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Association between outdoor artificial light at night and sleep duration among older adults in China: A cross-sectional study

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ABSTRACT

Background: Light after dusk disrupts the circadian rhythms and shifts the timing of sleep later; but it is unknown whether outdoor artificial light at night (ALAN) affects sleep quality. This study aimed to explore the association between residential outdoor ALAN and sleep duration in a nationally representative sample of Chinese older adults.

Methods: We examined the cross-sectional associations of outdoor ALAN with self-reported sleep duration in 13,474 older adults participating in the 2017–2018 wave of the Chinese Longitudinal Healthy Longevity Survey (CLHLS). Outdoor ALAN exposure was estimated at the residence level using satellite images. We applied generalized linear mixed models to investigate the association between ALAN exposure and sleep duration. We performed stratified analyses by age, sex, education, and household income levels. Moreover, we used multi-level logistic regression models to investigate the effects of ALAN on the short sleep duration (≤6 h) and the long sleep duration (>8 h), respectively, in reference to sleep for >6–8 h per day.

Results: We found a significant association between outdoor ALAN intensity and sleep duration. The highest quartile of ALAN was associated with 17.04 (95% CI: 9.42–24.78) fewer minutes of sleep as compared to the lowest quartile. The reductions in sleep duration per quartile change in ALAN were greater in the young old (≥65–85 years) and in those with higher levels of education, and those with higher household income, respectively. We did not detect a sex difference. In addition, those in the highest quartile of ALAN were more

Abbreviations: ALAN, artificial light at night; CLHLS, Chinese Longitudinal Healthy Longevity Survey; Suomi–NPP, Suomi National Polar-orbiting Partnership; DNB, day–night band; VIIRS, Visible Infrared Imaging Radiometer Suite; DMSP-OLS, Defense Meteorological Satellite Program/Operational Linescan System; EOG, Earth Observations Group; NOAA/NGDC, National Oceanic and Atmospheric Administration/National Geophysical Data Center; SD, standard deviation; IQR, interquartile range; BMI, body mass index; ADL, activities in daily living; OR, odds ratio; CI, confidence interval.

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likely to report a 25% (95% CI: 10%–42%) increase in short sleep (<6 h), and a 21% (95% CI: 9%–31%) decrease in long sleep (>8 h).

Conclusions: Increasing outdoor nighttime light intensity surrounding residences was associated with shorter sleep duration in older residents in China. This finding implies the importance of urban outdoor artificial light management as a potential means to lower the public health burden of sleep disorders.

1. Introduction

A rapid growth in human settlement, transport infrastructure, and economic activity has greatly increased the brightness of the Earth's surface at night since the 20th century. As artificial light became more widespread, increasing, and changing, it has caused a universal environmental problem so-named light pollution (Gallaway et al., 2010). Globally, China is the fastest growing country of nighttime light, with the annual growth of more than 6% (Hu and Zhang, 2020). There has been a growing awareness of health and ecological impacts of artificial light at night (ALAN) (Cho et al., 2015; Reiter et al., 2007; Sanders et al., 2021). Exposure to ALAN has been linked to a variety of health issues including sleep disorders, mood, obesity, and some cancers (e.g., breast cancer) (Garcia-Saenz et al., 2020; Lai et al., 2021; Min and Min, 2018b; Paksarian et al., 2020; Zhang et al., 2020). However, being faced with global environmental challenges, such as climate change and air pollution, the scientific community as well as governmental and NGOs interest in research on ALAN is limited.

Individual ALAN exposure consists of both indoor and outdoor sources. Indoor ALAN is known to have acute disruptive effects on sleep by suppressing the release of melatonin and delaying circadian rhythm (Chang et al., 2012; Obayashi et al., 2014; Wright et al., 2005). Evidence on the impacts of outdoor ALAN on human sleep is growing, but is still scarce especially for older populations (Paksarian et al., 2020; Xiao et al., 2020). Some scholars argue that outdoor ALAN is negligible compared with indoor ALAN due to the use of blackout shades (Garcia-Saenz et al., 2018; Rea et al., 2011). Nonetheless, the role played by the residence's surrounding ALAN in human sleep and its underlying mechanisms need further investigation.

There has been very little epidemiological research exploring the associations between ALAN and long sleep duration (Xiao et al., 2020). The connection between ALAN and long sleep duration, which may be an important mediator between ALAN and cancer, is still unclear. Besides, the role of individual characteristics (e.g. age, sex, socioeconomic status, etc.) in the impacts of ALAN on sleep duration was rarely studied. To our knowledge, only two recent US studies, with inconsistent findings, have investigated whether the associations between ALAN and sleep duration differed by sex (Paksarian et al., 2020; Xiao et al., 2020). In a study by Xiao at al., men were more sensitive to ALAN than women in declined sleep duration, yet the study by Paksarian et al. revealed no sex differences. A single study examined whether ALAN and sleep duration associations varied by age among adolescents (Paksarian et al., 2020). None of these studies, however, examined the associations in the older population who are more likely to be affected by the residential environments and to comorbid sleep disorders (Neikrug and Ancoli-Israel, 2010).

Over the last two decades, China's population has been aging at a faster rate. China now has the world's largest aging population, with over 200 million population aged 65 and above in 2021 (National Bureau of Statistics of China, 2022). Older adults commonly experience sleep problems. Poor sleep health, including both long and short sleep durations, has been linked to an increased risk of cognitive decline, heart disease, diabetes and mortality (Gates et al., 2018; Gulia and Kumar, 2018; Ren et al., 2020). In the meantime, China has experienced the largest increase in ALAN in the past decade (Hu and Zhang, 2020), and this trend is expected throughout the 21st century. As of yet, no studies have examined ALAN's impact on human sleep in China. In order to develop effective and targeted interventions and mitigation measures, it is essential to investigate the relationship between ALAN and poor sleep quality as well as its most pertinent determinants for older adults. To this end, we leverage residential location and sleep duration data from a nationally representative sample of Chinese older adults to demonstrate the associations of outdoor ALAN with both short and long sleep duration (>8 h). In addition, we assessed whether the associations differed by age, sex, education, and household income.

2. Material and methods

2.1. Study participants

This study used data from the 2017–2018 wave of the Chinese Longitudinal Healthy Longevity Survey (CLHLS). CLHLS is an ongoing prospective cohort study on the determinants of healthy ageing and longevity among older population (≥65 years) in China. The CLHLS aims to understand the health status and associated social, behavioral, and biological factors among Chinese older people and therefore, intended to interview all centenarians in the sampled counties/cities. Interviews were conducted in randomly selected halves of the counties/cities in the 23 of the 31 provinces, which represents 85% of the total population in China (Fig. 1). Trained interviewers conducted the surveys at participants' homes following a structured questionnaire. They collected data on sociodemographic characteristics, lifestyle, cognitive function, psychological status, and physical capacity. More details on the sampling procedure and assessment of data quality can be found in previous publications (Zeng et al., 2017). CLHLS was approved by the Biomedical Ethics Committee, Peking University (IRB00001052–13074). All participants provided written informed consent prior to participation.

The 2017–2018 wave of CLHLS interviewed 15,664 individuals aged 65 and older. In our analyses, the inclusion criteria were those community-dwelling participants aged over 65 years, with geo-information, without restrictions on gender proportion; while the exclusion criteria were those with missing information on sleep duration (N = 543) and address of residence (N = 3), were had abnormal data on key variables such as body mass index (BMI) (N = 1644). Eventually, 13,474 individuals were included (Figure S1).

2.2. Data collection

In addition to data on sleep duration, the 2017–2018 wave of CLHLS collected data through standardized questionnaires covering demographic characteristics, family and household characteristics, lifestyle, diet, psychological characteristics, economic resources, self-reported health, self-reported life satisfaction, lower and upper extremity performance, activities of daily living, instrumental activities of daily living, cognitive functioning, and chronic diseases. For those participants with disability who were not able to answer the questions, their primary family caregivers were interviewed as proxy respondents. Systematic assessments of the CLHLS regarding the reliability, validity, and consistency of numerous other measures and the randomness of attrition revealed good data quality (Yi et al., 2008).

2.3. Sleep duration measurement

The 2017–2018 CLHLS included one question about sleep duration: "how long do you usually sleep in a typical 24-h period". We treated self-reported daily hours of sleep as a continuous variable in the analysis. In order to capture possible non-linear associations between sleep duration and its associates, we followed a similar categorization used by previous studies (Aggarwal et al., 2013; Grandner and Drummond, 2007; Ren et al., 2020) and classified the integer values of sleep hours into three categories: ≤6 (short), >6–8 (moderate), and >8 (long) hours per day.

2.4. Outdoor ALAN measurement

Satellite imagery through remote sensing has provided a broad and synoptic view of how humans have shaped the planet and lit up the darkness. With the launch of the Suomi National Polar-orbiting Partnership (Suomi–NPP) satellite in 2011, the day–night band (DNB) of the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard represents a major advancement in nighttime imaging capabilities, because it surpasses its predecessor Defense Meteorological Satellite Program/Operational Linescan System (DMSP-OLS) in radiometric accuracy, spatial resolution and geometric quality.

For the current study, we obtained and used the 2018 global NPP-VIIRS map to measure individual-level outdoor ALAN exposure. Pixel-level ALAN data at a 15 arcsec (~500m) spatial resolution were from yearly average radiance composite NPP-VIIRS DNB image available through The Earth Observations Group (EOG) at the National Oceanic and Atmospheric Administration/National Geophysical Data Center (NOAA/NGDC) (Source: https://eogdata.mines.edu/nighttime_light/annual/v20/2018/). The ALAN map comprised the radiance values with the unit of nanowatts per steradian per square metre ($nWcm^{-2}sr^{-1}$) in the visible bands of cloud-free light composites collected by satellite of towns, cities, and other sites with persistent artificial lighting. Temporary events, such as fires, were discarded. Any detected background noise was exchanged with values of zero.

First, the residential address of each participant registered in the 2017–2018 CLHLS was converted to the latitude/longitude coordinates using XGeocoding v2.0 software. Then, we defined individual-level ALAN exposure as the averaged value of ALAN in circular buffers of 1 km around each residential location using ArcGIS 10.3. Effect estimates for the ALAN in 2 km buffer were also reported in sensitivity analyses.

The mean and standard deviation (SD) of individual-level ALAN exposure is 14.31 and 15.42 and its interquartile range (IQR) is 21.62 $nWcm^{-2}sr^{-1}$. ALAN exposure ($nWcm^{-2}sr^{-1}$) were converted into 4 quartiles: quartile 1 (Q1: ≤0.54), quartile 2 (Q2: >0.54–11.22), quartile 3 (Q3: >11.22–22.16), and quartile 4 (Q4: >22.16). In order to test the possible misclassification of ALAN exposure, we also used 3-year (2016–2018) averaged ALAN data. We found that the corresponding quartile to each participant was strongly robust by using 1-year or 3-year averaged ALAN.

2.5. Covariates

To minimize the effect of potential confounders, we used recent literature in 10 years to identify the variables as covariates including common predictors of sleep duration (Al Lawati et al., 2009; Gulia and Kumar, 2018; Luo et al., 2013), factors influencing people's choice of residential areas (e.g. socioeconomic factors) or variables linked with ALAN (Xiao et al., 2020). In our analysis, covariates included age groups (ages <75, ≥75–85, ≥85–95, or ≥95 years), sex (male or female), Body mass index [BMI, (underweight (<18.5 kg/m^2), normal weight (≥18.5–24.0 kg/m^2), overweight (≥24.0–28.0 kg/m^2), or obesity (≥28.0 kg/m^2)], marital status (married or not married), education level (0 year of schooling, ≥1–5 years of schooling, or ≥5 years of schooling), annual household income (<30000 Yuan or ≥30000 Yuan), smoking status (current smoker or others), drinking status (current drinker or others), tea (don't drink tea, drink green tea, drink scented tea, or drink fermented tea), self-rated life satisfaction (good or not good), food diversity (measured by food diversity score) (Zhang et al., 2021), activities in daily living (ADL, measured by ADL score), physical activity (current exerciser or others), chronic disease status (have one or more chronic diseases, or not have chronic disease). Chronic diseases include 24 major chronic diseases such as hypertension, diabetes, heart disease, cerebrovascular disease, arthritis, cataracts, cancer, pneumonia, or Parkinson's disease at the time of the interview (Gu, 2007).

In addition, covariates including the season of interview, the self-reported distance between participants' residential location and the main road (width>100 m), and city-level population density, land use

Fig. 1. Study area, locations of participants' residence and outdoor ALAN.

mixture, and air pollutants were used in the sensitivity analyses. Population density was calculated by the total population by each city's area. The population data in 2020 was derived from the Seventh National Census in China (http://www.stats.gov.cn/tjsj/pcsj/). Data on land use in 2018 was provided by Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn). The land use map was mainly derived from Landsat MSS/TM/ETM and Landsat 8 remote sensing data (Xia et al., 2022), and contains the dominant 32 types of land use of each 30 × 30 m grid cell in China. The Shannon index, based on all 32 types of land use, was used as diversity score to represent the land use mixture based on previous studies (Yamada et al., 2012; Zock et al., 2018). It was computed as $-\Sigma p_i * ln(p_i)$ with p_i being the proportion of grid cells belonging to type of land use *i*. Air pollution data was obtained from the China-High-Air-Pollutants (CHAP) dataset (https://weijing-rs.github.io/product.html). This ground-level air pollution dataset was generated using artificial intelligence combined with the ground-based measurements, remote sensing products, atmospheric reanalysis, and model simulations. The CHAP dataset yields a high data quality with high spatial resolutions, i.e., 1 km for $PM_{2.5}$ (Wei, 2020; Wei et al., 2021), and 10 km for O_3 and NO_2 (Wei et al., 2022). The 4-year (2014–2017) annually averaged air pollutant data containing $PM_{2.5}$, NO_2, and O_3 at the city level was used as the exposure to air pollution.

2.6. Statistical analysis

Given the potential clustering effect of sleep duration within provinces and the differences of sleep duration between provinces (*P* for F test < 0.001), we used generalized linear mixed models (GLMMs) to evaluate the association between outdoor ALAN exposure and sleep duration. Firstly, a crude model (Model 1) was developed incorporating ALAN as the fixed-effect term and provinces as the random-effect term. Model 2 based on Model 1 was then developed to adjust for age and sex. Finally, an adjusted model (Model 3) based on Model 2 was developed to further control for BMI, marital status, education level, household income level, smoking status, drinking status, tea, self-rated life satisfaction, food diversity, physical activity, and chronic disease. We introduced sleep duration as continuous outcome terms in the models. Because the distribution of ALAN is highly right skewed, we categorized ALAN as quartiles, and used the lowest quartile as the reference group. We also tested the effect modifications by age, sex, education, and household income by adding interaction term in GLMMs. We found significant interactions between ALAN and age, sex, education level and household income level in relation to sleep duration (*Ps-interaction* < 0.01) and therefore conducted the stratified analyses using separate regression models. In order to further test the impact of ALAN on the long sleep duration, we also run the multi-level logistic regression models contained a three-category outcome variable for sleep duration (≤6 h, >6–8 h (reference), >8 h). The results are presented as odds ratio (ORs) with corresponding 95% confidence intervals (CIs). We also calculated the P-trend value by modeling quartile of ALAN as a continuous variable (Ramon et al., 2000), in order to test the linear trends of the associations between ALAN and sleep duration across ALAN quartiles.

2.7. Sensitivity analyses

To assess the robustness of the results, we performed sensitivity analyses by changing the buffer radius to 2 km in the exposure assessment, changing the random effects to city-specific intercept, and controlling the season of interview and the distance between participants' home and the main road (width >100 m). We also considered the city-level population density, land use mixture, and air pollutants (i.e., $PM_{2.5}$, NO_2, and O_3) as the potential confounders and adjusted for them separately in Model 3 (Yao et al., 2022; Zock et al., 2018). Additionally, to test the potential bias of the results due to the sample selection (i.e., age, sex, and urbanicity), we conducted the sensitivity analysis by using the sampling weights for individuals in GLMMs. The sampling weights in the publicly released CLHLS data set were calculated based on the age–sex–(urban/rural) residence distribution of the population aged 65 and older in the 22 provinces (Gu, 2007; Yi et al., 2008).

All the statistical analyses were performed using R software (version 4.0.2). The "lme4" and "multcomp" packages were used for the generalized linear mixed model (Bates et al., 2007; Hothorn et al., 2009).

3. Results

3.1. Baseline information

A total of 13,474 subjects aged 65 or older were included in the analyses (6151 males [45.7%]; mean [SE] age, 84.29 [11.31] years) (Table 1). More than half (54.9%) of the participants are illiterate, and the majority (69.7% and 85.1%) do not smoke or drink currently. A total of 52.6% of participants had a normal BMI, over half were inactive in physical activity and had chronic diseases, and 71.1% of the participants had no habit in tea drinking. All covariates, except smoking status and drinking status, differed in outdoor ALAN levels (unit: $nW/cm^2/sr$). ALAN levels were lowest for the oldest participants aged over 95 years (median [IQR], 9.7 [21.1]; vs. aged ≥85–95: 11.3 [21.5]; aged ≥75–85: 11.3 [21.6] and aged ≥65–75: 11.5 [21.7]; $P < 0.01$), females (11.1 [21.7] vs. males: 11.5 [21.5]; $P < 0.01$), less educated (0 years of schooling: 8.5 [16.7]; ≥1–5 years of schooling: 8.5 [20.6]; ≥5 years of schooling: 18.1 [31.2]; $P < 0.001$), and less household income (less than 30,000 RMB per year: 7.6 [15.1]; more than ¥ 30,000 RMB per year: 13.1 [26.9]; $P < 0.001$). In addition, participants who had higher BMI, higher physical activity, were drinking tea, had a better self-rated life satisfaction, and at least one chronic disease were exposed to higher levels of ALAN than their counterparts (*Ps* < 0.001).

3.2. ALAN and sleep duration

Cross-sectional analysis revealed a significant association between outdoor ALAN and sleep duration (Table 2). Findings from the crude model (Model 1) and the adjusted model (Model 2) both showed that shorter sleep duration was associated with increased ALAN ($P_{trend} < 0.001$). After adjusting for potential confounders including age, sex, BMI, marital status, education, income, smoking, alcohol consumption, tea drinking, self-rated life satisfaction, food diversity, ADL score, physical activity, and chronic disease (Model 3), those exposed to a higher level of ALAN also had significantly shorter sleep duration than people exposed to a lower level of ALAN (compared to the lowest quartile of ALAN: second quartile, −11.64 [95% CI: 18.42 to −4.86] minutes; third quartile, −13.62 [95% CI: 20.40 to −6.84] minutes; highest quartile, −17.04 [95% CI: 24.78 to −9.42] minutes; $P_{trend} < 0.001$).

Table 3 shows the OR (95% CI) for short sleep duration (≤6 h) and long sleep duration (>8 h) by quartiles of outdoor ALAN levels for three models of increasing multivariable adjustment. A higher level of ALAN exposure was significantly associated with shorter sleep duration (≤6 h) in Model 3 ($P_{trend} < 0.001$), in contrast to the nonsignificant results in Model 1 ($P_{trend} = 0.52$) and Model 2 ($P_{trend} = 0.42$). When compared to the lowest quartile of ALAN in Model 3, people in the highest quartile was associated with a 25% (95% CI: 10%–42%) increased likelihood of reporting less than 6 h of sleep relative to 6–8 h of sleep.

The likelihood of participants with long sleep duration (>8 h) significantly decreased with an increase in outdoor ALAN levels. In comparison with the lowest quartile of ALAN, the quartile with the highest ALAN exhibited significantly lower odds of sleeping for more than 8 h (OR = 0.70, 95% CI: 0.62–0.79, Model 1; OR = 0.72, 95% CI: 0.63–0.81, Model 2). Even after adjusting for all potential variables (Model 3), the significant association remained (OR: 0.79, 95% CI: 0.69–0.91 in Quartile 4) in the adjusted Model 3.

Table 1
Median and Interquartile Range of Outdoor ALAN, by age, gender, education, income, and other individual characteristics.

Characteristic	N (%)	ALAN, nW/cm²/sr, median (IQR)	P value
Age (years)			
65–75	3145 (23.3)	11.5 (21.7)	*< 0.01*
75–85	3934 (29.2)	11.3 (21.6)	
85–95	3412 (25.3)	11.3 (21.5)	
≥95	2983 (22.2)	9.7 (21.1)	
Sex			
Male	6151 (45.7)	11.5 (21.5)	*< 0.01*
Female	7323 (54.3)	11.1 (21.7)	
Marital status			
Married	5942 (44.1)	11.5 (22.6)	*< 0.001*
Not married	7532 (55.9)	10.0 (21.5)	
Education level			
0 years of schooling	7391 (54.9)	8.5 (16.7)	*< 0.001*
1–5 years of schooling	2677 (19.9)	8.5 (20.6)	
>5 years of schooling	3406 (25.2)	18.1 (31.2)	
Annual household income (RMB yuan)			
<30000	5685 (42.2)	7.6 (15.1)	*< 0.001*
≥30000	7789 (57.8)	13.1 (26.9)	
BMI			
<18.5	2027 (15.1)	7.6 (17.4)	*< 0.001*
18.5–24	7091 (52.6)	10.4 (21.1)	
24–28	3276 (24.3)	12.8 (25.6)	
≥28	1080 (8.0)	12.8 (25.2)	
Smoking status			
Current smoker	4083 (30.3)	11.2 (21.7)	*0.05*
Current nonsmoker	9391 (69.7)	11.4 (21.7)	
Drinking status			
Current alcohol drinker	2005 (14.9)	11.2 (21.1)	*0.06*
Current non-consumer of alcohol	11,469 (85.1)	11.2 (21.6)	
Physical activity			
Yes	4401 (33.1)	12.8 (27.0)	*< 0.001*
No	9073 (66.9)	9.1 (17.3)	
Tea			
Don't drink tea	9578 (71.1)	9.7 (19.5)	*< 0.001*
Green tea drinker	1950 (14.5)	12.8 (29.0)	
Scented tea drinker	1164 (8.6)	12.8 (24.1)	
Fermented tea drinker	782 (5.8)	15.1 (29.5)	
Self-rated life satisfaction			
Good	6258 (46.4)	11.5 (21.4)	*< 0.001*
Not good	7216 (53.6)	10.8 (21.8)	
Chronic disease			
Having one or more chronic diseases	2208 (16.4)	11.5 (24.8)	*< 0.001*
Without chronic disease	11,266 (83.6)	11.2 (21.6)	

Note: The *P* values are from *F* tests from binary and multinomial logistic regressions with demographic characteristics as the dependent variables and ALAN as the independent variable.

Table 2
Associations between outdoor ALAN and sleep duration (as a continuous variable) in the CLHLS. P-trend value is reported for all models.

Quartile of ALAN	Model 1	Model 2	Model 3
	Estimate in minutes (95% CI)	Estimate in minutes (95% CI)	Estimate in minutes (95% CI)
Lowest	Reference	Reference	Reference
2nd	−7.62 (−14.28, −0.96) *	−8.04 (−14.58, −1.44) *	−11.64 (−18.42, −4.86) ***
3rd	−9.24 (−15.90, −2.64) **	−9.18 (−15.72, −2.64) **	−13.62 (−20.40, −6.84) ***
Highest	−12.78 (−20.16, −5.34) ***	−12.36 (−19.62, −5.04) ***	−17.04 (−24.78, −9.42) ***
P-trend value	*< 0.001*	*< 0.001*	*< 0.001*

Model 1 was a crude model.
Model 2 was adjusted for age and sex.
Model 3 included covariates from model 2 plus BMI, marital status, education, income, smoking, alcohol consumption, tea drinking, self-rated life satisfaction, food diversity, ADL score, physical activity, and chronic disease.
Significance levels: *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

Table 3
Associations between outdoor ALAN and sleep duration (as a categorical variable) in the CLHLS. P-trend value is reported for all models.

Quartile of ALAN	≤6 h vs. 6–8 h	>8 h vs. 6–8 h
	OR (95% CI)	OR (95% CI)
Model 1		
Lowest	Reference	Reference
2nd	1.05 (0.94, 1.02)	0.82 (0.72, 0.92) ***
3rd	1.10 (0.99, 1.23)	0.77 (0.68, 0.87) ***
Highest	1.02 (0.91, 1.14)	0.70 (0.62, 0.79) ***
P-trend value	*0.520*	*< 0.001*
Model 2		
Lowest	Reference	Reference
2nd	1.05 (0.94, 1.18)	0.81 (0.72, 0.92) ***
3rd	1.12 (1.00, 1.25)	0.78 (0.69, 0.88) ***
Highest	1.03 (0.92, 1.15)	0.72 (0.63, 0.81) ***
P-trend value	*0.421*	*< 0.001*
Model 3		
Lowest	Reference	Reference
2nd	1.13 (1.00, 1.28) *	0.81 (0.71, 0.92) **
3rd	1.23 (1.10, 1.39) ***	0.79 (0.70, 0.90) ***
Highest	1.25 (1.10, 1.42) ***	0.79 (0.69, 0.91) ***
P-trend value	*< 0.001*	*< 0.001*

Model 1 was a cruel model.
Model 2 was adjusted for age and gender.
Model 3 included covariates from model 2 plus BMI, marital status, education, income, smoking, alcohol consumption, tea drinking, self-rated life satisfaction, food diversity, ADL score, physical activity, and chronic disease.
Significance levels: *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

3.3. Stratified analyses

Age-stratified analysis showed that shorter sleep duration was significantly associated with higher ALAN only in age groups of ≥65–75 years and ≥75–85 years under full adjustment model (Model 3, $P_{trend} <$ 0.001, Fig. 2 and Table S1). For participants aged ≥65–75 years and ≥75–85 years, those in the highest quartile of ALAN had shorter sleep duration by 22.56 (95% CI: 10.62–34.80) minutes and 24.78 (95% CI: 11.76–37.92) minutes, respectively (Model 3). The association was not statistically significant for older participants aged ≥85–95 years and

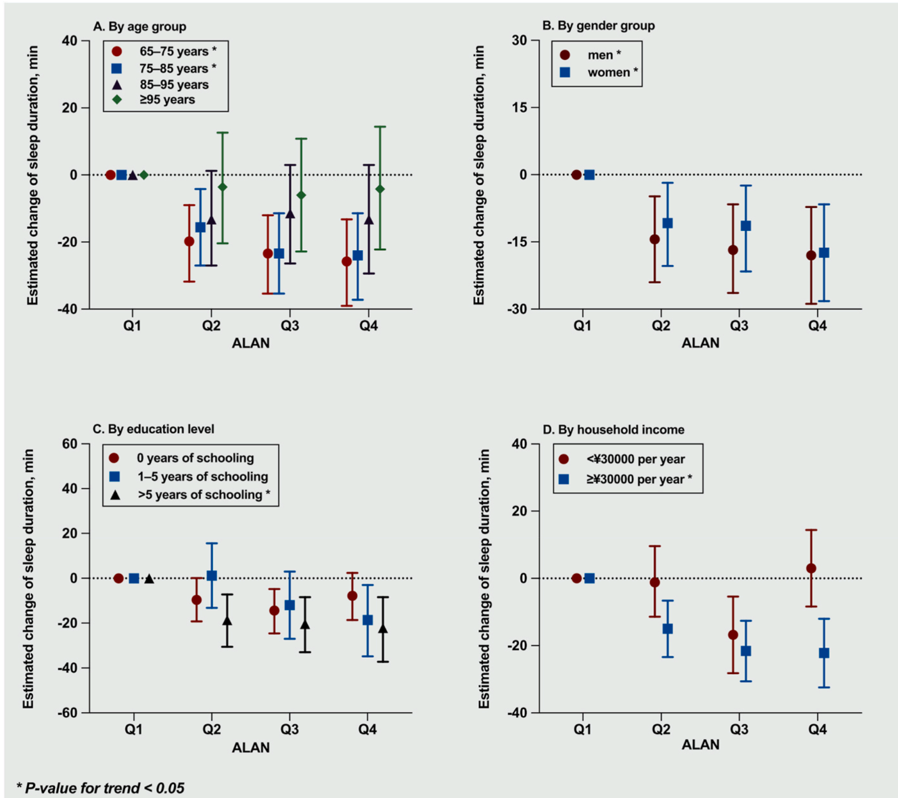

Fig. 2. Multivariable-adjusted association (Model 3) between ALAN and sleep duration by age group (A), sex group (B), education level (C) and household income level (D).

over 95 years (P_{trend} = 0.05 and 0.85, respectively).

In gender-stratified analysis, higher ALAN was significantly associated with the shorter sleep duration in both males (compared to the lowest quartile of ALAN in Model 3: second quartile, −14.94 [95% CI: 24.48 to −5.34] minutes; third quartile, −16.32 [95% CI: 26.28 to −6.54] minutes; highest quartile, −17.04 [95% CI: 28.20 to −6.66] minutes) and females (compared to the lowest quartile of ALAN in Model 3: second quartile, −10.68 [95% CI: 20.04 to −1.26] minutes; third quartile, −11.04 [95% CI: 20.64 to −1.62] minutes; highest quartile, −16.08 [95% CI: 26.88 to −5.40] minutes) (Table S2). The differences in estimates between females and males were not statistically significant.

Subgroup analyses showed that the ALAN's effects on sleep duration were more pronounced in the older people with higher educational attainment and higher income level (Fig. 2). The sleep duration decreased 17.40 (95% CI: 1.80–33.00) minutes for the participants with 1–5 years of schooling in Q4 of ALAN compared to Q1, while the decrease in sleep duration was estimated as 21.60 (95% CI: 7.80–36.00) minutes for the those with more than 5 years of schooling (Table S3). With higher household income, we found an increased likelihood of short sleep duration associated with increased ALAN (Estimated minutes $_{Q4\ vs.\ Q1}$ = −21.60 [95% CI: 31.80 to −11.40], $P_{trend} < 0.01$, Table S4). There was no clear exposure-response relationship for low-income participants (P_{trend} = 0.71).

3.4. Sensitivity analysis

The use of a larger radius of buffers (2 km) did not alter the significant associations between ALAN exposure and sleep duration (Table S5). Based on repeated analyses using cities as random effects, we found that the estimated effects were similar to those in the main analysis (Table S6). When the main models were additionally adjusted for the season of the interview, the horizontal distance between residences and the main road, or the city-level population density, land use mixture, or air pollutants (i.e., $PM_{2.5}$, NO_2, and O_3), the results were consistent with those from primary analyses (Table S7–**S11**). Additionally, Table S12 indicates no substantial differences in associations between ALAN and sleep duration after applying the sampling weights, supporting the robustness of the results in the main analyses.

4. Discussion

The results of our large population-based study suggested that higher outdoor ALAN levels were significantly associated with shortened sleep duration in the older people in China. Older adults residing with a higher outdoor ALAN had higher odds of short sleep duration and lower odds of long sleep duration. These associations were consistent in a series of sensitivity analyses. In addition, the associations may be greater in the young old (≥65–85 years), as well as those with higher education or income level. We did not observe a difference in sex. To our knowledge, this is among the first epidemiological study to report the association between outdoor ALAN exposure and sleep duration among the older populations.

Using PubMed and Web of Science, a systematic literature search yielded only five cross-sectional studies concerning outdoor ALAN exposures and sleep duration (Koo et al., 2016; Ohayon and Milesi, 2016; Paksarian et al., 2020; Patel, 2019; Xiao et al., 2020), and there is only a slight overlap in the age of participants with each of these five studies. Our findings concurred with 4 studies for both adults and adolescents in the US that reported significant associations for ALAN and sleep duration (Ohayon and Milesi, 2016; Paksarian et al., 2020; Patel, 2019; Xiao et al., 2020). The decrease in sleep duration in the highest vs. lowest quartile of ALAN in Paksarian and colleagues' study (2020) is 11 (95% CI: 2–19) minutes, which is lower than the estimate of 17.0 (95% CI: 9.4–24.8) minutes in our study. Koo et al. (2016) showed that within the South Korean population the high ALAN group was 22% (95% CI: 6%–

41%) more likely to report short sleep (<6 h) than their counterparts in the low ALAN group, which is in line with our findings of 25% (95% CI: 10%–42%). We also found a reverse association between ALAN and long sleep duration like one study in the US from Xiao et al. (2020), indicating that ALAN may only reduce sleep duration rather than extent the sleep duration. Although there was no relationship observed between outdoor ALAN and indoor ALAN in previous research (Rea et al., 2011), the overall evidence generally supports the outdoor ALAN may contribute to sleep deprivation.

Very few studies have examined the modification effects of individual characteristics on the associations between ALAN and sleep duration. Our findings extended the prior work by characterizing the relationships by age, sex, education, and income. It's interesting to observe that sleep duration was associated with ALAN only for the young old (≥65–85 years), but not for the oldest-old (>85 years). Younger old adults participating in more nighttime outdoor activities than the oldest-old could be one of the reasons. Walking after dinner and dancing in the park are popular activities among the younger old in China, leaving them to be exposed to more outdoor light than the oldest-old. The light stimulus may last for hours and delay the internal biological rhythm (Chang et al., 2012). Outdoor activity-induced exposure to noise and air pollution cannot be excluded as a potential confounding factor and needs to be explored further. Moreover, the younger old and the oldest-old may differ in terms of their use of personal electronics (e.g. television, computers, and smartphones) and sleep hygiene practices (e.g. the regular routine at night), both of which are associated with sleep deficiency. It is also possible that since melatonin levels decrease with age (Zhao et al., 2002), the younger old might be more susceptible to ALAN because light delays the circadian rhythm through suppressing the production of melatonin. In addition, the decreased eye-sight for the older old may also be one of the explanations (Cavallotti and Cerulli, 2008).

Our sex-stratified analysis did not detect any differences between women and men in the associations between ALAN and sleep duration. In contrast, the study from South Korea demonstrated that higher levels of ALAN were associated with a greater likelihood of reporting short sleep in men than in women (Koo et al., 2016). One study reported a stronger association between ALAN and sleep duration for residents with higher poverty rates, but failed to detect a significant effect of education on the association (Xiao et al., 2020). According to our study, residents with high education levels and income are more susceptible to ALAN. The reasons for the inconsistent results between our study and the previous studies are unclear, but they may be related to differences in the study populations (e.g. age, sex proportion, lifestyles, and genetic background), exposure assessment strategies (e.g. sources of satellite data, and exposure assessment method), and other co-exposures. We still need more research, notably well-designed and longitudinal studies, to explore the modifications of individual characteristics.

Light-induced disruption of circadian rhythms has been identified as an important contributor to sleep deficiency (Dewan et al., 2011; Rüger et al., 2013; Zeitzer et al., 2000). Such effects are largely due to alterations in melatonin production and secretion (Chang et al., 2012; Wright et al., 2005). Specifically, the suprachiasmatic nucleus (SCN) is the part of human hypothalamus often referred to as the circadian pacemaker. Upon light exposure, the SCN starts a signaling pathway that leads to a reduction in melatonin, and further results in the sleep disturbances (Blume et al., 2019). It is unclear, however, how the outdoor light would cause such a similar shift while people are inside the room. One natural explanation could be that the insufficient blocking of light by curtains or shades could create an environment where outdoor ALAN penetrated directly into the eye, thus affecting the suprachiasmatic nucleus clock and melatonin production (Moore, 2007). Besides, bright outdoor lighting possibly making the inside environment darker (Min and Min, 2018a). This could lead people to turn on more interior lights, which may be unnecessary and in turn contribute to disturbances of biological rhythms. Additionally, it is also possible that surrounding residences' outdoor ALAN stimulates people when going outside for work, dinner, exercise, or entertainment during evening or early night and lasts hours after. There has been evidence that even bright light exposure lasting for short durations, such as 15 min, can also shift the circadian pacemaker and suppress melatonin production (Chang et al., 2012; Gronfier et al., 2004).

The results of this study strengthen the relationship between outdoor ALAN and adverse sleep durations, suggesting that outdoor light pollution may be a novel risk factor for sleep deficiency. Considering the causal relation between outdoor ALAN and poor sleep (Al Lawati et al., 2009; Gates et al., 2018), it is reasonable to anticipate that outdoor ALAN might have adverse effects on mental health, cognitive function, cancers, and cardiovascular health. These findings have prompted calls for more research into the role of ALAN-induced sleep deprivation as a possible determinant of disparities in health. In addition, it highlights the importance of integrated effective management of artificial light into wider government policy-making, such as in the planning system, particularly in urban areas. To date, the developing countries like China still lack cross-sectoral efforts for the science-based standards and specifications for outdoor lighting. The concept of a win-win outdoor lighting strategy for people and the environment is feasible to minimize the energy use, as well as the negative impacts of lighting operation on landscape, ecology, and human health.

There are several limitations to our study that bear mentioning. First, the nighttime light map has the inherent problem of blooming effect (or named as over-glow), which is caused by light scattering and results in bright pixels extending beyond the real bright area (Shen et al., 2019a). Although the blooming effect is much smaller in NPP/VIIRS data than DMSP/OLS data (Cao et al., 2019; Shen et al., 2019b), this problem may have led to the misclassification of ALAN exposure and biased the estimates. Second, due to the inaccessibility of the data, the current study did not take into account important confounders correlated with the sleep duration (e.g., indoor ALAN, noise, shift work, and the availability of curtains) (Gabinet and Portnov, 2021; Helbich et al., 2020; Huang et al., 2013). Despite our best efforts, we could not eliminate the possibility of bias induced by non-observed covariates. Third, the NPP-VIIRS data was from the annual composite product without reflecting its temporal changes, which may result in the potential exposure misclassification. However, additional analyses using three year-averaged ALAN exposure (data not shown) also supported the significant associations between ALAN and sleep duration. On the other hand, ALAN exposure levels were assigned to individual addresses rather than to community centroids to minimize the measurement error, and the use of the NPP-VIIRS is superior to the DMSP-OLS due to its higher spatial and radiative resolution, as well as its onboard calibration system. Even so, the relatively coarse resolution of NPP-VIIRS (~500 m) and the radius (1 km) of the buffer zone may still, to some extent, introduce the measurement error. Fourth, causal inferences could not be drawn in this study due to its cross-sectional design. Further longitudinal studies are needed to support the link and to extend the findings by including other personal, behavioral, family, and environmental characteristics to help determine mediating factors and the underlying mechanisms. Fifth, the collection on sleep duration was self-reported. However, the error in sleep duration measurement is likely to have been non-differential with respect to ALAN and thus bias the results towards the null. Sixth, other aspects of sleep (such as sleep timing, quality and regularity, sleep-onset latency, the history of sleep disorders) were unavailable in the CLHLS, so we could not examine their relationships with ALAN.

5. Conclusions

This large nationwide cross-sectional study supports the hypothesis that ALAN influences sleep duration in the old population in China. Future studies on human sleep and the associated health outcomes (e.g. mental health, cancers) should incorporate individual-level measures of

ALAN as a risk or mediating factor. The risk may be greater in younger older people and those with a higher income or education level. Future research is needed to clarify the potential mechanisms underlying the observed association between sleep duration and ALAN. Our findings highlight the importance of having proper ALAN regulations as a potential preventive measure to lower the public health burden of sleep disorders, particularly in urban areas.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2022.113343.

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