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Can the implementation of the smart city pilot policy improve the social adaptive health and mental health of middle-aged and elderly people? Evidence from China

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ABSTRACT

With the accelerating pace of population aging in China and the implementation of the smart city pilot policy, whether the middle-aged and elderly population can integrate and adapt to this “smart” society has become an urgent problem that needs to be solved. In this context, exploring the impact of smart city pilot policies on the social adaptation health and mental health of middle-aged and elderly people has become a top priority for China to implement a national strategy to actively respond to population aging. Thus, based on panel data from the China Health and Retirement Longitudinal Study (CHARLS) for the years 2011, 2013, and 2015, this study employs the difference-in-differences (DID) method to investigate whether the smart city pilot policy can improve the social adaptive health and mental health of middle-aged and elderly people and to explore in depth the mechanism of its influence. The study finds that compared with non-pilot cities, the social adaptive health and mental health of middle-aged and elderly people in smart cities improve by 0.6% and 2.2%, respectively. The mechanism effect study shows that the smart city pilot policy can improve the mental health of the middle-aged and the elderly through the use of Information and Communication Technology (ICT) and the enhancement of human capital. Furthermore, for the social adaptive health of middle-aged and elderly individuals, the smart city pilot policy can only make improvements through the enhancement of human capital. Heterogeneity analysis shows that the effect of smart city pilot policies on social adaptive health is more pronounced in the middle-aged group than in the elderly group.

1. Introduction

As the urbanization of human society continues to grow, its focus is also constantly shifting towards cities. However, this rapid urbanization has brought many problems behind it, such as traffic congestion, environmental pollution, a shortage of resources, and the deterioration of the health of the population (Neirotti et al., 2014; Reddy et al., 2018), which seriously impede the effective performance of urban functions. Against this background, relevant scholars have put forward the concept of a “smart city”, which is a new solution to the problem of urban diseases (Hollands, 2008). Among them, scholars generally agree that the core of smart cities is Information and communication technology (ICT) (Camero & Alba, 2019), mainly including the Internet, the Internet of Things (IoT), and cloud computing. These technologies can achieve real-time data collection, transmission, and processing, which is conducive to urban management. However, cities with ICT are not necessarily smart cities, because ICT cannot automatically solve urban problems (Neirotti et al., 2014), and it is necessary to be human-based to fully exploit the potential of the technology to cope with the pressing problem of urban diseases. As mentioned by Caragliu et al. (2009), pointed out, the premise of a smart city is to invest in human and social capital and ICT, and to improve the lives of residents and promote economic growth through participatory governance. K. R. Yang. (2018), Noori et al. (2021), Echebarria et al. (2021), and Wang and Zhou (2023) proposed from an input-output perspective that the input elements of smart cities are ICT and human resources. This is because financial resources have an indirect impact on the city through expenditures on ICT infrastructure and human capital. They unanimously believe that the purpose of smart cities is to achieve their social, economic, and environmental goals. In short, cities can only achieve an effective transition

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to smart cities through investing in both ICT and human capital.

Existing studies have shown that research on smart cities focuses on the following aspects: physical technology aspects and human society aspects. The former mainly focuses on the application of advanced technologies in urban functions to improve the efficiency of urban management (Kandt & Batty, 2021); the latter mainly emphasizes how smart cities can help residents have a happier life, such as a better quality of life (Singh & Singla, 2021), better health, more equality, more participation, and more diverse culture. For example, Singh & Singla. (2021) view smart cities as a complex adaptive system, believing that smart cities are the use of ICT by residents/governments/businesses, in conjunction with favorable government policies, to promote infrastructure development, commercial convenience, and citizen participation, thereby improving the quality of life, achieving sustainable economic growth, and citizen satisfaction. Zhu et al. (2022) proposed a "happiness-driven smart city" and defined it as a city with the overall goal of improving human happiness in the universal digital transformation brought about by technology.

Moreover, smart cities have been favored by government officials of various countries since they were proposed, and have attracted widespread attention in the construction of cities around the world. For example, the "Digital Britain" program proposed by the United Kingdom, Japan's "I-Japan Strategy 2015" and Singapore's "Smart Nation 2015", and China's pilot smart city policy implemented in 2012, and so on. Among them, China is the country with the most smart city programs. According to relevant statistics, by 2020, China has over 800 smart city projects, accounting for 50% of the global total. This is more than Europe, India, and the United States combined. As a result, China's smart city policy has become increasingly a hotspot of research (Guo et al., 2023; D. Li et al., 2024). Therefore, this study takes China as the study area.

However, according to China's data from the Seventh National Population Census,[1] the proportion of people aged 60 and over in China is approximately 18.7%, approaching the standard of 14% for a profoundly aging society, and the situation of population aging[2] is becoming increasingly serious. Among them, with the aging of the population, the health issues of the elderly have attracted much attention, and health is also the foundation of active aging. The World Health Organization (WHO) defines health as a state of comprehensive physical, mental, and social health, not just the absence of illness or weakness.[3] Mental health and social adaptation health are important components of health and important concerns for public health. As potential elderly people, middle-aged people need to be included in the focus of research, as this group is the main component facing aging. In addition, the popularity of the internet in China's middle-aged and old-aged groups is also increasing. According to statistics, as of December 2022, the proportion of internet users over 50 years old reached 30.8%,[4] and the internet will further penetrate into the middle-aged and old-aged groups. It can be seen that the middle-aged and elderly groups are accelerating their integration into a "smart" society, and are gradually forming a complex situation in which the Internet-based "smart" society is intertwined with the basic national situation of an aging population. However, middle-aged and elderly people are a group with high incidence of diseases. Due to the decline in physical functions and cognitive abilities, as well as the decrease in interpersonal communication and outdoor activities after retirement, they are not only prone to be disconnected from the fast-changing "intelligent" society but also suffer from social isolation (Taylor, 2020), which can reduce their social adaptation health. At the same time, it is also easy to cause loneliness and reduce the mental health of the middle-aged and elderly (depression and other problems). The implementation of the smart city pilot policy enables elderly people to have more opportunities to learn new things independently through ICT and channels to understand social progress, enjoy more experiences of participating in social life and the rights and interests of integrating into social networks (Nordin et al., 2022), and at the same time, a high level of human capital can help to shape a clean, inclusive, and low-crime urban environment, to solve the problem of social adaptive health of middle-aged and elderly people under the background of population aging proactively. In this way, we can proactively address the challenges of improving the social adaptation and mental health of middle-aged and elderly people in the context of population ageing. Based on this background, an in-depth discussion of the impact of the implementation of China's smart city pilot policy on the social adaptive health and mental health of the middle-aged and elderly population will not only help to improve the quality of life of the elderly but also help to minimize the negative impacts of population aging on the socio-economic development of China, which is of great significance for the promotion of positive aging and the realization of a healthy China.

Currently, the literature on smart cities and health focuses on two main areas: physical technologies and empirical studies. The former mainly focuses on applying corresponding technologies to the health of residents, in order to achieve more sustainable, fair, and livable cities. For example, the "Smart Health Social Space" proposed by Thompson et al. (2023) and the URBANAGE project proposed by Tupasela et al. (2023). The latter mainly focuses on empirical research on smart cities and health. Among them, a large body of literature analyzes the impact of smart city pilot policies on residents' subjective health from the perspective of their subjective feelings (e.g., subjective well-being, subjective quality of life, and residents' sense of access). For example, Wang et al. (2023) used a generalized ordered logit model with residents of all ages to explore the impact of smart city investments (ICT and human capital) on residents' subjective quality of life; Li (2019) also used residents of all ages as research subjects and employed the Chinese General Social Survey (CGSS 2015) to explore the impact of the level of smart city construction and emerging ICT usage habits on the sense of acquisition of residents in the new era. Zhu et al. (2022) even introduced a happiness-driven smart city mechanism as a way to better guide smart cities toward people-centered development. In addition, some scholars have taken the perspective of residents' objective health status (self-rated health) of middle-aged and elderly people as a perspective to explore in depth the mechanism of the impact of smart cities on residents' objective health status. For example, Wu et al. (2022) found that smart cities can improve the health status of middle-aged and elderly people by reducing the use of outpatient services and increasing the use of inpatient services; Chen et al. (2022) studied the impact of regional smart healthcare service systems on the objective health status of the residents (self-assessed health) at the regional level. However, few studies have paid attention to the issue of whether middle-aged and elderly people can integrate and adapt to the "smart" society, which promotes active aging, as the aging population deepens and the "smart" society develops. Furthermore, few studies have examined the impact of the implementation of smart cities on both the (objective) social adaptive health and (subjective) mental health of older and middle-aged people. In addition, the impact mechanism of the implementation of smart city pilot policies on the social adaptation health and mental health of middle-aged and elderly people is still unclear.

To summarize, based on the China Health and Retirement Longitudinal Study (CHARLS) data of 2011, 2013, and 2015, this paper integrates the smart city pilot implemented in 2012 into a quasi-natural

[1] Sourced from Communiqué of the Seventh National Population Census (http://www.stats.gov.cn/sj/tjgb/rkpcgb/qgrkpcgb/202302/t20230206_1902002.html).

[2] Sourced from the National Bureau of Statistics of China's determination of population ageing (https://www.stats.gov.cn/zsk/snapshoot?reference=33e2b9cdb6391521c53328be6244e40b_69B6C8B87C97584F639081FC228209AE).

[3] World Health Organization WHO constitution Published online https://www.who.int/about/governance/constitution.

[4] Sourced from the 51st Statistical Report on China's Internet Development (https://www.cnnic.net.cn/n4/2023/0303/c88-10757.html).

experiment as a way of identifying the effects of the implementation of the smart city pilot policy on the social adaptation health and mental health of middle-aged and elderly people; the aim is to determine the causal effects of the implementation of the smart city pilot policy on the social adaptive health and mental health of middle-aged and elderly people. The contributions of this paper are as follows. (1) Against the backdrop of population aging and "smart" society, this study quantitatively analyzes the impact of the implementation of smart city pilot policies on the health of middle-aged and elderly people from two dimensions: objective health (social adaptation health) and subjective health (mental health). It explores whether middle-aged and elderly people can adapt to and integrate into "smart" life, enriches the research on the health of middle-aged and elderly people by smart city pilot policies, and still has positive practical implications for promoting the healthy aging process in China. (2) This study also aims to explore in depth whether the smart city pilot policy can improve the social adaptive health and mental health of middle-aged and elderly people through ICT use and enhancement of human capital from the connotation of smart city. Finally, (3) this study aims to further investigate the differences in the implementation of the smart city pilot policy on the social adaptive health and mental health of middle-aged and elderly people from the perspective of education level and age.

2. Policy background and theoretical analysis

2.1. China's smart city pilot policy

The Chinese government defines "smart city" as a new concept and mode of promoting the wisdom of urban planning, construction, management, and services by using new-generation information technologies such as the Internet of Things (IoT), cloud computing, big data, and spatial geographic information integration (Huang et al., 2020). Until now, China has conducted three rounds of national smart city pilots. China started to design, implement, and build smart cities in line with China's national conditions in 2010, and the basic principle of the construction is to pilot before promotion. Among them, in 2012, China's Ministry of Housing and Construction (MOHURD) selected 90 cities (districts, counties, and towns) as the first batch of smart city pilot projects, including 37 prefecture-level cities, 50 districts (counties), and 3 towns. Subsequently, the second batch of smart city pilot projects was announced in August 2013, which included 103 cities (districts, counties, and towns) in the second batch of pilots. In 2015, 84 new cities (districts, counties, and towns) were identified as smart cities 2014 smart city pilots, the distribution map is shown in Fig. 1, which shows that as of the end of 2014, 118 prefecture-level cities were smart city pilots.

2.2. Direct impacts of pilot smart city policies on the social adaptive health and mental health of middle-aged and older adults

The implementation of the smart city pilot policy has improved the level of community health services (Guo et al., 2023). Elderly people can utilize high-quality community health services for efficient management of chronic diseases, which not only slows down the process of debilitation, soothes the loneliness of the elderly (Kojima et al., 2022), and safeguards their mental health, but also greatly reduces the likelihood of social isolation occurring, thereby improving their social adaptation health (Menec et al., 2020). In addition, the construction of intelligent transportation service systems and intelligent environmental monitoring systems effectively reduces energy consumption and pollution emissions (Zhao et al., 2022), thereby reducing the risk of lung cancer and chronic diseases among middle-aged and elderly people (Burney & Amaral, 2019). Several studies have shown that older adults with multiple chronic diseases are more likely to suffer from social isolation (Kristensen et al., 2019), and older adults in social isolation are more prone to cognitive decline due to the lack of adequate social activities (Chou et al., 2011), which negatively affects the social adaptation and mental health of middle-aged and older adults. In addition, the implementation of smart city pilot policy can change the social and lifestyle of middle-aged and older adults. Some studies have shown that older adults who use online payments have better physical and mental health (Liu et al., 2021). Based on the above discussion, the following hypotheses are proposed in this study.

H1. The implementation of pilot smart city policies may improve the social adaptation health and mental health of middle-aged and older adults.

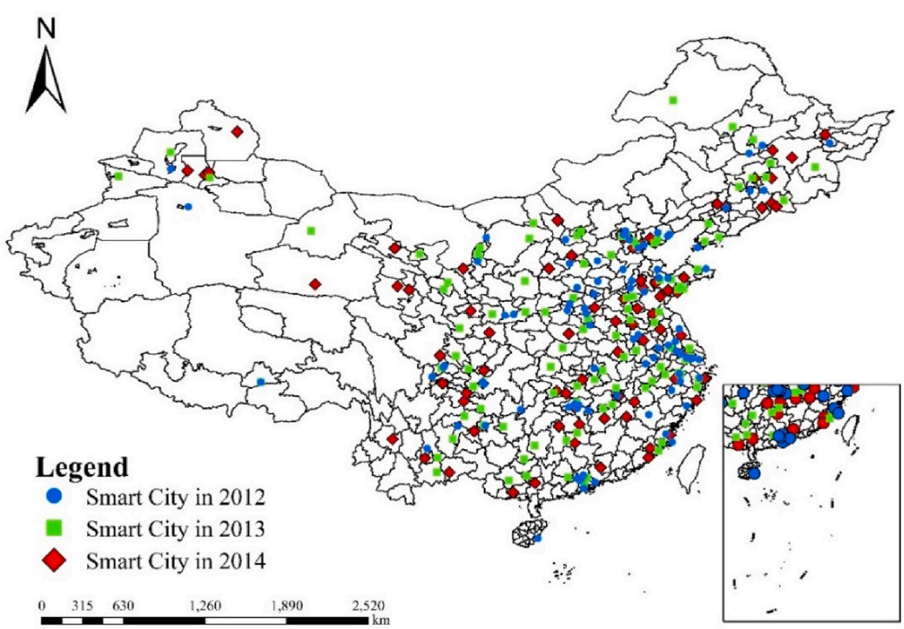

Fig. 1. Geographic distribution of smart city pilots in China.

2.3. Mechanism analysis of smart city pilot policies on social adaptation health and mental health of middle-aged and elderly people

Older people were able to participate in more social activities through the use of ICT, which in turn reduced loneliness, improved well-being, and had a positive impact on mental health (Y.-R. R. Chen & Schulz, 2016) and social adaptation health (Bidenko et al., 2022) of older people. Specifically, older adults were not only able to closely contact their family and friends but also make new friends by using the Internet, which to a certain extent increased the overall social participation of older adults, which in turn helped them to actively integrate into the society (Y. Yang et al., 2022), thus improving their social adaptive health and promoting their positive emotional experience (X. Liu & Larose, 2008). In addition, most studies still emphasize and acknowledge the positive effects of ICT on cognitive performance in older adults, with one study finding that older individuals with desktop computers or cell phones experienced a significant attenuation of cognitive decline over the following four years compared to those without computers or cell phones. Therefore, the following hypothesis is proposed in this paper.

H2. The implementation of smart city pilot policies may improve the socially adapted health and mental health of middle-aged and elderly people through the use of ICT.

The construction of smart cities can quantitatively and qualitatively enhance human capital. According to the theory of human capital, higher levels of human capital are associated with relatively high levels of health capital (T.-H. Wang & Lu, 2022). Regions with higher levels of human capital also have higher levels of quality of life (Winters, 2011), which in turn improves the mental health of older people (Boyacioglu et al., 2023). Moreover, the development of human capital in smart cities promotes technological innovation and economic development (Zeng et al., 2023), and then improves the quality of the environment and reduces energy consumption to a certain extent (J. Chen, 2023). A good environment can have a positive impact on the physiological and psychological health of middle-aged and older adults (H. Fan et al., 2022). For example, the emergence of smart Ambient Assisted Living (AAL) gardens increases the social activities of the elderly (Zschippig & Kluss, 2016), and improves the sense of social participation of the elderly, which in turn helps the elderly to actively integrate into the society and enhances their ability to adapt to social development and change. Finally, tailored transportation services or intelligent public transportation systems that support the mobility of older adults, thereby increasing their life satisfaction (Crotti et al., 2021; Samsik & Hyojin, 2020). In conclusion, this paper presents the following hypothesis.

H3. The implementation of pilot smart city policies may improve the socially adapted health and mental health of middle-aged and older adults by enhancing human capital.

This research suggests a framework diagram of the impact of smart city pilot policies on the socially adapted health and mental health of middle-aged and elderly people, which is shown in Fig. 2.

3. Data and methodology

3.1. Data source

Data on social adaptive health and mental health and individual characteristics of middle-aged and elderly people were obtained from the CHARLS. The information contained in the database is collected and processed by the Institute of Social Science Survey, Peking University. The survey, which began in 2011, is revisited at two-year intervals, and results are published on appropriate platforms, with the most recent data updated to 2018. This study used balanced panel data drawn from

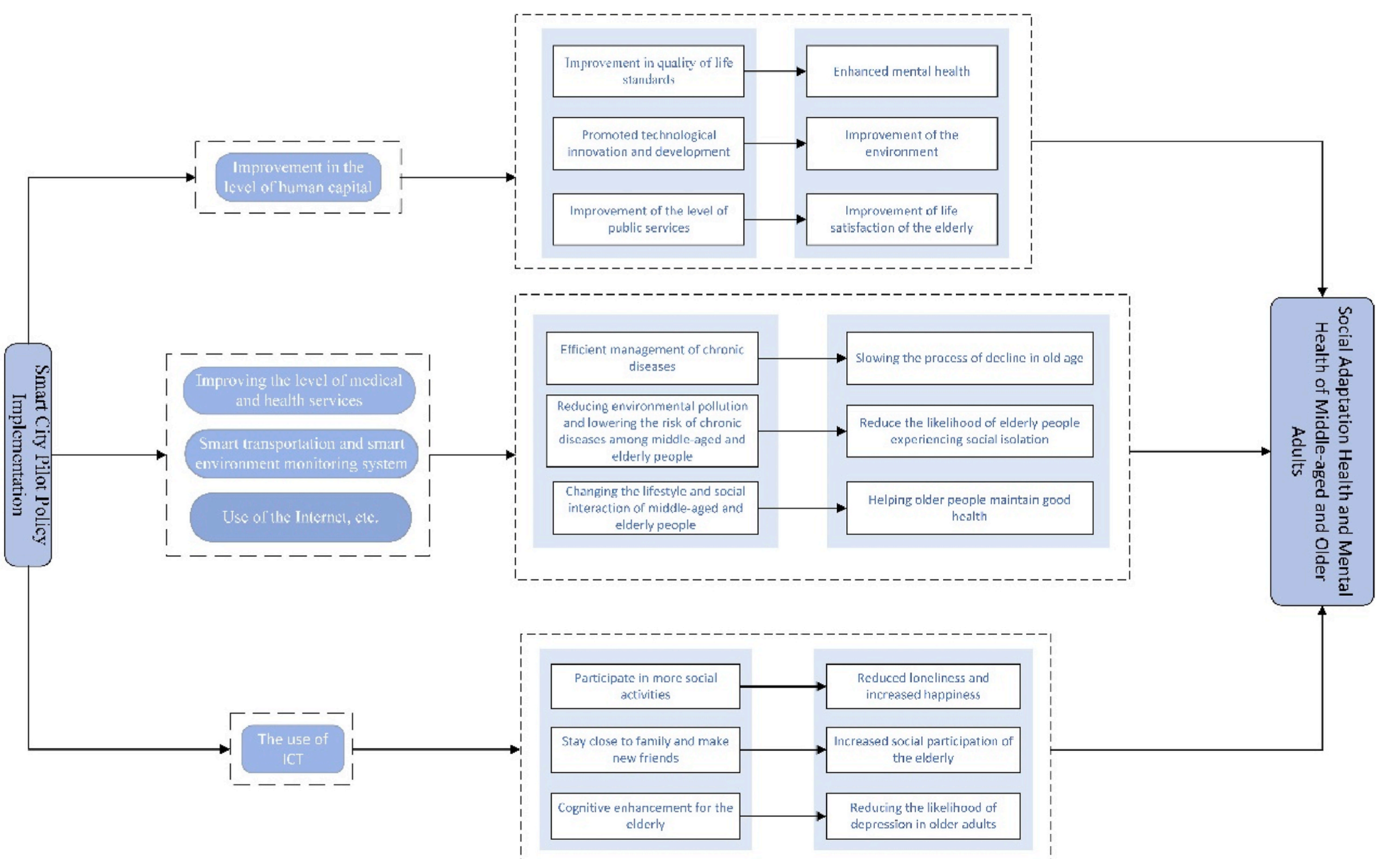

Fig. 2. Framework diagram of the impact of the implementation of the smart city pilot policy on social adaptive health and mental health.

the CHARLS for 2011, 2013, and 2015. The database adopts a multistage hierarchical sampling methodology to survey 28 provinces (autonomous regions and municipalities directly under the central government), 150 counties, and 450 communities or villages in China and collects data at the individual, household, and community levels. Data on macroeconomic variables were drawn from the *China Urban Statistical Yearbook*. First, this paper selected relevant variables from the CHARLS database. Then, considering that China's pilot smart city construction has been carried out in batches, residents in the 2012 pilot cities were selected as the treatment group, while residents in non-pilot cities were used as the control group. Furthermore, to eliminate the influence of the second and third batches of smart city construction, the residents from these cities were deleted from the sample. In addition, residents of districts (counties) within the pilot cities were also deleted. Next, the ICT and human capital data were matched with individuals, according to province and city information. Finally, after preprocessing these panel data, approximately 23,970 observations remained available for analysis.

3.2. Variables

3.2.1. Explained variables

The social adaptive health and mental health of middle-aged and older adults is the focus of this study. Especially under the concept of healthy ageing, better social adaptive health and mental health have a positive impact on, among other things, the quality of life of older people. Most of the literature has demonstrated that internet use opens up the social circle of older adults, reduces their levels of depression and loneliness (Tang et al., 2022), and enhances their psychological well-being, which in turn reduces their social isolation (Ni & Wang, 2022), thus improving their social adaptive health (Xu et al., 2023). In addition, the World Health Organization (WHO) believes that socially adapted health cannot be ignored.[3] Tables 1 and 2 provide a detailed description of the index. Referring to the study of Liu. (2022), the entropy method was used to calculate mental health and social adaptive health.

3.2.2. Core explanatory variables

The smart city pilot policy is defined as the interaction term between the smart city pilot and the time dummy variable (Treat x Time). Specifically, smart city pilots in China are implemented in batches, with the smart city construction pilot being launched in 2012 and the second and third batches of smart city pilots being launched in 2013 and 2015, respectively. In this paper, we include 2012 as a smart city pilot in the quasi-natural experiment. If a city is identified as a smart city pilot, the value of the core explanatory variable (Treat x Time) is 1 in the year identified as a smart city and the following years, and 0 otherwise.

3.2.3. Control variables

To minimize the estimation bias caused by missing variables, the following control variables were introduced in this paper based on studies on health by scholars Wu et al. (2022), Li et al. (2022), and Mu et al. (2022), as shown in Table 3. The control variables used in this study include demographic variables (age, marital status, etc.), socio-economic variables (per capita household income), and health variables (self-assessed health, smoking, and alcohol consumption, etc.).

Table 1
Health variables for middle-aged and elderly people.

First-level indicators	Secondary indicators	Indicator attributes
Mental health	Situational memory	Positive
	Psychological cognition	Positive
	Self-assessed depression	Negative
Social adaptive health	Social interaction	Positive
	Learning and adaptability	Positive
	Social support	Positive

Table 2
Definitions of health variables for middle-aged and elderly people.

Variables	Description
Situational memory	Contains short-term memory questions and delayed memory questions; the number of correct responses is a respondent's situational memory score. Score range: [0,20].
Psychological cognition	Contains questions about calculations, dates, seasons, and drawings; the number of correct responses is a respondent's mental cognition score. Score range: [0,12].
Self-assessed depression	Contains 10 questions dealing with the respondent's feelings and behaviors in the last week; the respondent chooses from four options by indicating the frequency of occurrence. The scores represented by the options are summed up as the depression self-assessment score. Score range: [0,30].
Social interaction	Asks about four activities, namely, visiting a door, playing mahjong or chess, going to a park or other places to dance or work out, and participating in activities organized by a club; one point is awarded for participation in each one of the abovementioned activities. Score range: [0,4].
Learning and adaptability	Contains three activities such as going to school or attending a training course, speculating on stocks, and surfing the internet; one point is awarded for having participated in each activity. Score range: [0,3].
Social support	Contains engagement in unpaid assistance to relatives or neighbors who do not live together, engaging in unpaid care for the sick or disabled who do not live together, and participation in volunteer activities or charitable activities; one point is awarded for participation in each activity. Score range: [0,3].

3.2.4. Mediating variables

The mechanism variables used to validate the effect of smart cities on the socially adapted health and mental health of middle-aged and elderly people included ICT and human capital. Most of the literature on the measurement of ICT indicators uses both single and composite indicators, and the selected indicators mainly include the internet penetration rate and cell phone penetration rate (Ben Ali & Gasmi, 2017). In this study, the entropy method was used to calculate the number of cell phone users per 100 people and internet users per 100 people to obtain an ICT index. In most studies on smart cities, the proportion of people with a higher education or with advanced degrees can be measured as a human capital index (Hu et al., 2023). In this paper, the number of college students per 10,000 people was selected as a proxy variable for human capital, as shown in Tables 3 and 4.

3.3. Model

3.3.1. Identification strategy

The DID method is a quasi-natural experimental method used for comparing outcomes over time between individuals affected by a policy (treatment group) and those not affected by the policy (control group). Therefore, the DID method is an effective method for assessing policy effects(J. Chen, 2023). Referring to the research of Wu et al. (2022), this paper also adopted the DID model to determine the impact of smart cities on the socially adapted health and mental health of the elderly, as follows:

$$Y_{it} = \alpha + \beta did_{it} + \delta X_{it} + \tau_t + \omega_i + \varepsilon_{it} \tag{1}$$

In the equation, Y_{it} represents a set of health variables of middle-aged and elderly people, including mental health and social adaptive health. did_{it} is the DID estimator, and its coefficient β is the coefficient of central concern in this study; this coefficient represents the difference between smart city pilots and non-pilot cities in the group of middle-aged and older people's outcome variables, which enables the exploration of the policy effect of smart cities, that is, whether smart cities improve the health of the middle-aged and older people. X_{it} represents a set of individual control variables, τ_t represents the time-fixed effect, ω_i represents the year fixed effect, and ε_{it} represents a disturbance term. It is important to note that the model does not control for community or city

Table 3
Meaning of variables.

Variable types	Variable symbols	Variable definitions
Explained variables		
Mental health	MH	Selecting situational memory, mental cognition, and self-assessed depression indicators and using the entropy method for calculations.
Social adaptive health	SAH	Selecting social interaction, learning and adaptability, and social support indicators and using the entropy method for calculations.
Explanatory variables		
Treat	–	Dummy variable: the value of 1 for the treatment group, and 0 for the control group.
Time	–	Dummy variable: value of 0 before 2012, 1 after 2012.
Did	did	Interaction items of Treat and Time.
Control variables		
Age	Age	Age of respondents in 2011, 2013, and 2015
Education	Edu	Educational attainment in order from 0 to 7 (0 for private school, illiteracy, or not having graduated from elementary school; 1 for having graduated from elementary school; 2 for having graduated from junior high school; 3 for having graduated from high school; 4 for having graduated from secondary school; 5 for having graduated from junior college or obtaining a bachelor's degree; 6 for having graduated with a master's degree; and 7 for having graduated with a doctoral degree).
Marriage	Mar	Marital status of respondents: the value of 1 for married and living with a spouse, 0 for others.
Self-rated health	Srh	Respondents scored their self-assessed health on a scale ranging from 1 to 5 (i.e., excellent, very good, good, fair, and bad).
Smoke	Smoke	Respondents who have smoked more than 100 cigarettes in their lifetime are categorized as 1, and those who have not smoked more than 100 cigarettes are categorized as 0.
Drink	Drink	Respondents are given a value of 1 if they have consumed alcoholic beverages (e.g., beer, wine, or liquor) in the past year, 0 otherwise.
Medical insurance	Insu	Respondents' participation in health insurance is given a value of 1; otherwise, it is 0.
Outpatients	Outpatient	Have the respondents visited an outpatient clinic in the past month? 1 if yes, 0 otherwise.
Hospitalization	Hosp	In the past year, did the respondent have a doctor say they should be hospitalized, but they were not? 1 if yes, 0 otherwise.
Household income per capita	Income	Total family income/family size (yuan/person)
Job	Job	Are the respondents employed? 1 if yes, 0 otherwise.
Mediating variables		
Information and communications technology	ICT	The data on the average number of cell phones per 100 people and the internet were selected via the entropy method for calculations
Human capital	HC	Number of university students per 10,000 population

Table 4
Descriptive statistical analysis of variables.

Variable	Obs	Mean	Std.Dev.	Min	Max
Explained variables					
Mental health	23970	0.442	0.185	0	0.965
Social adaptive health	23970	0.043	0.075	0	0.859
Control variables					
Age	23970	61.311	8.947	45	98
Age^2	23970	3839.147	1138.640	2025	9604
Education	23970	1.748	1.441	0	7
Marriage	23970	0.842	0.365	0	1
Self-rated health	23970	3.968	0.881	1	5
Smoke	23970	0.374	0.484	0	1
Drink	23970	0.336	0.472	0	1
Medical insurance	23970	0.726	0.446	0	1
Outpatients	23970	0.208	0.406	0	1
Hospitalization	23970	0.115	0.320	0	1
Income(yuan/person)	23970	76840.673	1210000	0	50000000
Job	23958	0.715	0.451	0	1
Mediating variables					
ICT	23970	0.206	0.162	0	1
Human capital	23680	162.709	148.050	9.03	1294

fixed effects, as factors that do not vary over time are absorbed by individual fixed effects.

To verify the previous theoretical analysis that smart cities improve the health of middle-aged and elderly people by enhancing ICT and human capital (HC), this paper constructs the following model:

$$Y_{it} = \varphi_0 + \varphi_1 did_{it} \times Med_{it} + \varphi_2 did_{it} + \varphi_3 Med_{it} + \varphi_4 X_{it} + \tau_t + \omega_i + \varepsilon_{it} \quad (2)$$

where Med_{it} represents the ICT and human capital (HC) of city i in year t. The marginal effect of the smart city policy on the health of the middle-aged and elderly is $\varphi_1 Med_{it} + \varphi_2$, If φ_1 is significantly positive, this suggests that the higher the value is for the city of Med_{it}, the more the health of the middle-aged and elderly can be significantly improved by the smart city policy; in other words, the smart city policy can improve the health of the middle-aged and elderly by enhancing both ICT and HC.

3.3.2. Abadie SDID reweighted regression

The processing method of Abadie SDID reweighted regression can make the DID results more credible, as the credibility of the DID results depends on the assumption of parallel trends, that is, the health status trend of the middle-aged and elderly population in pilot cities should be the same as that in non-pilot cities. However, there is not much data available in the CHARLS database to test these parallel trends directly. Even though individual fixed effects are controlled for in this paper, the validity of the DID results can be affected by factors such as time, chance, or other policies. Therefore, this paper conducted a robustness test through the reweighted semiparametric difference-in-difference (SDID) proposed by Abadie (2005). In addition, the research method of Ma et al. (2019) was also referred to regarding the robustness test. Specifically, as follows, since the premise of this method is to use only two-period balanced panel data, this paper caused the characteristics of these two groups of samples tend to be balanced by weighting the treatment group and the control group; finally, it measured the effect of the policy by comparing the amount of change in the outcome variables of the weighted treatment group and the control group in the two-period period. The average treatment effect of SDID is as follows:

$$E\left[\frac{\triangle Y_t}{P(d=1)} \times \frac{d_t - \pi(X_b)}{1-\pi(X_b)}\right] \quad (3)$$

where d_t is whether it is a treatment group at moment t, $P(d_t = 1)$ is the probability of the treatment group, and $\pi(X_b)$ denotes Abadie's weight value, which can be calculated by the linear probability model $\pi(X_b) = P(d_t = 1|X_b)$. According to Ma et al. (2019), SDID is a credible research method; if the DID model cannot satisfy the parallel trend assumption, then the ABS-DID method can be used for further validation.

4. Results and discussion

4.1. Baseline results

The DID model was used to test the impact of the smart city pilot policy on the health of middle-aged and elderly people, and the results are shown in Table 5. This paper focuses on the estimated coefficients obtained before the introduction of the DID variable. It can be seen that the coefficients of DID are significantly positive (coefficient values of 0.024, 0.022, 0.006, 0.006, with p-values of <0.01, <0.01, <0.1, <0.1, and <0.1, respectively) regardless of whether a control variable is introduced. Therefore, Hypothesis 1 is shown to be valid. The reasons for the above results may be related to the development of ICT in smart cities, which can help middle-aged and elderly individuals broaden their original social network (Tang et al., 2022) to establish better social activities, improve the social adaptive health of the middle-aged and the elderly (Ni & Wang, 2022), and reduce loneliness of the middle-aged and the elderly to maintain a good psychological state.

4.2. Robustness tests

4.2.1. Parallel trend test

The premise of using the DID method is to meet parallel trends, that is, when not impacted by pilot policies, the social adaptive health and mental health of the experimental group and the control group have the same trend of change. Therefore, this article draws on the research of Shen et al. (2024), using the year of the establishment of the smart city pilot project (2012) as the benchmark year, and constructs interaction terms between the treatment group and the dummy variables of each year before and after the base period, and finally conducts empirical regression testing. Figs. 3 and 4 show the results of the parallel trend test of the DID model. The analyses show that the treatment group and the control group share the same trend before 2012, so the results of this paper pass the parallel trend test.

Table 5
The impact of smart city pilot policies on the health of middle-aged and older adults.

Variables	MH		SAH	
	(1)	(2)	(3)	(4)
Did	0.024[a]	0.022[a]	0.006[c]	0.006[c]
	(5.29)	(4.88)	(1.77)	(1.73)
Age		0.013		0.018
		(1.34)		(7.00)
Age^2		−0.0002[a]		−0.0001[a]
		(-7.56)		(-8.71)
Edu		0.003		0.002
		(0.98)		(0.87)
Mar		0.005		0.001
		(1.31)		(0.69)
Srh		−0.006[a]		−0.002[a]
		(-5.34)		(-2.68)
Smoke		0.003		−0.003
		(1.05)		(-1.17)
Drink		0.005[c]		0.012[a]
		(1.85)		(6.76)
Insu		0.002		0.001
		(0.64)		(0.51)
Outpatient		−0.001		0.004[a]
		(-0.71)		(3.74)
Hosp		−0.003		−0.002
		(-1.03)		(-1.09)
Income		−0.000		0.000
		(-0.67)		(0.53)
Job		0.005[b]		0.007[a]
		(2.07)		(4.75)
Constant	0.490[a]	0.349	0.042[a]	−0.544[a]
	(1883.21)	(0.59)	(228.12)	(-4.74)
Observations	21,335	21,326	23,970	23,958
R-squared	0.761	0.763	0.605	0.610
id FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

Note: t-values in parentheses, clustered to individuals.
[a] $p < 0.01$.
[b] $p < 0.05$.
[c] $p < 0.1$; id and Year represent individual fixed effects and year fixed effects, respectively.

4.2.2. Abadie SDID weighted regression

This paper uses two periods of balanced panel data from 2011 to 2015, and the results are shown in Table 6. The coefficients before the interaction terms are significantly positive for the indicators of mental health and social adaptive health of middle-aged and elderly people, and the results are consistent with the previous section.

4.2.3. Exclude the sample self-selection bias

This paper adopted the PSM-DID method for robustness testing. As seen from Table 7, the p-values after matching the control variables are all much larger than 10%, which indicates that there is no significant difference between the control variables of the samples in the treatment and control groups, and the matching level is satisfactory. From the goodness of fit, it can be seen that the pseudo R^2 value after fitting decreases from 0.014 to 0.001, and the p-value rises from 0.000 to 0.962; that is, the significance of LR disappears, which indicates that the results after matching can better balance the sample distribution of the control variables in the two groups, and ensure the parallel trend of the samples. In addition, it can be seen from Fig. 5 that the difference between the treated group and the control group after matching is significantly reduced compared with that before sample matching. The regression results of the matched samples are also given in Table 8. From the results shown in Columns (1)–(2) in Tables 8 and it can be seen that the coefficient of did is significantly positive, indicating that the application of this method can effectively alleviate the self-selection bias problem from the samples and that the construction of a smart city policy significantly improves the mental health and social adaptive health of middle-aged and elderly people. Moreover, this paper also carried out corresponding validation with other matching methods, the results of which are shown in Columns (3) and (4) in Table 8; the results show not only that the PSM method is more reasonable but also that the obtained results are more robust.

4.2.4. Placebo test

To further exclude the suggestion that the effect of the smart city

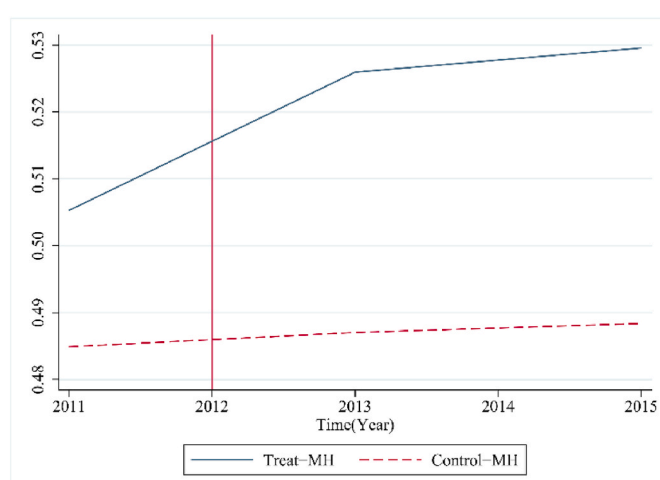

Fig. 3. The parallel trend tests of mental health.

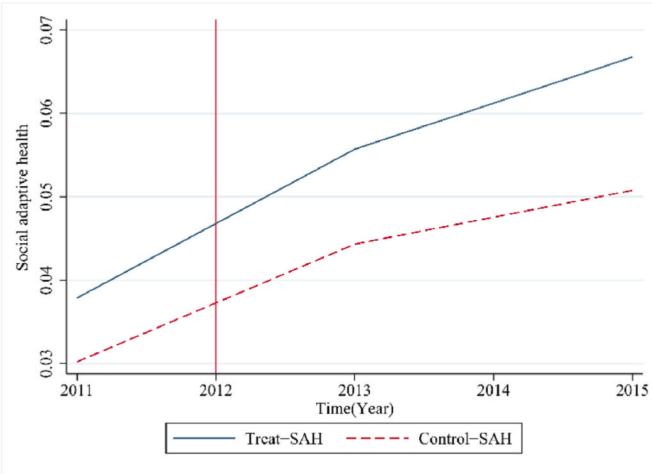

Fig. 4. The parallel trend tests of social adaptive health.

Table 6
Results of the reweighted semiparametric difference-in-difference (SDID) approach.

	MH		SA	
	(1) csinf(0.01) csup (0.99)	(2) sle	(3) csinf(0.01) csup (0.99)	(4) sle
ATT	0.007**	0.008**	0.006**	0.005**
	(2.08)	(2.18)	(2.25)	(2.14)
N	14,064	14,152	15,470	15,969
Covariate	YES	YES	YES	YES
id FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

Note: z-values in parentheses; *, **, and *** represent 10%, 5%, and 1% statistical significance levels, respectively. ATT: average treatment effect; N: sample size.

Table 7
Results of balanced hypothesis testing for caliper matching.

Variables	Unmatched	Mean		%bias	*t*-test	
	Matched	Treated	Control		t	p>|t|
Age	U	60.43	61.009	−6.7	−2.69	0.007
	M	60.43	60.647	−2.5	−0.75	0.455
Age2	U	3725.1	3796.9	−6.6	−2.66	0.008
	M	3725.1	3750.2	−2.3	−0.70	0.484
Edu	U	2.148	1.790	24.5	10.08	0.000
	M	2.148	2.129	1.4	0.42	0.677
Mar	U	0.896	0.849	14.1	5.38	0.000
	M	0.896	0.904	−2.4	−0.78	0.434
Srh	U	3.847	3.965	−13.5	−5.43	0.000
	M	3.847	3.864	−1.9	−0.56	0.574
Smoke	U	0.372	0.378	−1.2	−0.48	0.630
	M	0.372	0.373	−0.1	−0.03	0.972
Drink	U	0.368	0.334	6.1	2.49	0.013
	M	0.368	0.369	−0.1	−0.03	0.972
Ins	U	0.732	0.715	3.8	1.53	0.126
	M	0.732	0.742	−2.3	−0.68	0.494
Outpatient	U	0.168	0.212	−11.4	−4.44	0.000
	M	0.168	0.167	0.3	0.09	0.928
Hosp	U	0.095	0.117	−7.2	−2.79	0.005
	M	0.095	0.112	−5.5	−1.65	0.100
Income	U	58861	72548	−1.2	−0.48	0.635
	M	58861	49049	0.9	0.30	0.766
Job	U	0.670	0.727	−6.0	−2.44	0.015
	M	0.670	0.670	0.2	0.07	0.942

Sample	*pseudo* R^2	*LR* chi^2	P value
Unmatching	0.014	174.31	0.000
Matching	0.001	4.86	0.962

pilot policy on the health of middle-aged and older adults was influenced by other unknown unobservable factors and to ensure that the baseline results were indeed caused by the establishment of the smart city, the current study employed a placebo test for further certainty (Nie et al., 2023). Specifically, an indirect placebo test was used to randomly generate a list of smart cities, thus generating an incorrect estimate, $\widehat{\beta}^{random}$; this randomization process was repeated 500 times, thus generating 500 $\widehat{\beta}^{random}$ values accordingly. The results are shown in Fig. 6. The probability density distribution plot of the estimated coefficients reveals that the estimates of the randomized treatments are centrally distributed around zero, with most of the p-values above 0.1, indicating that there is no significant effect of smart cities in the 500 random samples. In other words, there is a significant difference from the baseline estimation; that is, the constructed dummy treatment effect does not exist.

4.3. Mechanism tests

First, the results in Table 9 report the impact of the smart city pilot policy on the mental health and social adaptive health of middle-aged and elderly people through ICT and human capital. As seen in Columns (1) and (3), the coefficients of ICT*did are positive (coefficients: 0.069, 0.009, and p-values: <0.01, >0.1, respectively); that is, the smart city policy has a stronger effect on improving the mental health of middle-aged and elderly people in cities with more advanced ICT, but the effect on improving the social adaptive health of middle-aged and elderly people is not significant. However, it may be influenced by other factors (Sun & Zhou, 2021a), such as the personal and social characteristics of the elderly population (Hanninen et al., 2021), and the way elderly individuals use the internet (He et al., 2020). Second, as seen in Columns (2) and (4), the coefficients of HC*did are significantly positive (coefficients: 0.013, 0.008, p-values: <0.01, <0.1, respectively), indicating that the smart city pilot policy can improve the mental health and social adaptive health of middle-aged and elderly people by improving human capital, which is consistent with the results of the studies by Winters (2011) and Xu et al. (2023).

4.4. Heterogeneity analysis

This paper tested the heterogeneous effects of smart city construction on the health of middle-aged and elderly people under different education levels and ages; the results are shown in Table 10. First, the heterogeneous effects of the smart city pilot policy on the mental health and social adaptive health of middle-aged and elderly people were estimated based on the education level of individuals, as shown in Columns (1) to (4) in Table 10. The effect of the smart city pilot policy on mental health is significantly positive for both junior high school education and junior high school education and above (coefficients: 0.033, 0.019, p-value <0.01, p-value <0.1 respectively), while the effect of the smart city pilot policy on the social adaptive health of middle-aged and elderly people is not significant. The reason for this outcome may be that the use of ICT narrows the health differences between the more educated and less educated populations. The ceiling effect theory proposed by Ettema and Kline. (1977) can explain the above result; this theory argues that an individual's pursuit of specific knowledge is never-ending and that once a specific "ceiling" is reached, the growth of knowledge will be slowed down or stopped; furthermore, although the growth of knowledge is slower among less-educated people, it will catch up with the more-educated people as time passes.

Second, the heterogeneous effect of age was tested, and the results are shown in Columns (5) to (8) of Table 10. The smart city pilot policy has a significant positive effect on mental health for those under 60 years old and above, which is consistent with the findings of most related studies (S. Fan & Yang, 2022a; H. Wang et al., 2022). This article argues that the development of ICT in smart cities allows middle-aged and

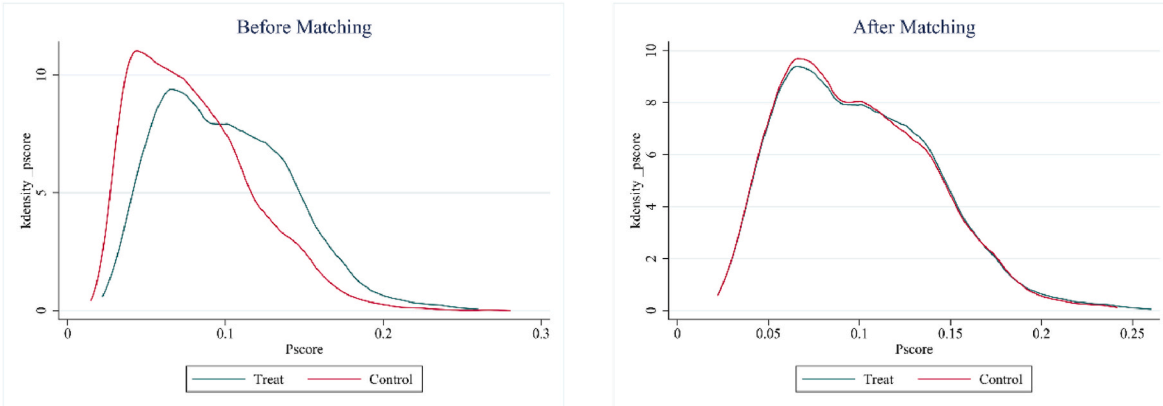

Fig. 5. Propensity score matching graph.

Table 8
PSM-DID results.

Variables	MH	SAH	MH	SAH
	(1) Caliper matching	(2) Caliper matching	(3) Nearest neighbor matching (1:4)	(4) Nearest neighbor matching (1:4)
Did	0.022[a]	0.006[b]	0.022[b]	0.006[b]
	(4.85)	(1.70)	(4.84)	(1.70)
Constant	0.600	−0.516	0.601 (1.01)	−0.513 (−4.51)
	(1.01)	(−4.53)		
Observations	21,182	23,746	21,185	23,754
R-squared	0.762	0.609	0.762	0.611
Covariate	YES	YES	YES	YES
id FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

Note: t-values in parentheses, clustered to individuals; **$p < 0.05$.
[a] $p < 0.01$.
[b] $p < 0.1$. id and Year represent individual fixed effects and year fixed effects, respectively.

elderly people to access more health knowledge and online services, alleviating middle-aged and elderly people and levels of loneliness and depression, thus improving their mental health (Zhang & Li, 2022). However, for those under 60 years old, the smart city pilot policy significantly improves their social adaptive health level, while for those over 60 years old, the smart city pilot policy has no significant effect on their social adaptive health level. It has been suggested that the frequency and activity of internet access is also lower for older groups, and their social adaptive health is relatively weaker (Mariano et al., 2021a). Therefore, the impact of the smart city pilot policy on the social adaptive health of this group is not significant.

5. Discussion

In recent years, smart cities based on ICT have attracted extensive attention from scholars, especially in the context of China's upcoming deep aging and "smart" society. This study explores the impact of smart city pilot policies on the objective health (social adaptation health) and subjective health (mental health) of middle-aged and elderly people, in order to promote active aging and achieve a healthy China. Based on CHARLS panel data from 2011, 2013, and 2015, this paper establishes a DID model to explore whether the smart city pilot policy can improve the mental health and social adaptive health of middle-aged and elderly people. Firstly, the results of this study indicate that the smart city pilot policy can significantly improve the mental health of middle-aged and elderly people, which has increased the mental health of middle-aged and elderly people by 2.4%. This is consistent with the results of D. Li et al. (2023), Yu et al. (2020), and M. M. Wang & Zhou. (2023). However, most studies on mental health have focused on single emotional indicators such as depression, happiness, and so on (S. Fan & Yang, 2022). Few scholars use comprehensive indicators of mental health. Given this, this study uses the entropy right method to calculate situational memory, psychology cognition, and self-assessed depression.

In addition, this study found that the impact of smart city pilot policies on the mental health of middle-aged and elderly people varies depending on their education level and age. In particular, the smart city

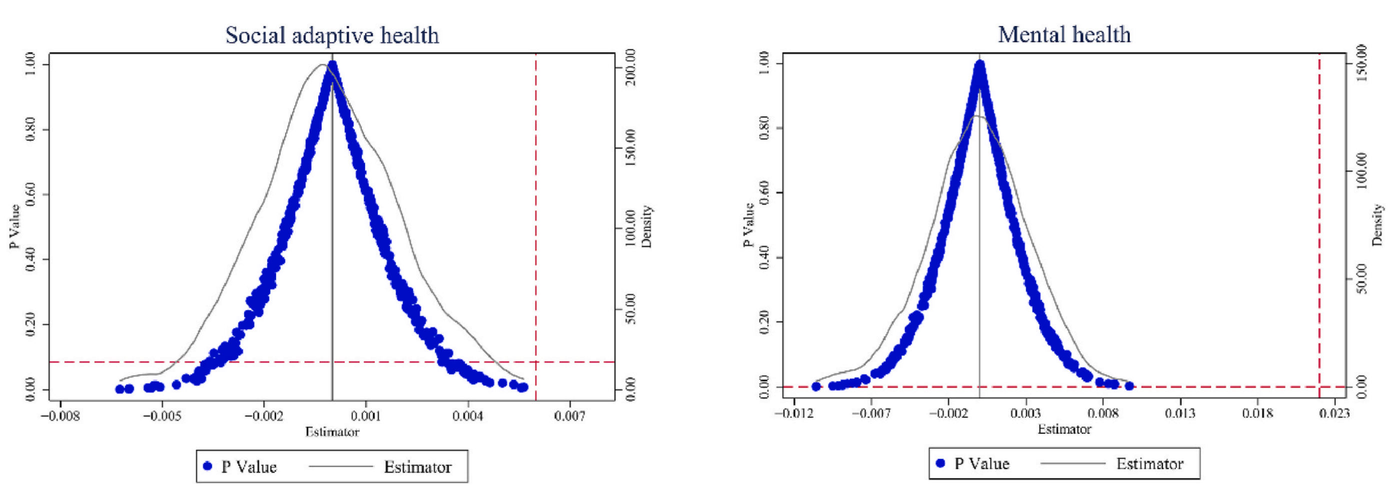

Fig. 6. Probability distribution plot and p-Value plot for placebo tests.

Table 9
Mechanism test results.

	MH		SAH	
	(1)	(2)	(3)	(4)
ICT[c]did	0.069[a] (3.77)		0.009 (0.87)	
HC[c]did		0.013[a] (2.61)		0.008[c] (1.68)
did	0.006 (0.70)	−0.075[b] (-2.42)	0.002 (0.43)	−0.038 (−1.50)
ICT	−0.039[a] (-2.64)		−0.002 (−0.22)	
HC		−0.005[a] (-3.47)		−0.000 (−0.37)
Constant	−0.322 (−0.43)	2.144[a] (3.48)	−0.492 (−4.51)	−0.058 (−0.66)
Observations	23,958	23,668	23,958	23,668
R-squared	0.697	0.647	0.590	0.591
Covariate	YES	YES	YES	YES
id FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

Note: t-values in parentheses, clustered to individuals.
[a] $p < 0.01$.
[b] $p < 0.05$.
[c] $p < 0.1$. id and Year represent individual fixed effects and year fixed effects, respectively.

pilot policy had a better impact on the mental health of older adults compared to the middle-aged group. This is different from previous studies that have found that the impact of smart city pilot policies on depression and life satisfaction is not significant when the age is over 60 and the education level is low (M. M. Wang & Zhou, 2023). The possible reason for this result is that the middle-aged group has a wider social network and can obtain more social support and connections through employment and other means, while the elderly group has fewer ways to maintain social connections and obtain social support. Due to the decrease in intergenerational support in real life, ICT in smart cities has become a key channel for spiritual support for the elderly. Further research has shown that watching news, watching videos, and playing games can significantly improve the mental health of middle-aged and elderly people in rural China (S. Fan & Yang, 2022).

Existing literature has paid little attention to the impact of smart city pilot policies on the social adaptation health of middle-aged and elderly people. This study takes China's upcoming entry into a deep aging and "smart" society as the background and considers whether middle-aged and elderly people can adapt and integrate into the "smart" society as the entry point. The focus is on exploring the impact of smart city pilot policies on the social adaptation and health of middle-aged and elderly people. This serves as an important complementary study in this area. These findings indicate that the smart city pilot policy has improved the social adaptive health of middle-aged and elderly people by 0.6%. In cities with relatively developed ICT technology, the impact of smart city policy on improving the social adaptive health of middle-aged and elderly people is not significant, which is contrary to the results of most scholars from the perspective of the impact of Internet use on social participation (Sun & Zhou, 2021; Q. Zhang & Li, 2022). This may be due to the "ceiling" effect theory mentioned earlier. In addition, the impact of smart city pilot policies on the social adaptive health of middle-aged and elderly people varies depending on their education level and age. Compared with the elderly population, the pilot policy of smart cities can significantly improve the social adaptive health of middle-aged people. This may be related to the internet usage and frequency of the elderly population (Mariano et al., 2021).

6. Conclusion

Using the China Health and Retirement Longitudinal Study (CHARLS) panel data from 2011 to 2015, this research investigated the impact of China's smart city pilot policy on the mental health and social adaptive health of middle-aged and elderly people using the DID method. The study found that (1) The pilot policy of smart cities has increased the mental health and social adaptation health of middle -aged and elderly people by 2.2% and 0.6%, respectively. (2) Mechanism analysis shows that smart city pilot policies can improve the mental health of middle-aged and elderly people through the use of ICT and the enhancement of human capital. As for the social adaptive health of middle-aged and elderly people, the pilot policy of smart cities can only be improved through the enhancement of human capital. (3) Heterogeneity analysis shows that the impact of smart city pilot policies on the mental health of middle-aged and elderly people is relatively similar across different age groups and educational levels. However, the impact of smart city pilot policies on the social adaptation health of middle-aged and elderly people varies greatly among different age groups. Compared with the elderly population, smart city pilot policies can significantly improve the social adaptation health of middle-aged people.

Based on the above results, this research puts forward the following policy recommendations: firstly, deepen the construction of smart cities, which can better play the role of smart city pilot policies in promoting the health and welfare of middle-aged and elderly groups, especially paying more attention to the middle-aged group. Compared with the elderly population, the middle-aged group has greatly improved their social adaptation health under the influence of smart cities. This helps middle-aged and elderly people to adapt and integrate into a "smart" life. Secondly, the construction of smart cities needs to focus on improving the overall level of urban human capital. Local governments can attract high-quality talents by providing comprehensive facilities and corresponding policies, such as more convenient public service facilities and more comprehensive human resource incentive policies. Finally, the construction of smart cities needs to increase the

Table 10
Impact of heterogeneity by age and educational level.

	Less than junior high school		Junior high school or above		Age<60		Age≥60	
	(1) MH	(2) SAH	(3) MH	(4) SAH	(5) MH	(6) SAH	(7) MH	(8) SAH
did	0.033[a] (3.68)	0.002 (0.72)	0.019[b] (1.75)	0.007 (1.02)	0.031[a] (3.13)	0.008[b] (1.65)	0.041[a] (4.12)	0.004 (0.80)
Constant	−0.065 (-0.08)	−0.264 (-2.58)	0.431 (0.13)	−0.675 (-1.70)	−0.487 (-0.38)	−0.834[a] (-3.06)	−1.853[b] (-1.87)	−0.560 (-3.34)
Observations	16,053	16,053	7768	7768	9986	9986	12,575	12,575
R-squared	0.671	0.491	0.564	0.642	0.658	0.637	0.723	0.570
Covariate	YES	YES	YES	YES	YES	YES	YES	YES
id FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES

Note: t-values in parentheses, clustered to individuals; $^{**}p < 0.05$.
[a] $p < 0.01$.
[b] $p < 0.1$; id and Year represent individual fixed effects and year fixed effects, respectively.

opportunities for middle-aged and elderly people to access ICT. Especially, it is necessary to enhance the willingness and convenience of the elderly population to use ICT, provide specific ICT service guidance for the elderly, improve their digital skills, and ultimately enhance their social adaptation health and mental health.

Although insights have been gained from this study, there are still some limitations. Firstly, this article evaluates the impact of smart city pilot policies on the social adaptation health and mental health of middle-aged and elderly people using data from the China Health and Retirement Longitudinal Study (CHARLS) from 2011 to 2015. With the upcoming CHARLS updates and access to the latest data, future research can provide more insights for evaluating policy impacts. Secondly, as the smart city pilot was conducted in batches, some pilot cities were not included in the CHARLS data and were excluded from this study. Fortunately, the sample size for excluding data is relatively small. With the expansion of the pilot scope, more comprehensive conclusions will be provided on the impact assessment of social adaptation health and mental health of middle-aged and elderly people in the future. Finally, this study did not investigate the impact of county (district, city) level administrative regions and the division of rural and urban areas on the health of middle-aged and elderly people in China in the pilot of smart cities. For example, matching the health of micro individuals in county-level administrative regions in the smart city pilot program with those in the CHARLS database to explore the impact of smart city pilot policies on the health of middle-aged and elderly people in different administrative regions. In addition, this study not only found that the pilot policies for smart cities did not significantly improve the social adaptation health of middle-aged and elderly people through the use of ICT, but also found that the methods for verifying the parallel trend hypothesis need to be further studied, and these two parts should be further explored in future research.

Ethical statement

I certify that this manuscript is original and has not been published and will not be submitted elsewhere for publication while being considered by SSM-Population Health. And the study is not split up into several parts to increase the quantity of submissions and submitted to various journals or to one journal over time. No data have been fabricated or manipulated to support our conclusions. No data, text, or theories by others are presented as if they were our own.

The submission has been explicitly derived from all co-authors. And authors whose names appear on the submission have contributed sufficiently to the scientific work and therefore share collective responsibility and accountability for the results. XL had full access to all the data in the study and takes responsibility for the integrity of data and the accuracy of the data analysis. HZ and XL conceptualized the analysis, developed the analysis plan, and conducted data analysis. XL wrote the first draft of the report. HL, HH, WZ and YS interpreted findings, critically reviewed the report for important intellectual content, contributed to manuscript writing, and approved the final version. The authors declare that they have no conflict of interest.

This article does not contain any studies with human participants or animals performed by any of the authors. Informed consent was obtained from all individual participants included in the study.

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CRediT authorship contribution statement

Xuena Liu: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Haibin Liu:** Writing – review & editing, Supervision, Funding acquisition. **Hui Huang:** Writing – review & editing, Supervision. **Hanwei Zhang:** Validation, Investigation, Data curation. **Weiqiang Zhang:** Writing – review & editing, Supervision. **Yinglong Shi:** Writing – review & editing, Supervision.

Declaration of competing interest

All authors declare no conflicts of interest in this paper.

Data availability

The authors do not have permission to share data.

References

Abadie, A. (2005). Semiparametric difference-in-differences estimators. *The Review of Economic Studies, 72*(1), 1–19. https://doi.org/10.1111/0034-6527.00321

Ben Ali, M. S., & Gasmi, A. (2017). Does ICT diffusion matter for corruption? An economic development perspective. *Telematics and Informatics, 34*(8), 1445–1453. https://doi.org/10.1016/j.tele.2017.06.008

Bidenko, L., Bilyakovska, O., Burnos, Y., Pylypenko-Fritsak, N., Lilik, O., & Demyanenko, N. (2022). Information and communication technologies for training future teachers: An adaptation to the aspects of the postmodern society. *Postmodern Openings, 13*, 106–121. https://doi.org/10.18662/po/13.3/479

Boyacioglu, N. E., Oflaz, F., Karaahmet, A. Y., Hodaei, B. K., Afsin, Y., & Tasabat, S. E. (2023). Sexuality, quality of life and psychological well-being in older adults: A correlational study. *European Journal of Obstetrics & Gynecology and Reproductive Biology X, 17*, Article 100177. https://doi.org/10.1016/j.eurox.2023.100177

Burney, P., & Amaral, A. F. S. (2019). Air pollution and chronic airway disease: Is the evidence always clear? *Lancet, 394*, 2198–2200. https://doi.org/10.1016/S0140-6736(19)32537-1, 10215.

Camero, A., & Alba, E. (2019). Smart city and information technology: A review. *Cities, 93*, 84–94. https://doi.org/10.1016/j.cities.2019.04.014

Caragliu, A., Del Bo, C., & Nijkamp, P. (2009). *Smart cities in Europe* (Vol. 18). VU University Amsterdam, Faculty of Economics, Business Administration and Econometrics, Serie Research Memoranda. https://doi.org/10.1080/10630732.2011.601117

Chen, J. (2023). Mitigating nitrogen dioxide air pollution: The roles and effect of national smart city pilots in China. *Energy, 263*. https://doi.org/10.1016/j.energy.2022.125652

Chen, Y.-R. R., & Schulz, P. J. (2016). The effect of information communication technology interventions on reducing social isolation in the elderly: A systematic review. *Journal of Medical Internet Research, 18*(1), e18. https://doi.org/10.2196/jmir.4596

Chen, Y., Zhang, L., & Wei, M. (2022). How does smart healthcare service affect resident health in the digital age? Empirical evidence from 105 cities of China. *Frontiers in Public Health, 9*. https://doi.org/10.3389/fpubh.2021.833687

Chou, K. L., Liang, K., & Sareen, J. (2011). The association between social isolation and DSM-IV mood, anxiety, and substance use disorders: Wave 2 of the National Epidemiologic Survey on Alcohol and Related Conditions. *The Journal of Clinical Psychiatry, 72*(11), 1468–1476. https://doi.org/10.4088/JCP.10m06019gry

Crotti, D., Maggi, E., Pantelaki, E., & Rossi, F. (2021). Public transport use and health status in later life: Which relationship? *Research in Transportation Business and Management, 40*. https://doi.org/10.1016/j.rtbm.2020.100591

Echebarria, C., Barrutia, J. M., & Aguado-Moralejo, I. (2021). The smart city journey: A systematic review and future research agenda. *Innovation-the European Journal of Social Science Research, 34*(2), 159–201. https://doi.org/10.1080/13511610.2020.1785277

Ettema, J. S., & Kline, F. G. (1977). Deficits, differences, and ceilings: Contingent conditions for understanding the knowledge gap. *Communication Research, 4*(2), 179–202. https://doi.org/10.1177/009365027700400204

Fan, H., Wang, Y., Wang, Y., & Coyte, P. C. (2022). The impact of environmental pollution on the physical health of middle-aged and older adults in China. *Environmental Science and Pollution Research, 29*(3), 4219–4231. https://doi.org/10.1007/s11356-021-15832-z

Fan, S., & Yang, Y. (2022). How does internet use improve mental health among middle-aged and elderly people in rural areas in China? A quasi-natural experiment based on the China health and retirement longitudinal study (CHARLS). *International Journal of Environmental Research and Public Health, 19*(20). https://doi.org/10.3390/ijerph192013332

Guo, L., Chai, Y. A.-O., Yang, C., Zhang, L., Guo, H., & Yang, H. (2023). Has smart city transition elevated the provision of healthcare services? Evidence from China's smart city pilot policy. *Digit Health, 9*. https://doi.org/10.1177/20552076231197335

Hanninen, R., Taipale, S., & Luostari, R. (2021). Exploring heterogeneous ICT use among older adults: The warm experts' perspective. *New Media & Society, 23*(6), 1584–1601. https://doi.org/10.1177/1461444820917353

He, T., Huang, C., Li, M., Zhou, Y., & Li, S. (2020). Social participation of the elderly in China: The roles of conventional media, digital access and social media engagement. *Telematics and Informatics, 48*. https://doi.org/10.1016/j.tele.2020.101347

Hollands, R. G. (2008). Will the real smart city please stand up? *City, 12*(3), 303–320. https://doi.org/10.1080/13604810802479126

Hu, W., Wang, S., & Zhai, W. (2023). Human-centric vs. technology-centric approaches in a top-down smart city development regime: Evidence from 341 Chinese cities. *Cities, 137*, Article 104271. https://doi.org/10.1016/j.cities.2023.104271
Huang, R., Tlili, A., Chang, T.-W., Zhang, X., Nascimbeni, F., & Burgos, D. (2020). Disrupted classes, undisrupted learning during COVID-19 outbreak in China: Application of open educational practices and resources. *Smart Learning Environments, 7*(1), 19. https://doi.org/10.1186/s40561-020-00125-8
Kandt, J., & Batty, M. (2021). Smart cities, big data and urban policy: Towards urban analytics for the long run. *Cities, 109*. https://doi.org/10.1016/j.cities.2020.102992
Kojima, G., Taniguchi, Y., Aoyama, R., & Tanabe, M. (2022). Associations between loneliness and physical frailty in community-dwelling older adults: A systematic review and meta-analysis. *Ageing Research Reviews, 81*. https://doi.org/10.1016/j.arr.2022.101705
Kristensen, K. A.-O., König, H. H., & Hajek, A. (2019). The association of multimorbidity, loneliness, social exclusion and network size: Findings from the population-based German Ageing Survey. *BMC Public Health, 19*(1). https://doi.org/10.1186/s12889-019-7741-x
Li, Y. (2019). Can smart city construction improve the sense of gain of residents? Heterogeneity analysis based on Chinese residents. *Jilin University Journal Social Sciences Edition, 59*(6), 107–119+221. https://doi.org/10.15939/j.jujsse.2019.06.jj3
Li, Y., Ning, X., Wang, Z., Cheng, J., Li, F., & Hao, Y. (2022). Would energy poverty affect the wellbeing of senior citizens? Evidence from China. *Ecological Economics, 200*. https://doi.org/10.1016/j.ecolecon.2022.107515
Li, D., Shang, X., Huang, G., Zhou, S., Zhang, M., & Feng, H. (2024). Can smart city construction enhance citizens' perception of safety? A case study of nanjing, China. *Social Indicators Research, 171*(3), 937–965. https://doi.org/10.1007/s11205-023-03304-5
Li, D., Wang, W., Huang, G., Zhou, S., Zhu, S., & Feng, H. (2023). How to enhance citizens' sense of gain in smart cities? A SWOT-AHP-TOWS approach. *Social Indicators Research, 165*(3), 787–820. https://doi.org/10.1007/s11205-022-03047-9
Liu, H. (2022). Health depreciation effect and medical cost effect of air pollution: Based on multidimensional health perspective. *Air Quality Atmosphere and Health, 15*(5), 877–892. https://doi.org/10.1007/s11869-022-01189-w
Liu, X., & Larose, R. (2008). Does using the internet make people more satisfied with their lives? The effects of the internet on college students' school life satisfaction. *CyberPsychology and Behavior, 11*(3), 310–320. https://doi.org/10.1089/cpb.2007.0040
Liu, L., Wu, F., Tong, H., Hao, C., & Xie, T. (2021). The digital divide and active aging in China. *International Journal of Environmental Research and Public Health, 18*(23), Article 12675. https://doi.org/10.3390/ijerph182312675
Ma, C., Yu, Q., Song, Z., & Chen, H. (2019). Long-Term care insurance, the control of medical expenses and "Value-Based Health Care". *China Industrial Economics, 12*, 42–59. https://doi.org/10.19581/j.cnki.ciejournal.2019.12.003
Mariano, J., Marques, S., Ramos, M. R., & de Vries, H. (2021). Internet use by middle-aged and older adults: Longitudinal relationships with functional ability, social support, and self-perceptions of aging. *Psychology and Aging, 36*(8), 983–995. https://doi.org/10.1037/pag0000643
Menec, V. A.-O., Newall, N. E., Mackenzie, C. S., Shooshtari, S., & Nowicki, S. (2020). Examining social isolation and loneliness in combination in relation to social support and psychological distress using Canadian Longitudinal Study of Aging (CLSA) data. *PLoS One, 15*(3). https://doi.org/10.1371/journal.pone.0230673
Mu, S., Li, W., & Mohiuddin, M. (2022). The impact of Low-Carbon City (LCC) on elderly people's health: Evidence from a natural experiment in China. *International Journal of Environmental Research and Public Health, 19*(15). https://doi.org/10.3390/ijerph19159424
Neirotti, P., De Marco, A., Cagliano, A. C., Mangano, G., & Scorrano, F. (2014). Current trends in smart city initiatives: Some stylised facts. *Cities, 38*, 25–36. https://doi.org/10.1016/j.cities.2013.12.010
Ni, C., & Wang, Z. (2022). The impact of internet use on social isolation in older adults. *Population Journal, 44*(3). https://doi.org/10.16405/j.cnki.1004-129X.2022.03.005
Nie, Y., Wang, Z., & Wu, F. (2023). The health effects of low-carbon province pilot policy in China: An empirical evidence based on China family panel studies (CFPS) from 2010 to 2016. *Journal of Experimental Nanoscience, 18*(1). https://doi.org/10.1080/17458080.2023.2197288
Noori, N., de Jong, M., Janssen, M., Schraven, D., & Hoppe, T. (2021). Input-output modeling for smart city development. *Journal of Urban Technology, 28*(1–2), 71–92. https://doi.org/10.1080/10630732.2020.1794728
Nordin, S. A.-O., Sturge, J. A.-O., Ayoub, M. A.-O., Jones, A. A.-O., McKee, K. A.-O., Dahlberg, L., Meijering, L. A.-O., & Elf, M. A.-O. (2022). The role of information and communication technology (ICT) for older adults' decision-making related to health, and health and social care services in daily life-A scoping review. *International Journal of Environmental Research and Public Health, 19*(1), 151. https://doi.org/10.3390/ijerph19010151
Reddy, M. R., Srinivasa, K. G., & Reddy, B. E. (2018). Smart vehicular system based on the internet of things. *Journal of Organizational and End User Computing, 30*(3), 45–62. https://doi.org/10.4018/JOEUC.2018070103
Samsik, L., & Hyojin, C. (2020). Impact of older adults' mobility and social participation on life satisfaction in South Korea. *Asian Social Work and Policy Review, 14*(1), 4–10. https://doi.org/10.1111/aswp.12187
Shen, M., Ma, N., & Chen, Q. (2024). Has green finance policy promoted ecologically sustainable development under the constraints of government environmental attention? *Journal of Cleaner Production, 450*. https://doi.org/10.1016/j.jclepro.2024.141854
Singh, A., & Singla, A. R. (2021). Constructing definition of smart cities from systems thinking view. *Kybernetes, 50*(6), 1919–1950. https://doi.org/10.1108/K-05-2020-0276
Sun, K., & Zhou, J. (2021). Understanding the impacts of internet use on senior citizens' social participation in China: Evidence from longitudinal panel data. *Telematics and Informatics, 59*. https://doi.org/10.1016/j.tele.2021.101566
Tang, B., Li, Z., Hu, S., & Xiong, J. (2022). Economic implications of health care burden for elderly population. *Inquiry: The Journal of Health Care Organization, Provision, and Financing, 59*. https://doi.org/10.1177/00469580221121511
Taylor, H. O. (2020). Social isolation's influence on loneliness among older adults. *Clinical Social Work Journal, 48*(1), 140–151. https://doi.org/10.1007/s10615-019-00737-9
Thompson, S., Rahmat, H., Marshall, N., Steinmetz-Weiss, C., Bishop, K., Corkery, L., Park, M., & Tietz, C. (2023). Merging smart and healthy cities to support community wellbeing and social connection. *Encyclopedia, 3*(3), 1067–1084. https://doi.org/10.3390/encyclopedia3030078
Tupasela, A., Clavijo, J., Salokannel, M., & Fink, C. (2023). Older people and the smart city - developing inclusive practices to protect and serve a vulnerable population. *Internet Policy Review, 12*. https://doi.org/10.14763/2023.1.1700
Wang, T.-H., & Lu, J. (2022). Does advanced human capital structure provide positive feedback on public health? Evidence from China. *Frontiers in Public Health, 10*. https://doi.org/10.3389/fpubh.2022.829716
Wang, H., Sun, X., Wang, R., Yang, Y., & Wang, Y. (2022). The impact of media use on disparities in physical and mental health among the older people: An empirical analysis from China. *Frontiers in Public Health, 10*. https://doi.org/10.3389/fpubh.2022.949062
Wang, M. M., & Zhou, T. (2023). Does smart city implementation improve the subjective quality of life? Evidence from China. *Technology in Society, 72*. https://doi.org/10.1016/j.techsoc.2022.102161
Wang, M., Zhou, T., & Wang, D. (2023). Environmental effects of smart city investment: Evidence from China. *Journal of Environmental Planning and Management*. https://doi.org/10.1080/09640568.2023.2183820
Winters, J. V. (2011). Human capital, higher education institutions, and quality of life. *Regional Science and Urban Economics, 41*(5), 446–454. https://doi.org/10.1016/j.regsciurbeco.2011.03.001
Wu, W. Q., Zhu, D. Y., Liu, W. Y., & Wu, C. H. (2022). Empirical research on smart city construction and public health under information and communications technology. *Socio-Economic Planning Sciences, 80*. https://doi.org/10.1016/j.seps.2020.100994
Xu, X., Zhou, Y., Su, D., Dang, Y., & Zhang, X. (2023). Does education influence life-course depression in middle-aged and elderly in China? Evidence from the China health and retirement longitudinal study (CHARLS). *International Journal of Environmental Research and Public Health, 20*(2). https://doi.org/10.3390/ijerph20021256
Yang, K. R. (2018). Intelligent evaluation approach for smart city based on DEA model: Taking Wuhan, China as an example. *Journal of Intelligent and Fuzzy Systems, 35*(3), 2667–2677. https://doi.org/10.3233/JIFS-169618
Yang, Y., Zeng, D., & Yang, F. (2022). Internet use and subjective well-being of the elderly: An analysis of the mediating effect based on social capital. *International Journal of Environmental Research and Public Health, 19*. https://doi.org/10.3390/ijerph191912087
Yu, C., Ye, B., Lin, C., & Wu, Y. J. (2020). Can smart city development promote residents' emotional well-being? Evidence from China. *IEEE Access, 8*, 116024–116040. https://doi.org/10.1109/ACCESS.2020.3004367
Zeng, Y., Zhang, Z., Ye, Z., & Li, L. (2023). Regional innovation effect of smart city construction in China. *PLoS One, 18*(2). https://doi.org/10.1371/journal.pone.0281862
Zhang, Q., & Li, Z. (2022). The impact of internet use on the social networks of the elderly in China-the mediating effect of social participation. *International Journal of Environmental Research and Public Health, 19*(15), 9576. https://doi.org/10.3390/ijerph19159576
Zhang, C., Wang, Y., Wang, J., & Liu, X. (2022). Does internet use promote mental health among middle-aged and older adults in China? *Frontiers in Psychology, 13*. https://doi.org/10.3389/fpsyg.2022.999498
Zhao, C., Wang, K., Dong, X., & Dong, K. (2022). Is smart transportation associated with reduced carbon emissions? The case of China. *Energy Economics, 105*. https://doi.org/10.1016/j.eneco.2021.105715
Zhu, H., Shen, L., & Ren, Y. (2022). How can smart city shape a happier life? The mechanism for developing a happiness driven smart city. *Sustainable Cities and Society, 80*, Article 103791. https://doi.org/10.1016/j.scs.2022.103791
Zschippig, C., & Kluss, T. (2016). Gardening in ambient assisted living. *Urban Forestry and Urban Greening, 15*, 186–189. https://doi.org/10.1016/j.ufug.2015.12.008