

<https://doi.org/10.1038/s41746-025-02076-1>

# Ten-year trends of the digital divides and its effect on healthy aging among older adults in China from 2011 to 2020

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We examined decade-long trends in digital divides and their causal impact on healthy aging among older adults in China. Using five waves of nationally representative data from the China Health and Retirement Longitudinal Study (2011–2020;  $n = 46,674$ , aged  $\geq 60$ ), we applied instrumental variable method with two-way fixed effects to address endogeneity. From 2011 to 2020, digital access divide declined from 88.0% to 47.3%, and digital usage divide from 99.0% to 75.7% ( $P$  for trend  $< 0.001$ ). However, both divides were significantly associated with poorer healthy aging outcomes across physical, cognitive, emotional, and social domains. The digital access divide was linked to increased functional limitations, multimorbidity, cognitive impairment, depressive symptoms, social isolation, and lower overall healthy aging index. The digital usage divide showed the same pattern. Subgroup analyses revealed heterogeneity by urban-rural residence, sex, economic level, marital status, education level, and region.

The rapid adoption of digital technologies has reshaped many aspects of daily life, including healthcare, communication, and social participation. These advancements have the potential to significantly improve the health and well-being of individuals, particularly older adults<sup>1</sup>. However, not all populations have equally benefited from this digital transformation. Among older adults, the digital divide remains a significant issue<sup>2</sup>. Digital access divide refers to the lack of household internet access, while digital usage divide refers to not using the internet due to various reasons, such as unequal skills and knowledge<sup>3</sup>. Access and usage can diverge among older adults for several reasons. Common barriers include limited digital skills and health literacy, visual or cognitive limitations, concerns about privacy and fraud, the cost of devices and data plans, and interfaces that are not age-friendly<sup>4</sup>. The rapid shift of public and commercial services into app-based ecosystems has also raised the skills needed to participate, which can widen the usage divide even when household access improves. The divide is especially pronounced in developing countries, where a large proportion of the older population remains disconnected from the digital world<sup>5</sup>. In China, this usage divide is often larger than the access divide, reflecting barriers in digital literacy and engagement<sup>6,7</sup>.

Limited internet access and low digital literacy have been linked to poorer health outcomes among older adults in China<sup>8</sup>. Older individuals without access to digital technologies face challenges in managing chronic conditions, accessing healthcare services, and maintaining

social ties<sup>9</sup>. As digital tools become increasingly integrated into healthcare systems and social networks, those who are excluded from these advancements may experience greater isolation and difficulty navigating the modern healthcare landscape<sup>10</sup>. Previous studies have documented the trends in digital access and usage among older adults in other countries, but similar analyses in China are scarce, especially in the context of the rapid changes in digital infrastructure in China over the past decade<sup>11</sup>. Between 2011 and 2020, China rapidly expanded fixed broadband and mobile networks, smartphones became widespread, and many everyday services moved online, including communication, transport ticketing, payments, appointment booking, and social benefit enquiries<sup>12,13</sup>. Although these reforms markedly expanded internet access for numerous households, the trend of access and usage among older adults remains unclear, and importantly, may be uneven across subgroups and regions. For instance, the eastern region (e.g., Beijing and Shanghai) benefited from earlier infrastructure rollout and broader digital service penetration, whereas the western region (e.g., Qinghai and Ningxia) continues to face greater constraints due to geography and delayed development<sup>14</sup>.

Given the accelerating pace of urbanization and digitalization, understanding the digital divide's role in aging is essential for addressing the needs of the elderly and ensuring equitable access to resources that can support healthy aging<sup>9</sup>. The concept of healthy aging encompasses a broad

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range of physical, mental, and social well-being<sup>15</sup>, including the absence of functional limitations, multimorbidity, cognitive decline, depressive symptoms, and social isolation. Each of these factors is essential for an individual's ability to live independently and maintain quality of life in later years. Previous studies on the digital divide and health outcomes have primarily focused on associations, often using cross-sectional designs<sup>16</sup>. These studies have highlighted the association between digital access and various aspects of health and well-being, such as functional dependence<sup>17</sup>, cognitive function<sup>18</sup>, mental health<sup>19</sup>, and social participation<sup>20</sup>. However, they have not been able to definitively establish causal links between digital divides and healthy aging outcomes. Most existing research suggests that digital inclusion may improve health outcomes, but without causal evidence, the direction and strength of this relationship remain uncertain. Moreover, much of the research has been cross-sectional, providing a snapshot of associations but failing to capture the dynamic changes in digital engagement and its long-term effects on aging<sup>7</sup>. Establishing causality is crucial for policymakers and healthcare providers designing interventions to reduce health disparities and improve the quality of life for older adults. Without a causal understanding, the potential for targeted, effective interventions is limited<sup>21</sup>.

This study seeks to fill this gap by analyzing the trends of the digital access divide and the digital usage divide among older adults in China over the past decade and examining the causal relationship between these divides and healthy aging. By utilizing data from the five-wave China Health and Retirement Longitudinal Study (CHARLS), this study uses longitudinal data to explore how the digital access and usage divides impact various dimensions of healthy aging. Additionally, by employing instrumental variables (IV) with fixed effects, this study aims to establish causality, offering a more robust understanding of how digital divides influence the healthy aging process.

## Results

### Characteristics of participants and ten-year trends in digital divides

Figure 1 shows the selection process of participants. This study included a total of 46,674 observations of the CHARLS survey. Table 1 shows the characteristics of participants. From 2011 to 2020, both the digital access and usage divides experienced significant declines. The digital access divide, measured as the proportion of older adults without household internet

access, decreased from 88.0% in 2011 to 47.3% in 2020. The digital usage divide, defined as the proportion of older adults not using the internet, declined from 99.0% to 75.7% over the same period. These trends indicate substantial progress in digital inclusion among older Chinese adults (*P* for trend < 0.05). However, subgroup analyses revealed persistent inequalities in both digital access and digital usage divides. Male participants experienced a slightly faster improvement in bridging the digital access divide compared to females. Urban residents consistently had lower levels of both digital access and digital usage divides than their rural counterparts. Older adults living in the eastern region, as well as those with higher education or income levels, were more likely to benefit from reductions in both types of digital divides. More details are displayed in Fig. 2. In addition, we also present the trends of digital access and usage divides in each province from 2011 to 2020 in Table S1.

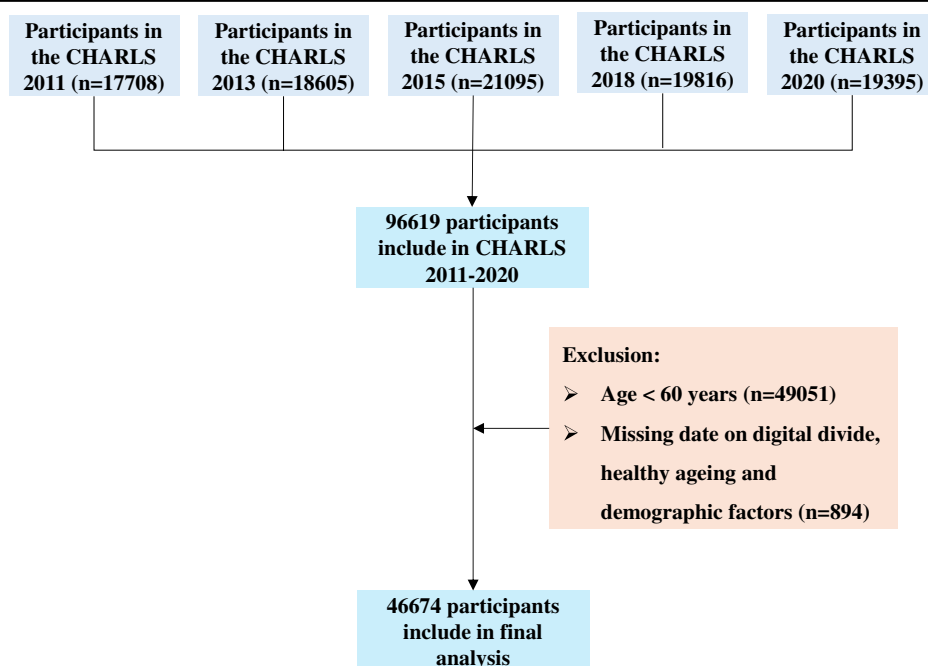
### Gaps between digital access and usage divides

Over the past decade, although both the digital access divide and the digital usage divide among older adults in China have narrowed, the gap between them has widened. Nationally, the difference between the proportion of older adults without household internet access (access divide) and those not using the internet (usage divide) increased from 11.0% in 2011 (99.0% vs. 88.0%) to 28.4% in 2020 (75.7% vs. 47.3%).

This pattern was observed consistently across various subgroups. By sex, the usage-access gap among males increased from 10.8% in 2011 (98.7% vs. 87.9%) to 25.0% in 2020 (70.9% vs. 45.9%), while among females, it expanded from 11.1% to 31.7% (99.4% vs. 88.3% in 2011; 80.4% vs. 48.7% in 2020). Urban-rural differences were also evident. In urban areas, the gap grew from 20.5% in 2011 (97.6% vs. 77.1%) to 27.6% in 2020 (64.5% vs. 36.9%), whereas in rural areas, it expanded more dramatically from 4.5% (99.9% vs. 95.4%) to 29.2% (86.7% vs. 57.5%).

By educational attainment, older adults with no formal education showed a usage-access gap that increased from 7.3% in 2011 (99.9% vs. 92.6%) to 34.4% in 2020 (94.7% vs. 60.3%). Among those with middle school education or above, the gap reduced from 20.7% to 18.5% (95.3% vs. 74.6% in 2011; 49.2% vs. 30.7% in 2020). Economically, the usage-access gap for the low-level group grew from 3.4% to 22.6% (99.8% vs. 96.4% in 2011; 81.3% vs. 58.7% in 2020), and for the high-level group from 20.1% to 34.2% (98.2% vs. 78.1% in 2011; 70.3% vs. 36.1% in 2020) over the study period. Regionally, all areas experienced an expansion of the usage-access gap. For example, in the

Fig. 1 | The selection process of participants.



**Table 1 | Characteristics of participants by years**

Variables	2011	2013	2015	2018	2020
Sample	<i>N</i> = 7176	<i>N</i> = 8356	<i>N</i> = 9762	<i>N</i> = 10,726	<i>N</i> = 10,654
Age, mean ± SD	68.3 ± 6.9	68.4 ± 7.0	68.5 ± 7.0	69.2 ± 7.1	69.0 ± 6.9
Sex, <i>n</i> (%)					
Males	3609 (50.3)	4197 (50.2)	4817 (49.3)	5231 (48.8)	5153 (48.4)
Females	3567 (49.7)	4159 (49.8)	4945 (50.7)	5495 (51.2)	5501 (51.6)
Residence, <i>n</i> (%)					
Rural	4338 (60.5)	5057 (60.5)	5888 (60.3)	6482 (60.4)	6382 (59.9)
Urban	2838 (39.5)	3299 (39.5)	3874 (39.7)	4244 (39.6)	4272 (40.1)
Regions, <i>n</i> (%)					
Eastern	2392 (33.3)	2786 (33.3)	3313 (33.9)	3674 (34.3)	3758 (35.3)
Central	2358 (32.9)	2751 (32.9)	3171 (32.5)	3496 (32.6)	3469 (32.6)
Western	2426 (33.8)	2819 (33.7)	3278 (33.6)	3556 (33.2)	3427 (32.2)
Marital status, <i>n</i> (%)					
Married	5578 (77.7)	6565 (78.6)	7664 (78.5)	8343 (77.8)	8131 (76.3)
Unmarried	1598 (22.3)	1791 (21.4)	2098 (21.5)	2383 (22.2)	2523 (23.7)
Education, <i>n</i> (%)					
Illiterate	2668 (37.2)	3029 (36.2)	3421 (35.0)	3463 (32.3)	3359 (31.5)
Primary school	3153 (43.9)	3664 (43.8)	4316 (44.2)	4616 (43.0)	4555 (42.8)
Middle school and above	1355 (18.9)	1663 (19.9)	2025 (20.7)	2647 (24.7)	2740 (25.7)
Economic level, <i>n</i> (%)					
Low	4075 (56.8)	4307 (51.5)	4915 (50.3)	5921 (55.2)	5632 (52.9)
High	3101 (43.2)	4049 (48.5)	4847 (49.7)	4805 (44.8)	5022 (47.1)
Smoking, <i>n</i> (%)					
No	4146 (57.8)	5289 (63.3)	6772 (69.4)	7927 (73.9)	7918 (74.3)
Yes	3030 (42.2)	3066 (36.7)	2990 (30.6)	2799 (26.1)	2736 (25.7)
Drinking, <i>n</i> (%)					
No	5041 (70.2)	5743 (68.7)	6659 (68.2)	7428 (69.3)	7229 (67.9)
Yes	2135 (29.8)	2613 (31.3)	3103 (31.8)	3298 (30.7)	3425 (32.1)
Exercise, <i>n</i> (%)					
Hardly	4451 (62.0)	5547 (66.4)	7814 (80.0)	7534 (70.2)	5549 (52.1)
Regularly	2725 (38.0)	2809 (33.6)	1948 (20.0)	3192 (29.8)	5105 (47.9)
Health insurance, <i>n</i> (%)					
No	475 (6.6)	328 (3.9)	912 (9.3)	333 (3.1)	574 (5.4)
Yes	6701 (93.4)	8028 (96.1)	8850 (90.7)	10,393 (96.9)	10,080 (94.6)
Digital access divide, <i>n</i> (%)					
Yes	6416 (89.4)	7056 (84.4)	7863 (80.5)	7013 (65.4)	5363 (50.3)
No	760 (10.6)	1300 (15.6)	1899 (19.5)	3713 (34.6)	5291 (49.7)
Digital usage divide, <i>n</i> (%)					
Yes	7101 (99.0)	8207 (98.2)	9527 (97.6)	10,083 (94.0)	8384 (78.7)
No	75 (1.0)	149 (1.8)	235 (2.4)	643 (6.0)	2270 (21.3)
Functional limitations, <i>n</i> (%)					
No	4435 (61.8)	5275 (63.1)	5308 (54.4)	6184 (57.7)	6194 (58.1)
Yes	2741 (38.2)	3081 (36.9)	4454 (45.6)	4542 (42.3)	4460 (41.9)
Multimorbidity, <i>n</i> (%)					
No	3839 (53.5)	4263 (51.0)	4109 (42.1)	5120 (47.7)	3225 (30.3)
Yes	3337 (46.5)	4093 (49.0)	5653 (57.9)	5606 (52.3)	7429 (69.7)
Cognitive impairment, <i>n</i> (%)					
No	5792 (80.7)	7011 (83.9)	7962 (81.6)	8714 (81.2)	8821 (82.8)
Yes	1384 (19.3)	1345 (16.1)	1800 (18.4)	2012 (18.8)	1833 (17.2)

**Table 1 (continued) | Characteristics of participants by years**

Variables	2011	2013	2015	2018	2020
Depressive symptoms, <i>n</i> (%)					
No	4414 (61.5)	5914 (70.8)	6557 (67.2)	7069 (65.9)	6832 (64.1)
Yes	2762 (38.5)	2442 (29.2)	3205 (32.8)	3657 (34.1)	3822 (35.9)
Social isolation, <i>n</i> (%)					
No	4820 (67.2)	6039 (72.3)	5315 (54.4)	5801 (54.1)	7224 (67.8)
Yes	2356 (32.8)	2317 (27.7)	4447 (45.6)	4925 (45.9)	3430 (32.2)
Healthy ageing index, <i>n</i> (%)					
0	128 (1.8)	76 (0.9)	238 (2.4)	214 (2.0)	214 (2.0)
1	550 (7.7)	473 (5.7)	993 (10.2)	975 (9.1)	951 (8.9)
2	1315 (18.3)	1356 (16.2)	2163 (22.2)	2274 (21.2)	2391 (22.4)
3	1883 (26.2)	2173 (26.0)	2726 (27.9)	3036 (28.3)	3015 (28.3)
4	2029 (28.3)	2592 (31.0)	2456 (25.2)	2878 (26.8)	2897 (27.2)
5	1271 (17.7)	1686 (20.2)	1186 (12.1)	1349 (12.6)	1186 (11.1)

Note: The percentages presented in this table are unweighted and may differ slightly from those reported in Fig. 2, which are weighted estimates of the digital access and usage divides.

western region, the gap widened from 7.7% in 2011 (99.5% vs. 91.8%) to 30.2% in 2020 (81.6% vs. 51.4%).

**Effect of digital access divide and digital usage divide on healthy aging**

Using instrumental-variable models via two-stage residual inclusion (2SRI), both the digital access and digital usage divides were associated with significantly lower odds of healthy aging outcomes (Table 2). For the five binary components, the access divide was consistently detrimental: no functional limitation (OR = 0.548; 95% CI: 0.460–0.653), no multimorbidity (OR = 0.718; 95% CI: 0.588–0.877), no cognitive impairment (OR = 0.408; 95% CI: 0.318–0.523), no depressive symptoms (OR = 0.556; 95% CI: 0.462–0.668), and no social isolation (OR = 0.603; 95% CI: 0.498–0.731). The usage divide showed a similar pattern: no functional limitation (OR = 0.694; 95% CI: 0.540–0.893), no multimorbidity (OR = 0.761; 95% CI: 0.590–0.982), no cognitive impairment (OR = 0.461; 95% CI: 0.272–0.782), no depressive symptoms (OR = 0.638; 95% CI: 0.496–0.820), and no social isolation (OR = 0.619; 95% CI: 0.555–0.691).

For the overall Healthy Aging Index (HAI, 0–5), analyzed as an ordinal outcome, the access divide was linked to lower odds of being in higher HAI categories (proportional OR = 0.459; 95% CI: 0.393–0.536), and the usage divide likewise indicated worse healthy aging profiles (proportional OR = 0.756; 95% CI: 0.623–0.916). To aid interpretation on the absolute scale, Supplementary Table S2 reports average marginal effects: the digital access divide reduced the probability of HAI = 5 by 1.43% (95% CI: –1.74% to –1.13%) and HAI = 4 by 5.29% (95% CI: –6.37% to –4.22%); the digital usage divide reduced these probabilities by 0.58% (95% CI: –0.93% to –0.22%) and 2.12% (95% CI: –3.43% to –0.82%), respectively. These ratio-scale estimates are directionally consistent with the 2SLS results presented in Supplementary Table S3, which provide effects on the absolute probability scale.

**Selection and robustness to differential follow-up**

At baseline in 2011, participants who were lost to follow-up by 2020 were older and showed poorer healthy aging profiles, with lower HAI scores and poorer performance across component indicators. In contrast, digital access and usage divides were similar between retained and lost groups (Table S4). We re-estimated all instrumental-variable models using inverse probability weights for retention, and the weighted 2SRI estimates were directionally and statistically consistent with the main results (Table S5).

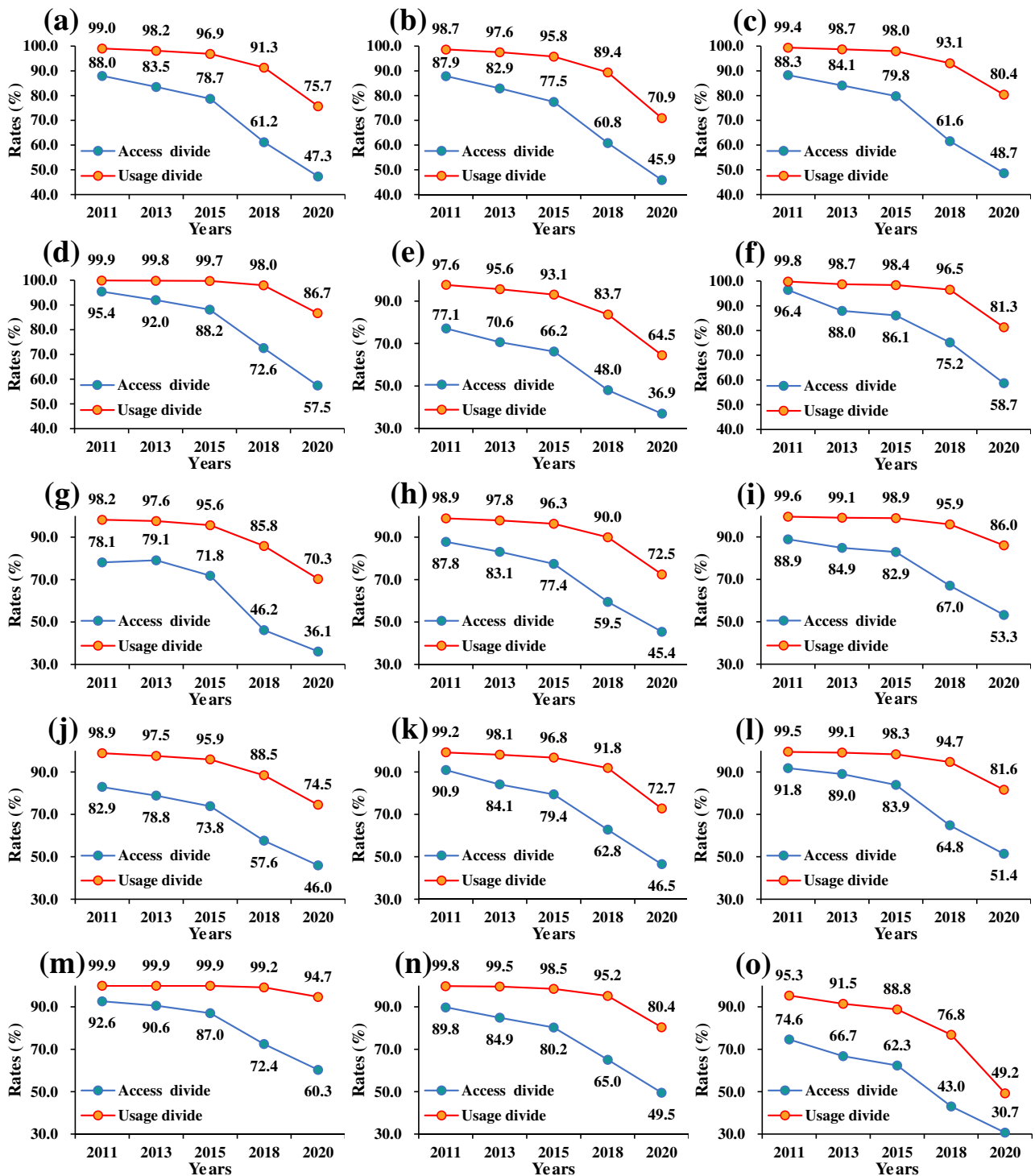
**Subgroup analysis of the effect of digital divides on healthy aging**

As shown in Figs. 3 and 4, both digital access and usage divides were significantly associated with poorer HAI across most of the subgroups, but the strength of effects varied. Females experienced larger negative associations than males for most healthy aging indicators in both divides. While urban and rural residents were adversely affected by the digital access divide, the effect appeared somewhat greater among urban residents. When comparing marital status groups, the adverse associations between both the digital access divide and the digital usage divide and healthy aging were more pronounced among married individuals than among unmarried individuals. With respect to education, two digital divides showed the negative effects among all educational groups. Regionally, the digital access divide was associated with poorer healthy aging in eastern, central, and western China. For the digital usage divide, the negative associations with healthy aging and its most components were most pronounced in the western region, followed by the central and eastern regions. In terms of economic status, both low and high economic levels experienced negative associations between digital divides and most healthy aging indicators.

**Discussion**

This study provides causal evidence on the relationship between digital divides and healthy aging among older adults in China, using ten-year nationally representative panel data and an IV approach. The findings reveal two key patterns: first, digital access and usage among older adults have substantially improved over the past decade; second, both digital access and usage divides exert significant negative effects on healthy aging.

The observed narrowing of digital divides is encouraging and reflects the success of China’s large-scale digital infrastructure initiatives, particularly in extending coverage to rural and western areas<sup>22,23</sup>. These trends align with prior findings that national investments in broadband and mobile technology can reduce access gaps over time<sup>8</sup>. However, despite this substantial progress, China continues to face challenges in addressing the digital divide among older adults. Our findings show that older adults who are female, rural, less educated, or economically disadvantaged remain disproportionately digitally excluded, which is consistent with previous research<sup>11,24,25</sup>. Such disparities are shaped not only by sociodemographic disadvantages but also by regional differences in development, urbanization, and the pace of digitalization, which affect both household connectivity and whether older adults actually go online. From a regional perspective, access and usage divides are smallest in the eastern provinces but appear larger in central and western regions. This pattern stands in contrast to experiences in many high-income countries, where infrastructure and digital literacy



**Fig. 2 | Ten-year trends of the digital access and usage divides among older adults in China from 2011 to 2020.** Blue lines represent the digital access divide, and red lines represent the digital usage divide across survey years. The figure is divided into multiple panels labeled a–u, each corresponding to a specific group. **a** shows the overall population of older adults. **b, c** show results for males and females, respectively. **d, e** compare rural and urban residents. **f, g** depict differences between low economic level and high economic level groups. **h, i** show the patterns among married and unmarried older adults. **j, k, l** represent the eastern, central, and western regions of China. **m, n, o** correspond to education levels, specifically illiterate, primary school, and middle school and above.

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programs have been implemented more evenly across regions, resulting in narrower divides between population groups<sup>26</sup>.

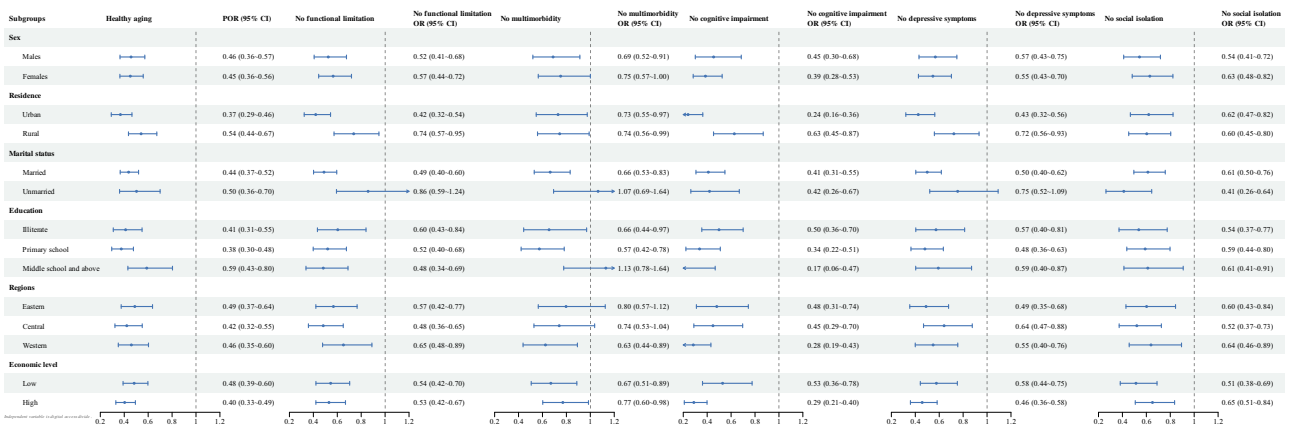
In addition to structural inequalities, our study reveals a divergence between the digital access divide and the digital usage divide among older adults in China. Nationally, the gap between digital access and usage divides expanded from 11.0% in 2011 to 28.4% in 2020. This pattern indicates that although more households now have internet

access, many older adults are still not using digital technologies. Barriers such as limited skills, lack of motivation, and low confidence continue to prevent many older adults from engaging with digital tools<sup>27</sup>. This divergence is also observed when examining subgroups. The gap has widened more rapidly among women than men, suggesting that improvements in infrastructure have not translated into equal gains in digital participation for older women. Similarly, while

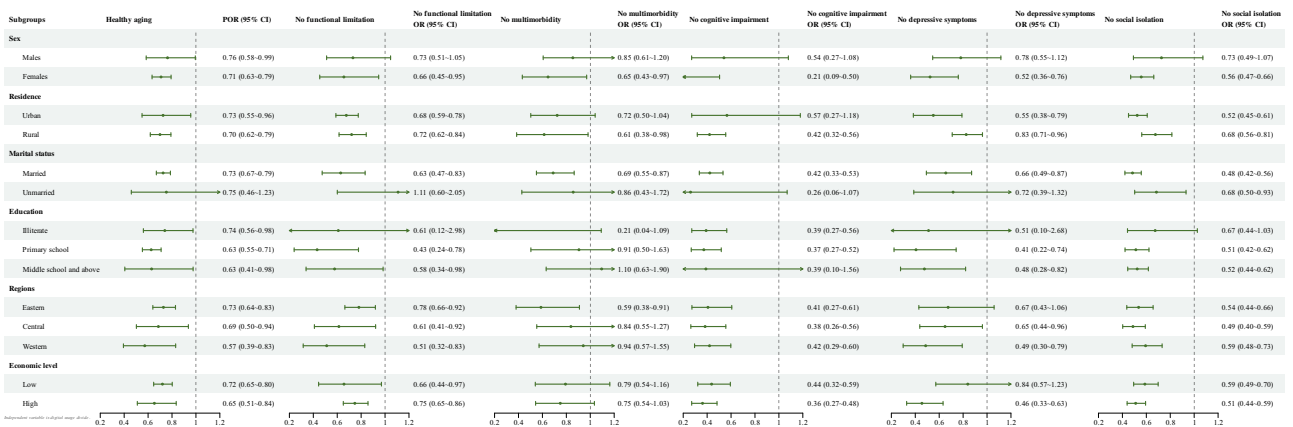
**Table 2 | The second stage estimation of 2SRI regression of the digital access and usage divide on healthy aging**

Outcomes	Digital access divide				Digital usage divide			
	OR	SE	P	95%CI	OR	SE	P	95%CI
No functional limitation <sup>a</sup>	0.548	0.049	<0.001	0.460 ~ 0.653	0.694	0.089	0.004	0.540 ~ 0.893
No multimorbidity <sup>a</sup>	0.718	0.073	0.001	0.588 ~ 0.877	0.761	0.099	0.036	0.590 ~ 0.982
No cognitive impairment <sup>a</sup>	0.408	0.051	<0.001	0.318 ~ 0.523	0.461	0.124	0.004	0.272 ~ 0.782
No depressive symptoms <sup>a</sup>	0.556	0.052	<0.001	0.462 ~ 0.668	0.638	0.082	<0.001	0.496 ~ 0.820
No social isolation <sup>a</sup>	0.603	0.059	<0.001	0.498 ~ 0.731	0.619	0.035	<0.001	0.555 ~ 0.691
Healthy ageing index <sup>b</sup>	0.459	0.036	<0.001	0.393 ~ 0.536	0.756	0.074	0.004	0.623 ~ 0.916

Note: <sup>a</sup> represents the outcome as a binary variable and <sup>b</sup> represents the outcome as an ordinal variable with proportional OR. All models adjust for covariates listed in Methods and include year and province fixed effects; SEs clustered at the individual level.



**Fig. 3 | Subgroup analysis of digital access and healthy aging and its components.** Forest plots show odds ratios (OR) with 95% CIs from IV-logit (2SRI) models for each binary component of healthy aging. Models include the same covariates and fixed effects as in Table 2; SEs clustered at the individual level. POR is proportional odds ratio.



**Fig. 4 | Subgroup analysis of digital usage divides and healthy aging and its components.** Forest plots show odds ratios (OR) with 95% CIs from IV-logit (2SRI) models for each binary component of healthy aging. Models include the same covariates and fixed effects as in Table 2; SEs clustered at the individual level. POR is proportional odds ratio.

usage-access gaps were once more evident in urban area, the gap has expanded in rural areas in recent years, underscoring the persistence of contextual barriers beyond connectivity. These findings show that expanding infrastructure alone is not enough to achieve digital inclusion among older adults<sup>28</sup>. Many individuals continue to face obstacles to meaningful digital participation. Closing these second-level digital divides will require targeted policies and programs that promote digital literacy, strengthen motivation, and build confidence among older

adults, so that they can fully benefit from the opportunities of the digital age<sup>29-31</sup>.

Importantly, by leveraging an IV strategy with two-way fixed effects, this study goes beyond correlational analysis and provides stronger causal inferences between digital divides and healthy aging<sup>32,33</sup>. This supports and strengthens prior observational findings from high-income settings, and places them in the context of a rapidly aging, middle-income country with significant digital disparities<sup>34</sup>. Both digital access and usage divides were

found to significantly impair multiple dimensions of healthy aging, including physical, cognitive, emotional, and social well-being<sup>35</sup>. This finding is consistent with existing cross-sectional studies on this topic in China, as well as research conclusions from other developing and developed countries<sup>17,36</sup>. Access to and use of digital technologies may promote healthy aging by increasing access to health information, enabling remote consultations, facilitating social connections, and supporting health-related behaviors<sup>37,38</sup>. Conversely, digital exclusion can exacerbate isolation, reduce access to resources, and limit health self-management<sup>39</sup>.

Notably, our findings indicate that the health impact associated with the digital access divide is even greater than that of the usage divide. This suggests that for older adults in China, the primary barrier to achieving healthy aging within the digital divide may still lie at the first level of the digital divide, which is access to the internet and related infrastructure. While theoretical arguments have emphasized the significance of the second-level digital divide, which involves skills, motivation, and actual engagement<sup>40–42</sup>, our results highlight that without foundational access, opportunities for digital participation and its potential health benefits cannot be realized in the first place. This interpretation is consistent with the “capability approach” in digital inclusion research<sup>43</sup>, which underscores that resources remain a prerequisite for exercising capabilities<sup>44</sup>. Policies aimed at bridging the digital divide among older adults should therefore prioritize ensuring equitable access to digital infrastructure, particularly in underserved communities, while also recognizing that subsequent efforts to enhance usability and literacy remain essential.

Subgroup analyses further revealed that the digital access divide exerted stronger and more consistent effects than the usage divide. Moreover, the adverse consequences of lacking access were most evident in urban residents, while the usage divide was more pronounced in rural areas, suggesting that connectivity is increasingly indispensable in cities<sup>45</sup> whereas meaningful use remains a barrier in rural contexts<sup>46</sup>. Sex differences were modest for access but clearer for usage, where females were more affected than males. Education and income gradients were also observed, while regional effects were broadly similar except for somewhat larger usage effects in the west. These results indicate that inequities in digital access represent a fundamental and widespread barrier to healthy aging<sup>47</sup>, while inequities in digital use tend to manifest in more specific ways that vary across subgroups<sup>48</sup>, such as sex, residence, and socioeconomic status. These findings underscore the importance of equity-focused digital health strategies that go beyond narrowing the access gap and actively support sustained and inclusive digital participation among high-risk older populations to promote healthy aging<sup>5,49</sup>.

This study has several strengths. First, it draws on a large, nationally representative longitudinal dataset, enabling detailed tracking of digital and health trends over a decade. Second, the use of a multidimensional HAI captures a comprehensive range of outcomes. In addition, the application of IV estimation with two-way fixed effects improves causal validity. Finally, subgroup analyses provide policy-relevant insights into population disparities in digital exclusion.

Nonetheless, some limitations should be noted. First, all health outcomes were self-reported, which may introduce reporting bias, especially among older adults with lower health or cognitive literacy. Second, internet usage was measured dichotomously without capturing frequency, duration, or quality of use, which may underestimate the variability in digital engagement. Thirdly, due to the limited set of variables in the dataset, although we included a wide range of observable controls and incorporated year and province fixed effects to account for unobserved factors, residual confounds such as health literacy, digital skill, and community social capital could still jointly influence both digital divides and the course of healthy aging. Moreover, it should be acknowledged that although we adjusted for education and socioeconomic status, residual influences on the IV, community internet access, cannot be entirely excluded. The instrument may also capture broader community digitalization that supports aging through local services, which we cannot fully disentangle from individual access or use.

Our estimates, therefore, apply to individuals whose digital-divide status is shifted by community context. Finally, another limitation is the potential for selection bias. Older adults with poorer health and lower cognitive ability may have been less likely to participate in the survey or remain in follow-up, which could bias the results. Robustness checks using inverse probability weighting (IPW) showed similar results, which reduces but does not eliminate this concern. Future research should consider adopting more rigorous causal designs, such as randomized controlled trials (RCTs), to validate and extend our findings.

## Methods

### Data sources

This study utilized data from the CHARLS<sup>50</sup>, a nationally representative longitudinal survey designed to collect high-quality microdata on the health and socioeconomic status of individuals aged 45 and above in China. CHARLS employed multistage stratified probability-proportional-to-size sampling to ensure national representativeness, covering 28 provinces, 150 counties/districts, and 450 villages/urban communities. We constructed a longitudinal person–period panel from five waves of publicly available data collected in 2011, 2013, 2015, 2018, and 2020. The initial combined sample included 96,619 respondents across these survey years. To ensure the study focused on the older adult population, individuals younger than 60 years at the time of the survey ( $n = 49,051$ ) were excluded. In addition, participants with missing data on digital divide measures, healthy aging indicators, or key demographic characteristics ( $n = 894$ ) were also excluded. After applying these criteria, a total of 46,674 participants aged 60 years and older with complete data were included in the final analysis. CHARLS has been approved by the Biomedical Ethics Review Committee of Peking University (ID: IRB00001052-11015). All participants signed a paper-informed consent form before the survey.

### Measure

**Healthy aging.** Referring to a previous study<sup>51</sup>, this study operationalizes healthy aging using a composite index derived from five core indicators: absence of functional limitations, absence of multimorbidity, absence of cognitive impairment, absence of depressive symptoms, and absence of social isolation. Each indicator is scored dichotomously (0 or 1), with higher total scores (ranging from 0 to 5) indicating better healthy aging status. Based on a previous study in CHARLS<sup>52</sup>, functional limitations were assessed through 11 activities of daily living (BADLs and IADLs). Basic Activities of Daily Living (BADLs) included six items: dressing, eating, bathing, transferring, toileting, and maintaining continence. Instrumental Activities of Daily Living (IADLs) included five items: housekeeping, meal preparation, shopping, financial management, and medication management. A participant was classified as having functional limitations if they reported an inability to independently complete any of these activities. For multimorbidity, CHARLS collected 14 physician-diagnosed chronic conditions: hypertension, dyslipidemia, diabetes, cancer, chronic lung disease, liver disease, heart disease, stroke, kidney disease, gastrointestinal disease, emotional/nervous/psychiatric conditions, memory-related diseases, arthritis/rheumatism, and asthma. Multimorbidity was defined as having two or more physician-diagnosed chronic diseases (out of 14 conditions collected in CHARLS).

Cognitive function was evaluated using a battery of tests<sup>53</sup>, including immediate and delayed recall of ten words, five-item orientation (year, season, month, day, and day of the week), serial subtraction of seven, and a drawing task. Total cognitive scores ranged from 0 to 31. Following the Aging-Associated Cognitive Decline (AACD) diagnostic criteria of the Working Party of the International Psychogeriatric Association<sup>54</sup>, participants were stratified into age groups (every 5 years), and cognitive impairment was defined as a score below the mean minus one standard deviation for each age group. Depressive symptoms were measured using the 10-item Center for Epidemiologic Studies Depression Scale (CESD-10)<sup>55</sup>, with total scores ranging from 0 to 30. A score of  $\geq 10$  indicated the presence of depressive symptoms.

Social isolation was assessed using a four-item social isolation index<sup>56</sup>, including marital status, frequency of communication with children, participation in social activities, and living arrangements. Marital status was coded as 1 (unmarried, divorced, or widowed) or 0 (married). Communication with children was coded as 1 (less than once per week) or 0 ( $\geq$  once per week). Participation in social activities (e.g., interacting with friends, playing games, volunteering, or attending educational courses) was coded as 1 (no participation) or 0 (participation in any activity in the past month). Living arrangements were coded as 1 (living alone) or 0 (living with spouse, children, or others). A total social isolation score (0–4) was calculated, with scores  $\geq 2$  indicating social isolation.

**Digital divides.** Digital divide is categorized into two types<sup>57</sup>: the digital access divide and the digital usage divide. The digital access divide is measured based on whether the respondent's residence has a broadband internet connection. Specifically, a binary variable is constructed: respondents are coded as 1 if their residence does not have internet access and 0 otherwise. The digital usage divide is defined according to whether the individual reports using the internet. A binary variable is used, with 1 indicating that the respondent does not use the internet and 0 indicating internet use.

**Instrumental Variable.** To address the potential endogeneity, we employed an IV strategy. The instrument used in this study is the community-level household internet access rate, defined as the proportion of households with internet access within the respondent's community. As suggested in previous literature<sup>58–60</sup>, this variable reflects the overall level of network infrastructure and digital connectivity in the local community, which in turn shapes the digital environment to which individuals are exposed, including peer effects and the ease of access to digital services in their community. Hence, the relevance condition for this instrument is supported. Moreover, while the digital infrastructure level of a community can influence individual internet behavior, it is unlikely to directly affect personal health outcomes such as cognitive function, depression, or social isolation, which are shaped by complex individual and biomedical factors. Hence, the exclusion restriction is also plausible.

Finally, to support the exchangeability assumption, we incorporated as many observable control variables from the database as possible, including education, socioeconomic status, age, sex, urban residence, marital status, smoking, drinking, exercise, and health insurance. In addition, we included year and province fixed effects to account for unobserved factors at the temporal and regional levels, thereby minimizing the potential correlation between the IV and the error term in the outcome equation. Consequently, conditional on these covariates, the IV can be regarded as plausibly independent of the unobserved determinants of healthy aging.

**Covariates.** A rich set of covariates is included to control for confounding factors. Age is treated as a continuous variable. Sex is a binary variable coded as 1 for male and 0 for female. Residence is classified using the National Bureau of Statistics standard, with urban areas coded as 1 and rural areas as 0. Educational attainment is categorized into three groups: illiterate (0), primary school (1), and middle school or above (2). Socioeconomic status is proxied by household per-capita consumption, which is split at the median into “low” (below median) and “high” (at or above median). Marital status is coded as 1 if the respondent is married and 0 otherwise. Smoking, drinking, and exercise behaviors are coded as binary variables, where 1 indicates engagement in the behavior (e.g., smoking or drinking in the past month, regular exercise at least once per week), and 0 otherwise. Health insurance coverage is also included as a binary variable, with 1 indicating current enrollment in any health insurance scheme and 0 indicating no coverage.

We also include a three-region indicator (eastern, central, western) because provinces differ in development, urbanization, and the pace of digitalization. The eastern region covers coastal and municipality provinces

with earlier infrastructure rollout and higher service digitalization (for example, Beijing, Shanghai, Jiangsu, Zhejiang, Guangdong). The central region includes the middle provinces with intermediate development. The western region covers inland and north-western provinces and autonomous regions, where geography and later rollout can constrain internet access and uptake. The exact province-to-region mapping for provinces covered by CHARLS is provided in Supplementary Table S1.

### Statistical analysis

All analyses were conducted using Stata version 17.0. We analyzed a person–period panel with repeated observations per individual and cluster standard errors at the individual level. Descriptive statistics were used to summarize the demographic and socioeconomic characteristics of the study participants across the five survey waves. Categorical variables were presented as frequencies and percentages, and continuous variables as means with standard deviations. To examine the trends in digital access and usage divides from 2011 to 2020, we estimated the weighted proportions of older adults experiencing each type of divide in each survey year. Linear trends over time were examined using survey-weighted proportion estimations across survey years.

To evaluate the causal effects of digital divides on healthy aging outcomes, we employed the IV method with two-way fixed effects. Year fixed effects captured time-varying national shocks, while province fixed effects adjusted for time-invariant regional characteristics. Correlation of repeated measurements was handled by clustering at the individual level. All models were adjusted for a set of covariates.

For binary outcomes (absence of functional limitations, multimorbidity, cognitive impairment, depressive symptoms, and social isolation), we estimated odds ratios using an instrumental-variable logit specification implemented via two-stage residual inclusion (2SRI)<sup>61</sup>. Odds ratios and 95% confidence intervals were obtained by exponentiating the logit coefficient on the endogenous exposure. For the overall HAI (0–5), which is ordinal by construction, we additionally fitted an IV ordered logit (2SRI-ologit) and report proportional odds ratios (PORs). For interpretability, we also report marginal changes in the probability of being in the top HAI categories from the IV ordered logit, which convey the effect on clinically meaningful thresholds. For transparency on the absolute scale, we report the 2SLS models in the Supplement (Table S3). First-stage results are reported in Supplementary Table S6, and all tests indicated strong instrument relevance.

To assess and mitigate potential selection bias, we conducted robustness analyses. First, we compared baseline characteristics of participants retained to 2020 versus those lost to follow-up (Supplementary Table S4). Then, we applied IPW for sample retention. Retention probabilities were estimated via logistic regression on baseline covariates, with weights defined as  $1/p$  and trimmed at the 1st and 99th percentiles, then applied in both stages of the 2SRI estimators for binary and ordinal outcomes.

Finally, to explore potential heterogeneity in the estimated relationships, subgroup analyses were conducted by sex, residential location (urban vs. rural), marital status, education level, geographic region (eastern, central, western), and household economic level. Within each subgroup, we re-estimated the fixed-effects 2SRI model. All analyses adhered to a two-sided significance level of  $p < 0.05$ .

### Data availability

The CHARLS datasets for this study can be found in <http://charls.pku.edu.cn/>.

Received: 4 June 2025; Accepted: 8 October 2025;

Published online: 21 November 2025

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## Acknowledgements

The authors would like to thank the CHARLS research team, investigators and all participants for their time and commitment.

## Author contributions

S.L., Y.O., and M.H. participated in Conceptualization, Methodology, Formal analysis, and Writing - original draft. M.H. was responsible for supervision and project administration. All authors contributed to drafting the manuscript, preparing figures and tables, and refining the methodological approach. The revisions and final editing were performed jointly. All authors had full access to the data and approved the final version for submission.

## Competing interests

The authors declare no competing interests.

## Additional information

**Supplementary information** The online version contains supplementary material available at <https://doi.org/10.1038/s41746-025-02076-1>.

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