned a value of 0. For missing or refused responses, the data were marked as missing values. This sleep disorder variable provided crucial data for subsequent statistical analyses, helping to reveal potential associations between sleep issues and other health variables [27].

Covariates

We controlled for several covariates to minimize potential confounding. Respondents' age was divided into two categories: 75 years and younger, and older than 75 years, to analyze the effect of different age groups on the study results. Gender was based on respondents' self-reports and categorized as male or female [28-30]. Marital status was classified as married or other statuses (such as cohabitating, separated, divorced, widowed, or never married) to evaluate the potential impact of marital status on the study variables [31-33]. Race/ethnicity included categories for non-Hispanic

White, non-Hispanic Black, Hispanic, and other races (such as Native American, Asian, and Native Hawaiian) [34, 35]. Smoking status was determined based on whether respondents were regular smokers, aiming to assess the impact of smoking on health outcomes [36].

Hearing impairment was defined as the use of hearing aids or reported difficulty hearing in quiet or noisy environments [37]. Vision impairment was determined based on respondents' reports of difficulty seeing, even with corrective lenses, such as glasses [38]. For mental health, the PHQ-2 scale was used to measure depressive symptoms, with higher scores indicating a potential risk of depression [39]. Similarly, the GAD-2 scale assessed anxiety symptoms, where higher scores suggested a potential anxiety problem [40]. Additionally, we assessed respondents' chronic conditions based on the self-reported number of chronic diseases and categorized them into groups with three or fewer conditions and more than three conditions [41]. These covariates were included in subsequent multivariable analyses to control for potential confounding effects of health and demographic characteristics on study outcomes.

Statistical Analysis

All statistical analyses were sequentially conducted on the discovery, validation, and combined samples to ensure the robustness and generalizability of the findings. Descriptive analyses of baseline characteristics were first performed. Chi-square tests were applied to examine differences among groups in baseline characteristics across levels of digital isolation. These descriptive analyses provided an initial overview of population characteristics and informed subsequent regression analyses.

In the cross-sectional analysis, multivariable logistic regression models were employed to evaluate the association between digital isolation and sleep disorders. Model 1 was unadjusted, reflecting the crude association, whereas Model 2 adjusted for potential confounders to minimize bias. Covariates included in the adjusted model were age group, gender, race/ethnicity, smoking status, marital status, chronic disease status, hearing impairment, vision impairment, depression, and anxiety. Results were reported as odds ratios (ORs) with 95% confidence intervals (CIs); P-values < 0.05 were considered statistically significant. Analyses were initially conducted in the discovery sample to identify preliminary associations, then replicated in the validation sample to confirm robustness and consistency. Finally, analyses using the combined sample were performed to enhance statistical power and generate more generalizable conclusions.

For longitudinal analysis, Cox proportional hazards regression models were utilized to examine the link between digital isolation and the likelihood of incident sleep disorders among participants

without baseline sleep disorders. Model 1 and Model 2 will also be calculated. Kaplan Meier survival curves were used to estimate the incidence rate of sleep disorders across digital isolation groups, with differences assessed using the log-rank test. Survival analyses were initially performed in the discovery sample, validated in the validation sample, and subsequently applied to the combined sample to ensure generalizability.

Additionally, subgroup analyses were conducted to explore potential effect modifications of digital isolation on specific populations (e.g., different age groups, genders, races/ethnicities). Interaction terms were added to the Cox regression model to detect potential interactions between subgroups, with corresponding P-values used to assess significance. To ensure robustness, sensitivity analyses were also performed to verify the stability and consistency.

All statistics were performed using R (version 4.4.1), employing two-tailed tests with statistical significance set at $p < 0.05$.

Results

Study Population

Table 1 presents the baseline characteristics of the study population. In the discovery sample ($N = 5,989$), 54.73% of participants were aged 75 years or older, whereas in the validation sample ($N = 3,443$), this proportion was slightly lower at 48.57%. In the combined sample ($N = 9,432$), 52.50% of participants were aged 75 years or older. Regarding gender distribution, females comprised 55.82% of the discovery sample and 55.27% of the validation sample, resulting in an overall female proportion of 55.62% in the combined sample. Analysis of marital status revealed that approximately 52.81% of participants were married across the combined sample. In terms of racial/ethnic composition, non-Hispanic Whites were the dominant group (68.95%), while non-Hispanic Blacks and Hispanics accounted for 20.48% and 5.59%, respectively. Additionally, the distribution of digital isolation differed significantly between samples; the proportion of the high-isolation group was lower in the validation sample compared to the discovery sample (27.88% vs. 36.17%).

Table 1. Baseline characteristics of the study population

Variables	Discovery Sample (N = 5,989)	Validation Sample (N = 3,443)	Pooled Sample (N = 9,432)
Age Group, n (%) *			
< 75	2,710 (45.27)	1,770 (51.43)	4,480 (47.50)
≥ 75	3,279 (54.73)	1,673 (48.57)	4,952 (52.50)
Sex, n (%) **			
Female	3,343 (55.82)	1,903 (55.27)	5,246 (55.62)
Male	2,646 (44.18)	1,540 (44.73)	4,186 (44.38)
Marital Status, n (%) **			
Married	3,195 (53.35)	1,786 (51.87)	4,981 (52.81)
Others	2,788 (46.55)	1,653 (48.01)	4,441 (47.08)
Race/Ethnicity, n (%)			
White, non-Hispanic	4,204 (70.20)	2,299 (66.77)	6,503 (68.95)
Black, non-Hispanic	1,249 (20.85)	683 (19.84)	1,932 (20.48)
Hispanic	313 (5.23)	214 (6.22)	527 (5.59)
Other	159 (2.65)	114 (3.31)	273 (2.89)
Smoking Status, n (%)			
Non-smoker	2,828 (47.22)	1,713 (49.75)	4,541 (48.14)
Smoker	3,158 (52.73)	1,725 (50.10)	4,883 (51.77)
Hearing Impairment, n (%) *			
No	4,654 (77.71)	2,713 (78.80)	7,367 (78.11)
Yes	1,313 (21.92)	713 (20.71)	2,026 (21.48)

Visual Impairment, n (%) **			
No	3,619 (60.43)	2,006 (58.26)	5,625 (59.64)
Yes	2,352 (39.27)	1,416 (41.13)	3,768 (39.95)
Depression, n (%) **			
No	5,146 (85.92)	3,020 (87.71)	8,166 (86.58)
Yes	843 (14.08)	423 (12.29)	1,266 (13.42)
Anxiety, n (%) **			
No	5,274 (88.06)	3,083 (89.54)	8,357 (88.60)
Yes	715 (11.94)	360 (10.46)	1,075 (11.40)
Chronic Disease, n (%) **			
≤ 3 diseases	4,556 (76.07)	2,659 (77.23)	7,215 (76.49)
> 3 diseases	1,433 (23.93)	784 (22.77)	2,217 (23.51)
Isolation Group, n (%) **			
Low Isolation	3,823 (63.83)	2,483 (72.12)	6,306 (66.86)
High Isolation	2,166 (36.17)	960 (27.88)	3,126 (33.14)
Items of Digital Isolation, n (%)			
Phone Isolation	635 (10.60)	214 (6.22)	849 (9.00)
Computer Isolation **	1,925 (32.14)	1,064 (30.90)	2,989 (31.69)
Email Isolation **	3,600 (60.11)	1,585 (46.04)	5,185 (54.97)
Online Isolation **	3,462 (57.81)	1,609 (46.73)	5,071 (53.76)

Note

All categorical variables were analyzed using chi-square tests to assess their association with the occurrence of hearing impairment. Statistical significance is

indicated by asterisks: * denotes $p < 0.05$, and ** denotes $p < 0.001$. In the race/ethnicity category, the "Other" group includes African Americans, Native Americans, Alaska Natives, Asians, Native Hawaiians, Pacific Islanders, and other unspecified races or ethnicities. The assessment of chronic disease burden is based on the cumulative number of the following conditions: heart disease, hypertension, arthritis, osteoporosis, diabetes, lung disease, stroke, cancer, and other illnesses. Missing data were handled as follows: In the discovery sample, missing values were present for race/ethnicity (n=51), smoking status (n=3), marital status (n=5), dementia (n=1), vision impairment (n=12), and sleep disorders (n=10). In the validation sample, missing values were observed for race/ethnicity (n=107), smoking status (n=2), marital status (n=4), dementia (n=2), vision impairment (n=13), and sleep disorders (n=5). These missing data were excluded from the analysis.

Cross-Sectional Association Between Digital Isolation and Sleep Disorders

Table 2 shows the cross-sectional association between digital isolation and sleep disorders. In the discovery sample, the prevalence of sleep disorders was significantly higher in the high-isolation group compared to the low-isolation group (67.03% vs. 59.06%). In the unadjusted model (Model 1), the odds of sleep disorders were 41% higher in the high-isolation group compared to the low-isolation group (OR = 1.41 and $P < 0.001$). After adjusting for potential confounders, the association was still significant (OR = 1.23 and $P < 0.001$). Similar results were observed in the validation sample, with a significantly increased odds of sleep disorders in the high-isolation group (OR = 1.22; 95% CI: 1.02–1.47; $P = 0.033$). In the combined sample, the adjusted odds of sleep disorders were 21% higher in the high-isolation group compared to the low-isolation group (OR = 1.21; 95% CI: 1.10–1.34; $P < 0.001$).

Table 2. Cross-sectional association between digital isolation and the risk of sleep disorder

Sample/Variables	Event/N (%)	Model 1 OR (95% CI)	P-Value	Model 2 O
Discovery Sample				
Low Isolation (Ref)	2,259/3,823 (59.06%)	1 (Ref)		1 (
High Isolation	1,452/2,166 (67.03%)	1.41 (1.26, 1.57)	<0.001	1.23 (1.
Validation Sample				
Low Isolation (Ref)	1,524/2,483 (61.38%)	1 (Ref)		1 (
High Isolation	673/960 (70.10%)	1.48 (1.26, 1.73)	<0.001	1.22 (1.
Pooled Sample				
Low Isolation (Ref)	3,783/6,306 (59.98%)	1 (Ref)		1 (
High Isolation	2,125/3,126 (67.96%)	1.42 (1.29, 1.55)	<0.001	1.21 (1.

Note

Model 1: Unadjusted logistic regression model.

Model 2: Logistic regression model adjusted for age group, sex, race/ethnicity (white, non-Hispanic), smoking status, marital status, chronic disease (binary), hearing impairment, visual impairment, depression, and anxiety.

Abbreviations: OR = Odds Ratio; CI = Confidence Interval; Ref = Reference category.

This table presents the cross-sectional association between digital isolation and the risk of sleep disorder across discovery, validation, and pooled samples. Model 1 provides unadjusted odds ratios, while Model 2 adjusts for various covariates to control for confounding factors.

Longitudinal Association Between Digital Isolation and Sleep Disorders

Table 3 summarizes the longitudinal association between digital isolation and incident sleep disorders among participants without baseline sleep disorders. In the discovery sample, the unadjusted Cox regression analysis showed a significantly increased hazard of sleep disorders in the high-isolation group (HR = 1.30; 95% CI: 1.15–1.47; $P < 0.001$). After adjusting for age, gender, race/ethnicity, and other confounders, the association remained significant (HR = 1.21; 95% CI: 1.05–1.38; $P = 0.006$). In the validation sample, the unadjusted model also showed a higher hazard in the high-isolation group (HR = 1.29; 95% CI: 1.07–1.55; $P = 0.008$), but this association was no longer statistically significant after adjustment (HR = 1.11; 95% CI: 0.91–1.36; $P = 0.298$). In the combined sample, the adjusted hazard of sleep disorders in the high-isolation group was 17% higher (HR = 1.17; 95% CI: 1.05–1.31; $P = 0.005$).

Table 3. Association between digital isolation and the risk of developing sleep disorder in baseline sleep disorder-free samples using Cox regression analysis

Sample/Variables	Event/N (%)	Model 1 HR (95% CI)	P-Value	Model 2 HR (95% CI)	P-Value
Discovery Sample					
Low Isolation (Ref)	762/1,564 (48.73%)	1 (Ref)	-	1 (Ref)	-
High Isolation	385/714 (53.92%)	1.30 (1.15, 1.47)	<0.001	1.21 (1.05, 1.38)	0.006
Validation Sample					
Low Isolation (Ref)	536/959 (55.88%)	1 (Ref)	-	1 (Ref)	-
High Isolation	140/287 (48.78%)	1.29 (1.07, 1.55)	0.008	1.11 (0.91, 1.36)	0.298
Pooled Sample					
Low Isolation (Ref)	1,298/2,523 (51.45%)	1 (Ref)	-	1 (Ref)	-
High Isolation	525/1,001 (52.45%)	1.31 (1.18, 1.45)	<0.001	1.17 (1.05, 1.31)	0.005

Note

Model 1: Unadjusted Cox proportional hazards model.

Model 2: Cox proportional hazards model adjusted for age group, sex, race/ethnicity, smoking status, marital status, hearing impairment, visual impairment, depression, anxiety, and chronic disease (binary).

Association Between Digital Isolation Components and Sleep Disorders

Table 4 displays the link between different items of digital isolation and sleep disorders. In the discovery sample, phone isolation was not significantly associated with sleep disorders (HR = 1.01, $P = 0.878$), but in the validation sample, phone isolation significantly increased the hazard of sleep disorders (HR = 1.46, $P = 0.030$). Computer isolation, email isolation, and online activity isolation were all significantly associated with sleep disorders in both the discovery and combined samples, with adjusted HRs ranging from 1.16 to 1.20 ($P < 0.05$). However, in the validation sample, the associations for computer isolation and online activity isolation lost significance after adjustment.

Table 4. Association between digital isolation items and the risk of developing sleep disorder

Sample/Variables	Model 1 HR (95% CI)	P-Value	Model 2 HR (95% CI)	P-Value
Discovery Sample				
Phone Isolation	1.07 (0.89, 1.29)	0.462	1.01 (0.84, 1.23)	0.878
Computer Isolation	1.27 (1.12, 1.44)	<0.001	1.20 (1.04, 1.38)	0.01
Email Isolation	1.28 (1.14, 1.44)	<0.001	1.18 (1.04, 1.34)	0.01
Online Isolation	1.26 (1.13, 1.42)	<0.001	1.16 (1.02, 1.32)	0.019
Validation Sample				
Phone Isolation	1.65 (1.19, 2.28)	0.003	1.46 (1.04, 2.07)	0.03
Computer Isolation	1.20 (1.01, 1.44)	0.046	1.11 (0.91, 1.34)	0.291
Email Isolation	1.41 (1.21, 1.65)	<0.001	1.21 (1.01, 1.44)	0.034
Online Isolation	1.30 (1.11, 1.52)	0.001	1.11 (0.94, 1.32)	0.219
Pooled Sample				
Phone Isolation	1.18 (1.01, 1.39)	0.043	1.09 (0.93, 1.29)	0.287
Computer Isolation	1.25 (1.13, 1.39)	<0.001	1.16 (1.04, 1.30)	0.008
Email Isolation	1.33 (1.21, 1.46)	<0.001	1.19 (1.08, 1.32)	0.001
Online Isolation	1.28 (1.17, 1.41)	<0.001	1.15 (1.04, 1.27)	0.008

Notes:

Model 1: Unadjusted Cox proportional hazards model.

Model 2: Cox proportional hazards model adjusted for age group, sex, marital status, race, smoking status, hearing impairment, visual impairment, depression, anxiety, and chronic disease.

Kaplan–Meier Survival Curve and Forest Plot Analysis

Kaplan–Meier survival curves further illustrated the incidence of sleep disorders during follow-up across different digital isolation groups (Figure 2). The incidence of sleep disorders was significantly higher in the high-isolation group compared to the low-isolation group, with the log-rank test showing a statistically significant difference between the two groups ($P < 0.001$). Additionally, the forest plot in Figure 3 demonstrated the link between digital isolation and sleep disorder among subgroups. The analysis showed consistent effects of digital isolation across different subgroups (e.g., age, gender, race/ethnicity), but stronger effects were observed in certain subgroups, such as the older age group and female participants, where interaction term P-values indicated significant heterogeneity ($P < 0.05$).

Figure 2. Kaplan–Meier curves of the relationship between digital isolation and developing sleeping disorder

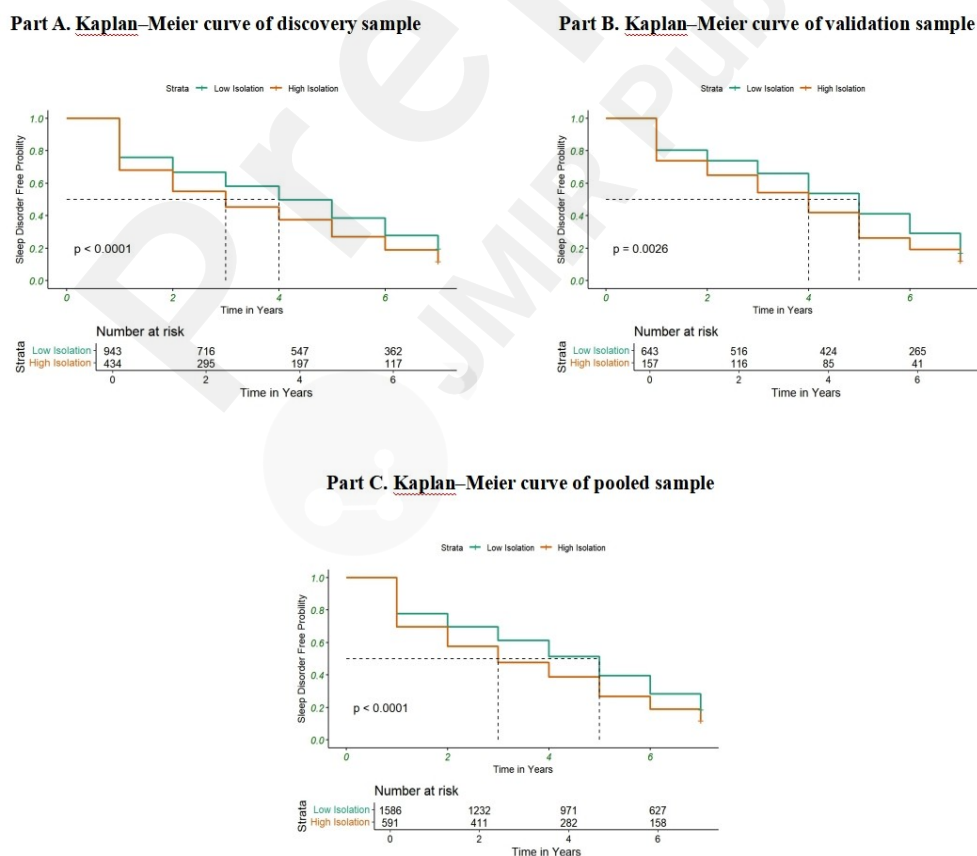
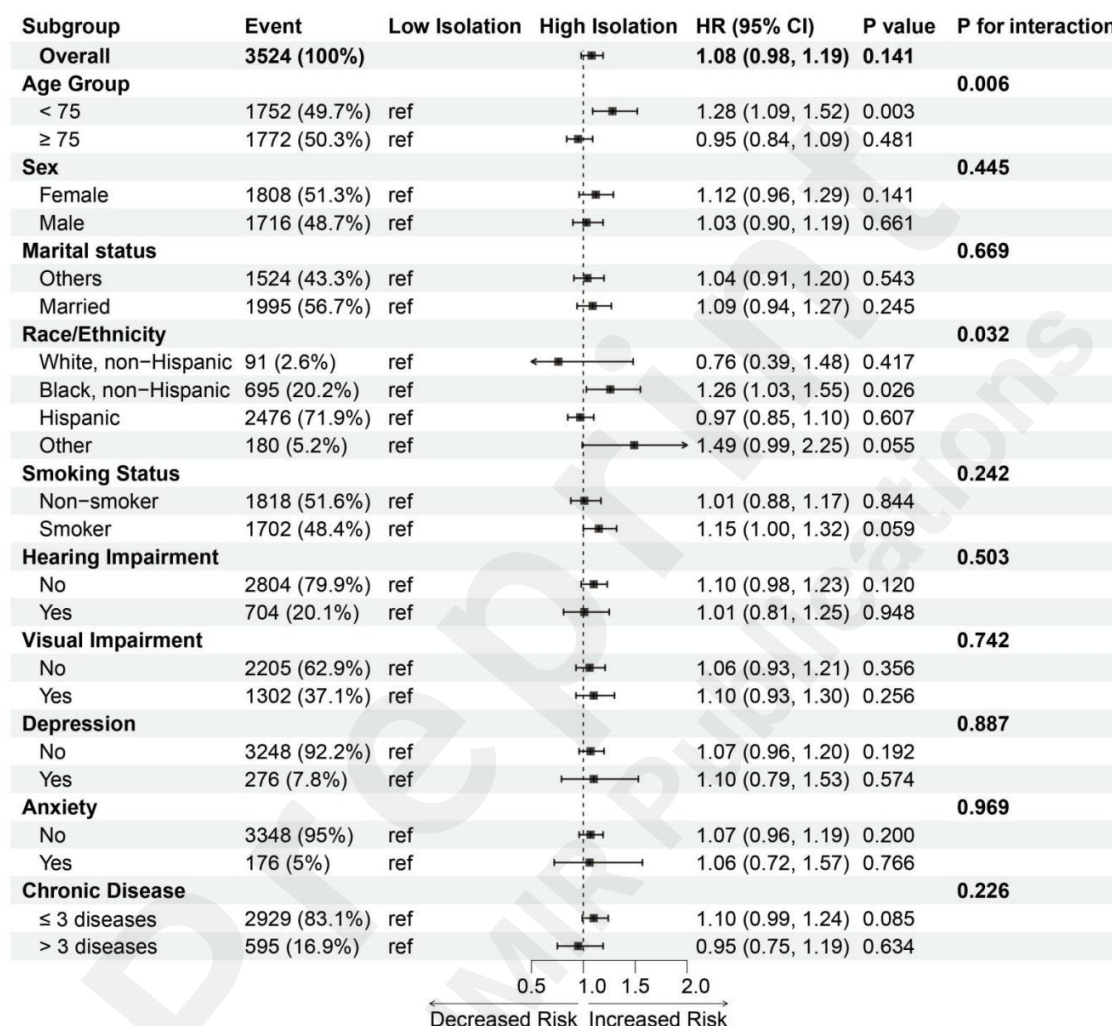


Figure 3. Subgroup analysis of digital isolation's impact on sleep disorder risk across various demographic and health factors



Sensitivity Analysis

To further explore why the univariate model was significant in the validation sample while the multivariable model was not, we conducted a sensitivity analysis by incrementally introducing confounders. By gradually adding variables, we assessed how each confounder impacted the association between digital isolation and sleep disorders and examined why this association weakened or disappeared as more confounders were introduced. In the univariate model, digital isolation significantly increased the hazard of sleep disorders (HR = 1.29; P = 0.008). However, as we

gradually introduced confounders—starting with gender, marital status, and race/ethnicity, and then adding smoking status, hearing impairment, vision impairment, depression, anxiety, chronic disease, and age—the effect of digital isolation diminished. In the final multivariable model, the association between digital isolation and sleep disorders was no longer significant (HR = 1.11; P = 0.298). Specifically, the introduction of depression and anxiety significantly weakened the effect of digital isolation. These mental health factors were strongly associated with sleep disorders (depression HR = 1.52; P = 0.014; anxiety HR = 1.67; P = 0.009), suggesting that they may mediate the relationship between digital isolation and sleep disorders. Additionally, chronic disease (HR = 1.34; P = 0.006) and age (HR = 1.32; P = 0.001) were important confounders that further attenuated the effect of digital isolation. This sensitivity analysis indicates that the lack of significance in the multivariable model in the validation sample was due to the introduction of key variables, such as health conditions and age, which gradually weakened the independent effect of digital isolation. These confounders explained the primary risks for sleep disorders, particularly depression, anxiety, and chronic disease, which may have served as mediators between digital isolation and sleep disorders.

Discussion

This study explored the association between digital isolation and sleep disorders using both cross-sectional and longitudinal designs. The results indicated that digital isolation was significantly associated with sleep disorders in univariate and multivariate analyses in the discovery and combined samples. However, in the validation sample, while a significant association was observed in the univariate analysis, the effect of digital isolation weakened as confounding factors were introduced, ultimately losing significance in the multivariate model. This suggests that health conditions such as depression, anxiety, and chronic diseases may mediate the association between digital isolation and sleep disorders.

The findings align with previous literature, particularly regarding the significant

association between digital isolation and sleep disorders. For example, earlier studies have shown that social isolation, depression, and anxiety are closely related to sleep disorders [42-44]. Our study corroborates these findings, demonstrating that digital isolation is significantly associated with sleep disorders in the absence of adjustment for other confounders. However, as we incrementally introduced confounders, particularly health conditions, the effect of digital isolation diminished or disappeared. This is consistent with some studies suggesting that mental health factors such as depression and anxiety may act as key mediators between digital isolation and sleep disorders [45]. In contrast to our findings of a reduced effect, some studies have emphasized the independent effects of digital isolation; this discrepancy may be due to differences in study design, sample characteristics, or data handling [24, 46]

In the validation sample, we observed that digital isolation was significantly associated with sleep disorders in the univariate model, but this association lost significance in the multivariate analysis. Conversely, in the discovery and combined samples, the association between digital isolation and sleep disorders remained significant in both univariate and multivariate models. This discrepancy suggests that the independent effect of digital isolation in the validation sample diminished as more confounders were introduced, possibly due to differences in the health characteristics of individuals in the validation sample. The prevalence or severity of depression, anxiety, and chronic diseases in the validation sample may differ significantly from those in the discovery and combined samples, leading to stronger confounding effects. Additionally, differences in the representativeness and statistical power of the validation sample could also explain why the multivariate model was not significant in this sample. Therefore, further research should investigate the mediating role of these health factors in different populations, especially in the validation sample.

The multivariate model results suggest that depression, anxiety, and chronic diseases may mediate the association between digital isolation and sleep disorders. Mental health factors such as depression and anxiety have been confirmed in numerous studies as important contributors to sleep disorders [47-49]. In our study, as

these mental health factors were gradually introduced, the effect of digital isolation diminished, indicating that psychological health problems may partially mediate this relationship. Similarly, chronic diseases were significantly associated with sleep disorders in the multivariate model, suggesting that chronic health issues may not only directly affect sleep quality but also contribute indirectly by increasing psychological stress or exacerbating depression and anxiety, thereby influencing the occurrence of sleep disorders.

One of the major strengths of this study is the combination of cross-sectional and longitudinal research designs. This approach allowed us not only to analyze the association between digital isolation and sleep disorders at a specific time point but also to explore dynamic changes over time through longitudinal data, which enhances the ability to infer causality. Moreover, the study systematically evaluated the impact of each confounder by incrementally introducing them through sensitivity analysis, strengthening the interpretability and robustness of the results. The large sample size and independent analyses in both the discovery and validation samples provided opportunities to verify the robustness of the findings. The combined sample ensured the generalizability and applicability of the results.

Despite these strengths, there are some limitations to this study. First, the data were self-reported, particularly for psychological health variables such as depression and anxiety, which may be influenced by subjective factors, leading to bias. Future studies should use more objective health assessment tools to ensure data accuracy. Second, although we controlled for a variety of confounders through multivariate analysis, unmeasured or unaccounted-for potential confounders may still exist, potentially influencing the association between digital isolation and sleep disorders. Future research could introduce more relevant factors for a more comprehensive analysis. Finally, while significant results were obtained in the discovery and combined samples, the non-significant findings in the multivariate model of the validation sample suggest that sample characteristic differences may influence the results. Future studies should further explore the potential reasons for these

differences.

Future research should continue to investigate the complex interactions between digital isolation and other health outcomes, such as depression and anxiety, especially in different age groups and cultural contexts. Additionally, longitudinal studies could further reveal the long-term impact of digital isolation on health outcomes, particularly the mediating role that psychological health problems may play in this process. Experimental designs or intervention studies could also be used to assess whether reducing digital isolation helps improve sleep quality, providing practical evidence for public health interventions.

This study revealed an association between digital isolation and sleep disorders through a combination of cross-sectional and longitudinal designs. Although digital isolation was significantly associated with sleep disorders before controlling for confounders, the association weakened and lost significance with the introduction of confounders such as depression, anxiety, and chronic diseases. This suggests that psychological health problems may mediate the link between digital isolation and sleep disorders. Therefore, following public health interventions need focus on improving mental health to mitigate the adverse impacts of digital divide on sleep quality in aging population.

Ethics consideration

The study protocol was approved by the Ethics Committee of Union Hospital, Tongji Medical College, Huazhong University of Science and Technology.

Acknowledgements

We gratefully acknowledge NHATS for providing the publicly available dataset that supported this research. We also acknowledge the dedicated efforts of the NHATS data collection team, whose work was essential to the success of the project. Authors' contributions were as follows: S.Y., as the first author, conceived and designed the study and drafted the manuscript. W.T. and F.Y., as co-corresponding authors,

contributed equally to data mining, analysis, supervision, critical revision, and final approval of the manuscript. We also thank the DeepSeek R1 large language model for its assistance in translating and refining the initial draft of this manuscript.

Funding

This study was supported by the National Natural Science Foundation of China (Grant No. 82151217).

Conflicts of Interest

The authors declare no conflicts of interest.

Abbreviations

CI - Confidence Interval

GAD-2 - Generalized Anxiety Disorder-2

HR - Hazard Ratio

NHATS - National Health and Aging Trends Study

OR - Odds Ratio

PHQ-2 - Patient Health Questionnaire-2

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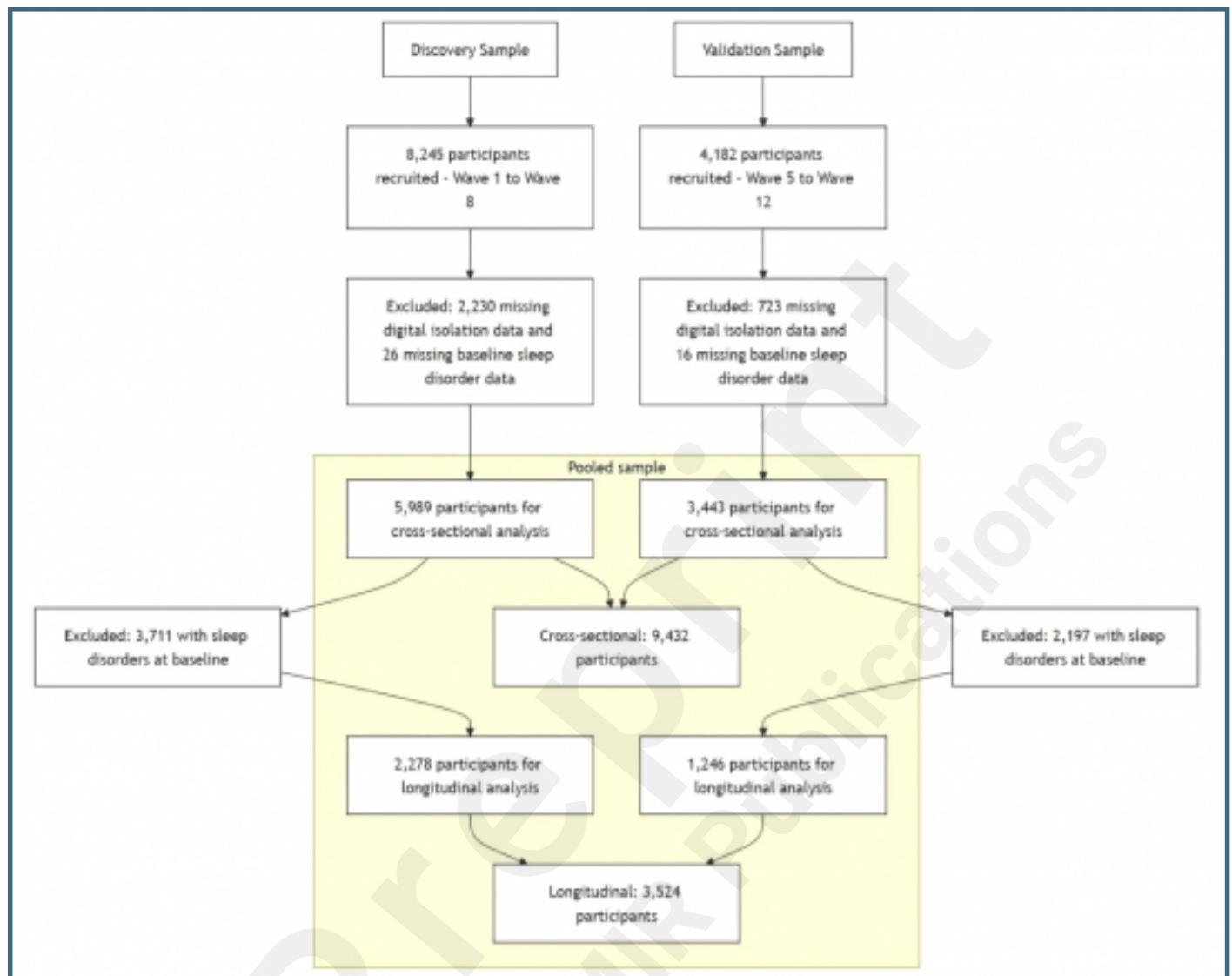
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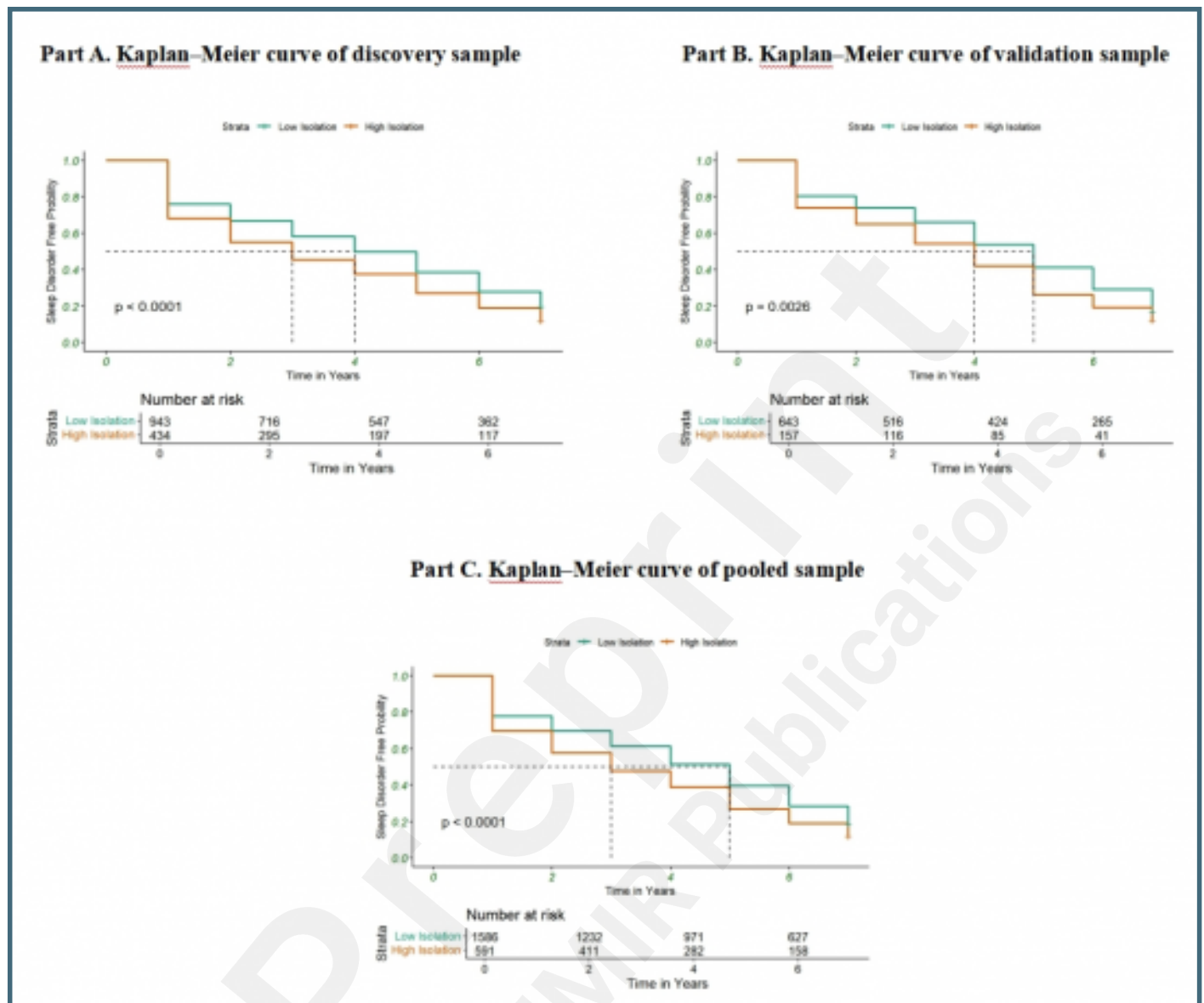
Supplementary Files

Figures

Study flowchart: derivation and selection of the final analytical sample.



Kaplan-Meier curves of the relationship between digital isolation and developing sleeping disorder.



Subgroup analysis of digital isolation's impact on sleep disorder risk across various demographic and health factors.

