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RESEARCH ARTICLE

Association of outdoor artificial light at night with mental health among China adults: a prospective ecology study

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Abstract
Multiple environmental changes are related to mental disorders. However, research on the association between artificial light at night (ALAN) and mental health in China is limited, particularly at the national level. We used a "difference-in-differences" design and logistic regression to explore the relationship between ALAN changes and scores on self-assessed mental health. Participants were drawn from the China Family Panel Studies of adults in 2012 and 2018. The final analysis was based on 21,036 adults from 25 provinces throughout China. The brighter the ALAN, the worse was the mental health, and this connection was unaffected by particulate matter 2.5 ($PM_{2.5}$) or temperature. ALAN sensitivity may differ among populations. Our findings suggest that exposure to brighter ALAN is associated significantly with worse mental health among Chinese adults. Environmental policies that reduce ALAN could improve the mental health of the Chinese public.

Keywords outdoor artificial light at night · mental disorders · environmental risk factors · CFPS · China adults · prospective ecology study

Introduction

More than one out of every four individuals have suffered from a common mental disorder at some point in their lifetimes (Ginn and Horder 2012; Prince et al. 2007). Studies on the global burden of disease (GBD) have highlighted the contribution of mental disorders worldwide (Lopez and Murray 1998). Mental disorders account for one quarter of all disability-adjusted life-years, and one-third of those who ascribed to non-communicable diseases (NCDS). Major depression (No.2), anxiety disorders (No.7), schizophrenia (No.11), dysthymia (No.16), and bipolar disorder (No.17) were among the top-20 causes of GBD in 2013 (Global Burden of Disease Study 2015).

A better understanding of the risk factors for mental disorders can help to lessen the disease burden. Traditional factors

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such as tobacco smoking, "binge" alcohol consumption, inadequate sleep, lack of physical activity, or being overweight or obese have been studied deeply (Massetti et al. 2017). However, environmental factors, such as artificial light at night (ALAN), have been shown to have harmful impacts on mental health recently in several studies (An et al. 2020; Stevens et al. 2013). For instance, overexposure to ALAN inhibits and delays melatonin secretion, as well as disrupts the normal circadian rhythm (Tähkämö et al. 2019) and changes the release of corticotropin and other hormones (Navara and Nelson 2007). Autism spectrum disorder is linked to neuroendocrine and neurological disorders (Wilson et al. 2021). From the standpoint of physiological mechanisms, those studies have shown an epidemiological relationship between environmental factors and mental disorders.

Most research on ALAN has been carried out in developed countries (Obayashi et al. 2013; Obayashi et al. 2018). A cohort study of 863 Japanese individuals revealed that those exposed to brighter ALAN in their bedroom carried a greater risk of depression. Obayashi and colleagues showed that exposure to 5 luminous flux per unit area (5 lx) of ALAN at home was associated significantly with depressive symptoms. In China and other developing countries, the evidence for the relationship between ALAN and mental health is limited, especially at the national level (Xie et al. 2022). In addition, as the interventions to reduce indoor ALAN become more common (e.g., night filters for personal electronics, changes in indoor lighting), ALAN from outdoor sources may become more influential (Paksarian et al. 2020).

Several studies have linked mental health risks to outdoor ALAN in which individuals are simultaneously exposed to multiple environmental factors, but the multicollinearity of these environmental factors has not been clearly explained (Osibona et al. 2021; Paksarian et al. 2020). For instance, studies have shown that exposure to particulate matter 2.5 ($PM_{2.5}$) or high temperatures had been previously associated with poor mental health (Buguet 2007; Frey et al. 2007; Jia et al. 2018; Mullington et al. 2009). To rule out that outdoor ALAN may be a type of environmental factor which is difficult to separate from ALAN, it has been suggested that a multi-index evaluation method should be used to determine the actual risk of ALAN.

We undertook a "difference-in-difference" design based on the China Family Panel Studies (CFPS) database to explore the relationship between ALAN and mental health in Chinese adults after adjustment for other environmental factors (e.g., $PM_{2.5}$ and temperature) and individual variables.

Methods

Study population

The cohort for this study was drawn from the CFPS (Xie and Lu 2015) . The CFPS is a comprehensive social-tracking survey conducted by the Social Science Research Center of Peking University (Beijing, China). This survey reflects the economic, educational, and health status of Chinese households through questionnaires administered to various households and populations. The CFPS adopts a multiple-probability sampling strategy. The baseline sample covers 25 provinces in China, representing 95% of the population of China.

We used the CFPS database for adults in 2012 as the baseline, and matched it to 2018 data using personal identification. Individuals with missing geographic information or incomplete responses to the mental-health questionnaire were excluded. A total of 21,036 participants were evaluated in the final dataset. Comparison with the total data for 2012 showed that exclusion did not change the population structure significantly (Fig. S1).

Mental health

Mental health was measured using a brief Center for Epidemiologic Studies Depression questionnaire. Six items were considered: "feeling depressed" (Q1), "activities took effort" (Q2), "restless sleep" (Q3), "feeling lonely" (Q4), "feeling sad" (Q5), and "did not enjoy life" (Q6). The self-rated questionnaire was based on a four-point scale, ranging from 1 ("rarely or no" [≤1 day a week]) to 4 ("most of the time" [5–7 days a week]) for each item. Therefore, a higher score reflected worse mental health. Q1, Q4, Q5, and Q6 reflect the individual's depressive affect, whereas Q2 and Q3 reflect the individual's somatic and retarded activity (Radloff 1977). For 2012 and 2018, we used the same questionnaire to measure mental health.

ALAN assessment

ALAN data were derived from the Suomi National Polar-orbiting Partnership-Visible Infrared Imaging Radiometer Suite (NPP-VIIRS) obtained from the Harvard Dataverse (https://dataverse.harvard.edu/) (Chen et al. 2020). Two data sources on artificial nighttime lighting are the Defense Meteorological Satellite Program Operational Linescan System (DMSP-OLS) stable nighttime light data and Suomi NPP-VIIRS nighttime light data (Shi et al. 2014). The latter were utilized in the present study because NPP-VIIRS data: (1) feature a higher spatial resolution (15 arc-second, ~500 m) than DMSP-OLS data (30 arc-second, ~1,000 m); (2) do not suffer from the oversaturation that exists in DMSP-OLS data; (3) employ onboard calibration, which enhances the data quality (Elvidge et al. 2013).

To preserve respondents' privacy, the CFPS database stores only participants' provincial address (a two-digit number). As a result, we calculated the respondents' ALAN exposure by averaging the ALAN data as the yearly average for the province. Simultaneously, and in light of the lag effect of ALAN on health (Fig. S2), we matched respondents using the ALAN from the previous year of the survey. That is, respondents from the same province were allocated to the same time period of the ALAN.

Covariates

$PM_{2.5}$

The $PM_{2.5}$ data came from a global dataset available (V5.GL.02) on the Internet website of Washington University (Saint Louis, MO, USA). This dataset contains annual and monthly data for ground-level $PM_{2.5}$ from 1998 to 2020 by combining aerosol-optical-depth retrievals from the National Aeronautics and Space Administration Moderate Resolution Imaging Spectroradiometer, Multi-Angle Imaging Spectroradiometer, and Sea-viewing Wide Field-of-View Sensor instruments with GeOS-Chem chemical transport models, and subsequently calibrating to global ground-based observations using a geographically weighted regression (van Donkelaar et al. 2021). For assessment of $PM_{2.5}$ exposure at the individual level, we used the same method as that employed for ALAN.

Temperature

Temperature data were from the China Surface Climatic Data Daily Set (V3.0) in the China Meteorological Data Network (http://data.cma.cn). The dataset includes temperature elements, including daily and monthly average temperature, maximum temperature, and minimum temperature. The sources of temperature data were twofold: (i) the basic meteorological elements data of China's national surface meteorological stations collected and sorted by the National Meteorological Information Center; (ii) the 0.5°×0.5° Digital Elevation Model of China's landmass was resampled from Global 30-Arc-Second Elevation Data Set (GTOPO30) data (resolution = 0.05°×0.05°). We utilized the same procedure as that employed for ALAN to determine temperature exposure for each individual.

Individual-level variables

Previous studies demonstrate that mental health could be influenced by individual-level variables such as age, gender, education, marriage (Helbich et al. 2020) , nationality, residence, income level (Paksarian et al. 2020), drinking, smoking, physical activity and obesity status (Massetti et al. 2017). The purpose of this study was to explore the relationship between environmental factor ALAN and mental health. In order to avoid the confounding influence of individual-level variables on the results, this study needed to control as many individual level factors as possible.

The potentially adjusted covariates were selected based on previous literature (Helbich et al. 2020; Massetti et al. 2017; Paksarian et al. 2020), including baseline individual-level covariates and changes in individual variables from 2012 to 2018 (see Table S1). The following baseline (2012) individual-level covariates were considered and controlled in the analysis: age (<20, 20–29, 30–39, 40–49, 50–59, 60–69, or 70+ years), gender (female or male), education ("illiterate", "primary school", "middle school", "high school", or "college and above"), marriage (single, married, cohabiting, divorced, or widowed), nationality (Han or non-Han), residence (rural or urban), income level ("very low", "low", "medium", "high", or "very high"), drinking (yes or no), smoking (yes or no), physical activity (no or yes), and obesity status ("normal" (body mass index (BMI) ≤25 kg/m2), "overweight" (BMI, 25–30 kg/m2), or "obese" (BMI >30 kg/m2)). We also considered changes in individual variables from 2012 to 2018 (e.g., smoking (from yes to no, unchanged, or from no to yes), education (unchanged or increased), migration (yes or no), obesity (decreased, unchanged, or increased), physical activity (decreased, unchanged, or increased), and drinking (from yes to no, unchanged, or from no to yes)). Migration status was based on whether the provincial address before and after the two surveys (2012 and 2018) was consistent.

Study design and statistical analyses

By comparing each respondent with himself/herself, we explored the association between ALAN and mental health using a difference-in-difference approach (Xue and Zhu 2018). This strategy controls for unmeasured confounding variables (e.g., genetic factors) that vary across individuals but which are longitudinally identical.

The main analytical method was binary logistic regression to explore the relationship between mental health (Q1–Q6) and ALAN changes using the following equation:

$$\text{Logit}\left(y_j\right) \sim x_j\beta + z_j b;$$

where i or j denotes the index for the mental-health questionnaire or CFPS subject, respectively; $Q_{i,j}$ denotes the score of the i^{th} question for the j^{th} subject; y_j denotes a binary variable that indicates the change in mental health from 2012 to 2018 ($y_j = 1$ for $Q_{i,j2018} \geq Q_{i,j,2012}$, and $y_j = 0$ for $Q_{i,j,2018} < Q_{i,j,2012}$); x_j represents the change in ALAN exposure at the individual level ($x_j = ALAN_{j,2018} - ALAN_{j,2012}$); z_j denotes the above-mentioned covariates at the individual-level; β and b denote regression coefficients.

Table 1 Associations between each mental health scores and ALAN

Variables	Qi	Odds ratio per unit increment of LAN (95% confidence intervals)			
		Model 1	Model 2	Model 3	Model 4
ALAN	Q1*	1.070 (1.032, 1.109)	1.065 (1.026, 1.105)	1.060 (1.017, 1.104)	1.052 (1.008, 1.097)
	Q2	1.017 (0.984, 1.052)	1.014 (0.979, 1.050)	1.013 (0.974, 1.053)	1.013 (0.974, 1.054)
	Q3	1.011 (0.977, 1.046)	1.004 (0.970, 1.040)	0.995 (0.957, 1.034)	0.994 (0.956, 1.034)
	Q4*	1.122 (1.076, 1.170)	1.134 (1.086, 1.184)	1.100 (1.049, 1.154)	1.105 (1.053, 1.160)
	Q5*	1.067 (1.026, 1.110)	1.078 (1.035, 1.123)	1.050 (1.003, 1.099)	1.050 (1.003, 1.099)
	Q6*	1.232 (1.159, 1.310)	1.229 (1.152, 1.311)	1.160 (1.081, 1.245)	1.158 (1.079, 1.243)

Model 1: unadjusted model;

Model 2: adjusted for changes in individual-level variables, including drinking, education, migration, obesity, physical activity, and smoking;

Model 3: adjusted for baseline in individual-level variables, including age, drinking, education, gender, income, marital status, nationality, physical activity, obesity, residence, and smoking;

Model 4: fully adjusted model.

*P-value <0.05

Q1: "feeling depressed"; Q2: "activities took effort"; Q3: "restless sleep"; Q4: "feeling lonely"; Q5: "feeling sad"; Q6: "did not enjoy life".

ALAN, artificial light at night.

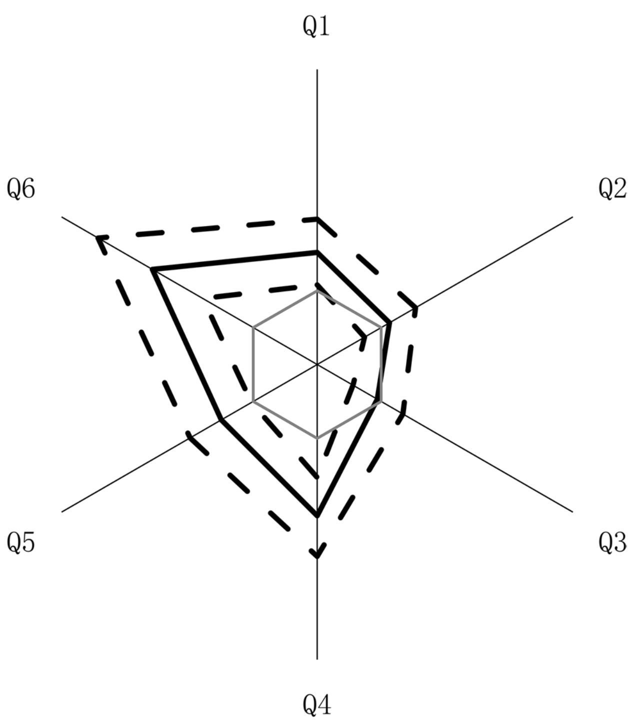

Fig. 1 Effects of ALAN on different dimensions of mental health. Black solid polygons: estimated odds ratios (ORs); black dashed polygons: corresponding 95% confidence intervals; gray polygons: reference of no effect (OR = 1); black radial lines: different dimensions of mental health; Q1: "feeling depressed"; Q2: "activities took effort"; Q3: "restless sleep"; Q4: "feeling lonely"; Q5: "feeling sad"; Q6: "did not enjoy life"

Four models were established to explain the potential confounding factors in the binary logistic regression model. Model 1 included only ALAN. Model 2 included the changes (e.g., drinking, education, migration, obesity, physical activity status, and smoking) based on Model 1. Model 3 included baseline individual-level variables based on Model 1. Model 4 was a fully adjusted model.

Collinearity among environmental factors (Dadvand et al. 2015) can have an impact on results. Hence, we used a multi-exposure model to ascertain the relationship between ALAN and mental health. We established three models on the basis of the fully adjusted model. Model 5 included $PM_{2.5}$ based on Model 4. Model 6 included temperature based on Model 4. Model 7 included $PM_{2.5}$ and temperature based on Model 4. The comparison between the single-exposure model (Model 4) and the multiple-exposure model (Model 5, Model 6, and Model 7) could reveal whether the influence of ALAN was sensitive to the additional adjustment of other environmental factors (i.e., $PM_{2.5}$, temperature, or $PM_{2.5}$ + temperature).

In addition to testing the relationship between continuous ALAN and mental health, a fully adjusted model was established using categorical variables (classified by quartile) of ALAN. Some studies have shown that the effects of ALAN may vary depending on sex (Xu et al. 2021) and life stage (Cissé et al. 2016). Hence, we assessed the connection between ALAN and mental health using various stratifications of covariables.

Significance was set at $p<0.05$. Analysis was undertaken using Stata MP 17.0 (StataCorp LP, College Station, TX,

Table 2 The associations between mental health sore and different types of ALAN

Qi	ORs of continuous ALAN(CIs)	*P*	ORs of categorical ALAN(CIs)	*P*
Q1	1.052 (1.008, 1.097)	0.019	1.062(1.028, 1.098)	0.000
Q2	1.013 (0.974, 1.054)	0.525	1.023(0.990, 1.057)	0.176
Q3	0.994 (0.956, 1.034)	0.772	1.014(0.981, 1.048)	0.402
Q4	1.105 (1.053, 1.160)	0.000	1.119(1.079, 1.161)	0.000
Q5	1.050 (1.003, 1.099)	0.038	1.030(0.992, 1.068)	0.119
Q6	1.158 (1.079, 1.243)	0.000	1.182(1.126, 1.242)	0.000

ALAN, artificial light at night

Q1: "feeling depressed"; Q2: "activities took effort"; Q3: "restless sleep"; Q4: "feeling lonely"; Q5: "feeling sad"; Q6: "did not enjoy life".

Table 3 Pairwise Spearman correlation coefficients of the relationships between changes in mental health and environmental exposure

	Q1	Q2	Q3	Q4	Q5	Q6	ALAN	$PM_{2.5}$
Q2	0.3120***							
Q3	0.1790***	0.1625***						
Q4	0.2289***	0.1870***	0.1577***					
Q5	0.2411***	0.1872***	0.1629***	0.2944***				
Q6	0.1571***	0.1341***	0.1354***	0.2510***	0.2472***			
ALAN	0.0327***	0.0191	0.0107	0.0561***	0.0200**	0.0630***		
$PM_{2.5}$	-0.0092	-0.0076	-0.0150*	-0.0207**	-0.0072	-0.0337***	-0.5248***	
T	0.0342***	0.0442***	0.0481***	0.0686***	0.0539***	0.0681***	0.3754***	-0.2615***

*** P-value <0.001; **P-value ~ (0.001,0.01); *P-value ~ (0.01,0.05)

Question scores (Q1-Q6) were significantly positively correlated with each other. The ALAN was significantly correlated with $PM_{2.5}$ and T.

Q1: "feeling depressed"; Q2: "activities took effort"; Q3: "restless sleep"; Q4: "feeling lonely"; Q5: "feeling sad"; Q6: "did not enjoy life".

$PM_{2.5}$, fine particulate matter; ALAN, artificial light at night; T, temperature

USA). Figures were drawn using Prism 8 (GraphPad, La Jolla, CA, USA) and Origin 2019.

Results

After excluding people who did not provide geographic information or who gave incomplete responses to the mental-health questionnaire, we evaluated 21,036 individuals. The characteristics of this study population are summarized in Table S1. The age of participants (46.25%) was mainly between 40 years and 59 years, and 51.35% were female. We discovered that 75.00% were of normal bodyweight and did not smoke tobacco (70.11%) or consume alcohol (83.86%). Additionally, 73.65% of the study population resided in a rural environment.

Changes in self-mental health scores from 2012 to 2018 were documented. We found that 28.68% of individuals felt more depressed (Q1), 30.60% felt activities took more effort (Q2), and 31.08% had worse sleep quality (Q3). Additionally, 22.97% and 24.61% of people felt lonely (Q4) and sad (Q5), respectively. In addition, 12.93% felt that they did not enjoy life (Q6). In accordance with the trend of accelerated urbanization in China (Wang et al. 2020), the average ALAN increased by 0.49. The average temperature increased by 1.02°C, which is in line with the trend towards global warming. The $PM_{2.5}$ level decreased by 15.67 μg m^{-3}, possibly as a result of meteorological factors and the reduction in human emissions brought about by the Clean Air Act in China (Xue et al. 2021).

The relationship between continuous ALAN and risk to mental health is shown in Table 1. In the fully adjusted model (Model 4) (Fig. 1), the OR (95%CI) was 1.052 (1.008–1.097), 1.105 (1.053–1.160), 1.050 (1.003–1.099), and 1.158 (1.079–1.243) for Q1, Q4, Q5, and Q6. These data suggested that brighter ALAN was associated significantly with a higher risk of a depressive affect (Q1, Q4, Q5, and Q6). This association remained when ALAN was a categorical variable

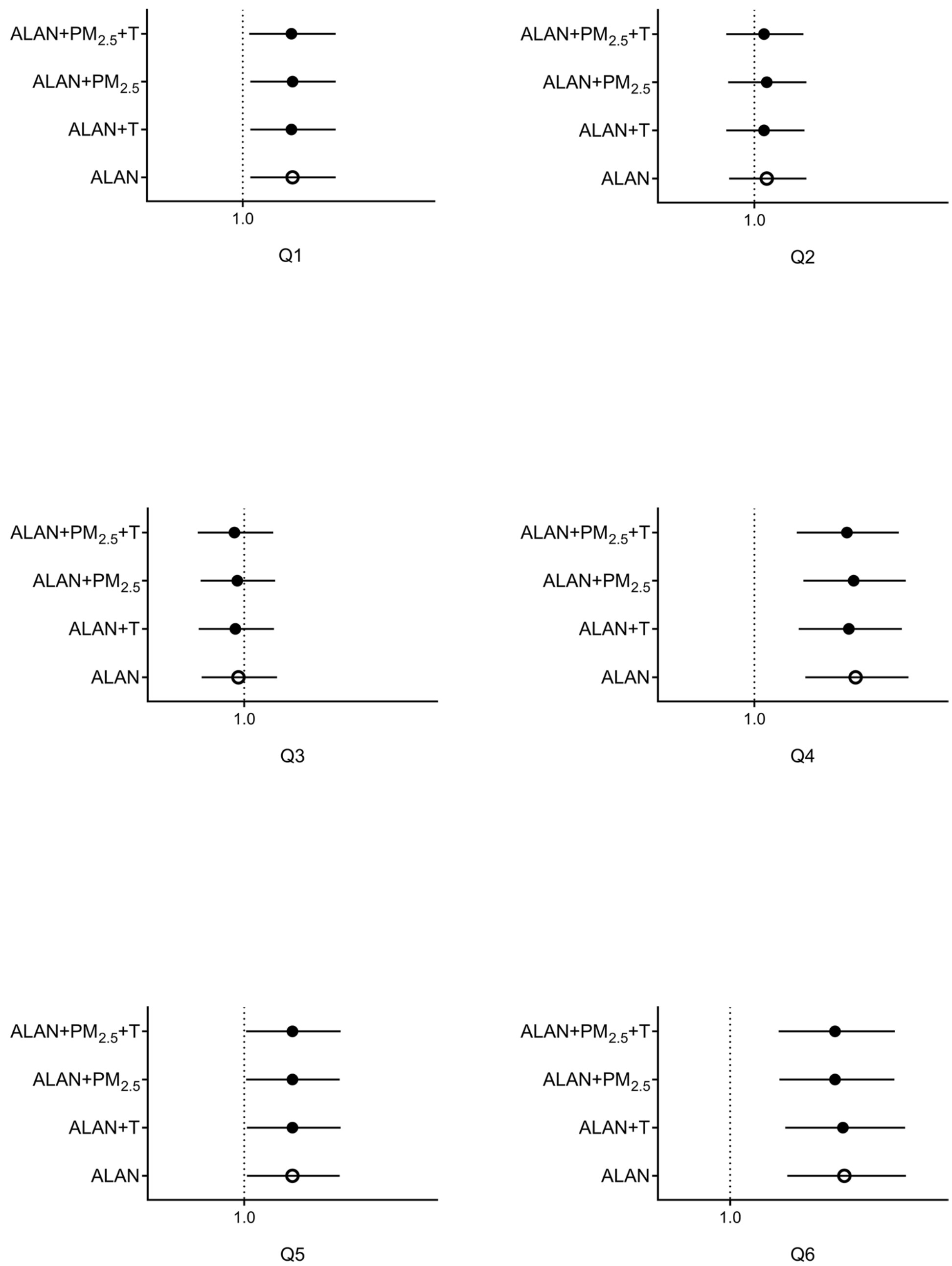

Fig. 2 Results using multi-exposure models. In different dimensions of mental health, the fully adjusted odds ratios of ALAN with their 95% confidence intervals (black dots with error bars) estimated by multi-exposure models were compared with the estimate of the corresponding single-exposure model (black circles with error bars). Q1: "feeling depressed"; Q2: "activities took effort"; Q3: "restless sleep"; Q4: "feeling lonely"; Q5: "feeling sad"; Q6: "did not enjoy life". $PM_{2.5}$, particulate matter 2.5; ALAN, artificial light at night; T, temperature

(Table 2). For instance, an increase in risk of 6.2% (95%CI, 2.8–9.8%) of feeling depressed (Q1) was correlated with a per-quartile increment in ALAN. The risk to mental health increased significantly with a per-quartile increment in ALAN.

Spearman correlation analysis between ALAN and other environmental factors are summarized in Table 3. The Spearman correlation coefficient between ALAN and $PM_{2.5}$ was −0.5248 ($p<0.001$), and the Spearman correlation coefficient with temperature was 0.3754 ($p<0.001$). Therefore, we used multi-exposure models to explore the relationship between ALAN and mental health. After adjustment for other environmental parameters, the effect remained robust (Fig. 2).

In the stratified analysis (Table 4), we found that the sensitivity of ALAN may be different in different populations. For example, under the same ALAN, being male (OR, 1.126; 95%CI, 1.049–1.209) made you more likely to feel lonely (Q4) than if you were female (1.090; 1.020–1.165). The impact of ALAN on mental health may have a time-lagged effect (Fig. S2).

Discussion

Our results are based on a representative sample of people in 25 provinces across China. We discovered a significant correlation between brighter ALAN and a higher risk of

Table 4 The associations between mental health score and ALAN by demographic subgroups

Characteristics		Q1		Q2		Q3		Q4		Q5		Q6	
		OR (95%CI)	*P*	OR (95%CI)	*P*	OR (95%CI)	*P*	OR (95%CI)	*P*	OR (95%CI)	*P*	OR (95%CI)	*P*
Age	<20	0.722(0.484, 1.078)	0.111	0.893(0.518, 1.540)	0.685	0.919(0.558, 1.513)	0.739	1.049(0.678, 1.622)	0.831	0.947(0.681, 1.316)	0.744	1.139(0.656, 1.975)	0.644
	20-29	0.985(0.883, 1.098)	0.779	1.018(0.913, 1.136)	0.745	0.912(0.835, 0.995)	0.039	0.981(0.889, 1.083)	0.710	0.956(0.869, 1.053)	0.362	0.937(0.793, 1.108)	0.447
	30-39	0.955(0.861, 1.059)	0.383	0.883(0.802, 0.972)	0.012	0.977(0.889, 1.074)	0.627	0.997(0.889, 1.117)	0.953	0.940(0.844, 1.046)	0.257	0.991(0.843, 1.166)	0.918
	40-49	1.044(0.947, 1.150)	0.385	1.038(0.943, 1.143)	0.442	1.041(0.944, 1.148)	0.424	1.198(1.055, 1.361)	0.005	1.120(0.997, 1.257)	0.056	1.180(1.001, 1.392)	0.048
	50-59	1.056(0.965, 1.154)	0.236	1.000(0.921, 1.086)	0.997	0.982(0.900, 1.072)	0.690	1.216(1.083, 1.364)	0.001	1.047(0.945, 1.160)	0.383	1.454(1.203, 1.757)	0.000
	60-69	1.181(1.065, 1.309)	0.002	1.114(1.011, 1.228)	0.029	1.051(0.957, 1.153)	0.301	1.137(1.010, 1.280)	0.033	1.331(1.153, 1.536)	0.000	1.340(1.088, 1.651)	0.006
	70+	1.061(0.885, 1.273)	0.520	1.008(0.855, 1.188)	0.926	1.059(0.880, 1.274)	0.546	1.252(0.995, 1.575)	0.055	1.081(0.862, 1.356)	0.501	0.998(0.755, 1.319)	0.988
Drinking	no	1.053(1.004, 1.104)	0.033	1.000(0.958, 1.045)	0.986	0.997(0.955, 1.041)	0.883	1.091(1.034, 1.150)	0.001	1.054(1.002, 1.109)	0.041	1.134(1.049, 1.225)	0.002
	yes	1.050(0.955, 1.155)	0.314	1.074(0.976, 1.182)	0.143	0.992(0.904, 1.089)	0.866	1.169(1.039, 1.314)	0.009	1.027(0.916, 1.151)	0.648	1.275(1.074, 1.514)	0.006
Education	below elementary school	1.025(0.932, 1.127)	0.617	1.021(0.932, 1.118)	0.658	1.015(0.920, 1.119)	0.771	1.173(1.046, 1.314)	0.006	1.122(1.003, 1.255)	0.044	1.225(1.068, 1.406)	0.004
	elementary school	1.148(1.033, 1.277)	0.011	1.005(0.919, 1.099)	0.911	1.058(0.965, 1.161)	0.228	1.163(1.034, 1.307)	0.012	1.075(0.960, 1.203)	0.212	1.163(0.993, 1.362)	0.061
	middle school	1.025(0.950, 1.106)	0.525	1.026(0.954, 1.104)	0.489	0.949(0.883, 1.020)	0.157	1.042(0.955, 1.137)	0.353	1.017(0.936, 1.105)	0.688	1.044(0.909, 1.199)	0.540
	high school	0.993(0.904, 1.090)	0.879	1.030(0.935, 1.133)	0.551	0.973(0.889, 1.065)	0.550	1.045(0.939, 1.163)	0.419	1.026(0.925, 1.137)	0.631	1.144(0.953, 1.373)	0.149
	college and above	1.133(0.991, 1.295)	0.068	0.953(0.856, 1.060)	0.376	0.997(0.901, 1.104)	0.959	1.159(1.003, 1.339)	0.045	1.005(0.891, 1.133)	0.937	1.197(0.913, 1.568)	0.193
Gender	female	1.069(1.007, 1.135)	0.030	0.984(0.932, 1.039)	0.560	1.010(0.956, 1.067)	0.729	1.090(1.020, 1.165)	0.011	1.060(0.995, 1.128)	0.069	1.134(1.035, 1.243)	0.007
	male	1.040(0.980, 1.103)	0.200	1.049(0.989, 1.111)	0.109	0.984(0.930, 1.041)	0.575	1.126(1.049, 1.209)	0.001	1.044(0.976, 1.118)	0.211	1.198(1.072, 1.339)	0.001

Table 4 (continued)

Characteristics		Q1		Q2		Q3		Q4		Q5		Q6	
		OR (95%CI)	*P*	OR (95%CI)	*P*	OR (95%CI)	*P*	OR (95%CI)	*P*	OR (95%CI)	*P*	OR (95%CI)	*P*
Income	very low	1.030(0.951, 1.115)	0.473	1.042(0.963, 1.127)	0.304	0.978(0.907, 1.055)	0.566	1.108(1.011, 1.213)	0.028	1.076(0.987, 1.174)	0.098	1.089(0.971, 1.221)	0.145
	low	0.997(0.929, 1.071)	0.944	0.960(0.897, 1.028)	0.240	0.954(0.891, 1.020)	0.168	1.074(0.984, 1.173)	0.108	0.996(0.919, 1.080)	0.922	1.215(1.048, 1.408)	0.010
	middle	1.132(1.049, 1.220)	0.001	1.046(0.979, 1.118)	0.185	1.029(0.962, 1.101)	0.403	1.120(1.034, 1.212)	0.005	1.064(0.985, 1.150)	0.117	1.177(1.038, 1.335)	0.011
	high	1.006(0.795, 1.274)	0.958	0.914(0.743, 1.124)	0.394	1.024(0.842, 1.244)	0.813	1.138(0.873, 1.483)	0.339	1.089(0.852, 1.391)	0.496	1.250(0.885, 1.766)	0.206
	very high	0.767(0.481, 1.221)	0.263	1.206(0.691, 2.106)	0.510	1.916(0.771, 4.760)	0.162	1.139(0.599, 2.164)	0.691	1.508(0.666, 3.419)	0.325	1.020(0.525, 1.981)	0.953
Nationality	Han	1.053(1.010, 1.099)	0.016	1.011(0.971, 1.052)	0.598	0.994(0.956, 1.034)	0.772	1.105(1.053, 1.160)	0.000	1.051(1.003, 1.100)	0.036	1.180(1.097, 1.269)	0.000
	Non-Han	0.788(0.473, 1.313)	0.361	1.011(0.592, 1.725)	0.969	0.833(0.501, 1.387)	0.483	1.135(0.611, 2.108)	0.688	1.008(0.588, 1.731)	0.976	0.500(0.289, 0.865)	0.013
Physical activity	No	1.068(1.006, 1.134)	0.030	0.991(0.938, 1.046)	0.740	0.999(0.945, 1.056)	0.972	1.126(1.051, 1.205)	0.001	1.084(1.015, 1.157)	0.016	1.165(1.057, 1.284)	0.002
	Yes	1.040(0.979, 1.105)	0.201	1.043(0.984, 1.106)	0.156	0.995(0.941, 1.052)	0.853	1.090(1.017, 1.168)	0.014	1.021(0.957, 1.090)	0.532	1.154(1.039, 1.282)	0.007
Obesity status	Normal	1.031(0.982, 1.083)	0.212	1.025(0.978, 1.074)	0.295	0.988(0.944, 1.033)	0.595	1.101(1.042, 1.164)	0.001	1.036(0.984, 1.092)	0.180	1.130(1.045, 1.223)	0.002
	Overweight	1.102(1.008, 1.206)	0.034	0.972(0.897, 1.054)	0.493	1.002(0.919, 1.091)	0.971	1.093 (0.984, 1.214)	0.097	1.069(0.965, 1.184)	0.202	1.259(1.062, 1.491)	0.008
	Obese	1.198(0.909, 1.580)	0.200	0.976(0.770, 1.237)	0.843	1.122(0.847, 1.485)	0.423	1.262(0.861, 1.850)	0.232	1.353(0.928, 1.973)	0.116	1.331(0.692, 2.558)	0.392
Residence	Rural	1.022(0.958, 1.090)	0.518	1.001(0.943, 1.063)	0.974	0.966(0.910, 1.024)	0.245	1.117(1.037, 1.202)	0.003	1.006(0.941, 1.074)	0.866	1.154(1.046, 1.273)	0.004
	Urban	1.059(1.001, 1.121)	0.046	1.017(0.964, 1.073)	0.529	1.005(0.953, 1.060)	0.850	1.081(1.014, 1.154)	0.018	1.077(1.010, 1.149)	0.024	1.140(1.027, 1.266)	0.014
Smoking	No	1.061(1.008, 1.116)	0.023	1.006(0.959, 1.055)	0.805	0.984(0.940, 1.031)	0.498	1.097(1.035, 1.163)	0.002	1.059(1.003, 1.118)	0.040	1.154(1.061, 1.255)	0.001
	Yes	1.037(0.961, 1.118)	0.351	1.028(0.957, 1.105)	0.452	1.029(0.956, 1.109)	0.445	1.126(1.032, 1.229)	0.008	1.031 (0.945, 1.125)	0.490	1.179(1.032, 1.347)	0.016

Q1: “feeling depressed”; Q2: “activities took effort”; Q3: “restless sleep”; Q4: “feeling lonely”; Q5: “feeling sad”; Q6: “did not enjoy life”.

a mental disorder among Chinese adults. We observed a significant increase in a depressive affect (Q1, Q4, Q5, and Q6) (Radloff 1977) with an increase in the ALAN level in the unadjusted model. This association remained significant after adjustment for baseline individual-levels and changes in individual variables. After adjustment for environmental factors, ALAN remained highly correlated with a mental disorder. This result suggested that the linkage between a mental disorder and ALAN was inevitable and independent of $PM_{2.5}$ and temperature.

Our study provided evidence that outdoor ALAN may be a risk factor for mental health. Considering previous studies, following possible pathways could explain the negative effects of ALAN on mental health. Melatonin is an essential hormone required for metabolism and neurodevelopment. According to the amount of light received, the pineal gland releases melatonin on a 24-hour cycle to regulate the circadian rhythm (van Bommel and van den Beld 2004; Zeitzer et al. 2000). ALAN can inhibit melatonin secretion, thereby affecting the normal circadian rhythm (Zeitzer et al. 2000). It has been shown that patients with a mental disorder were often reported disorders in their circadian rhythms and lower level of melatonin, suggesting that disruption of the melatonin system and circadian rhythm disturbances were potential mechanisms for the development of mental disorders (Vallée et al. 2020; Wu et al. 2020). Therefore, ALAN may exert an effect on mental disorders through melatonin and circadian rhythms. In addition, LAN may also increase the risk of a mental disorder by causing an immune disorder (McClung 2013). Pro-inflammatory cytokines can induce a syndrome resembling depression (Dantzer et al. 2008), so immune function may be another possible pathway between ALAN and mental disorders.

Our stratified analysis suggested that the effects of ALAN may vary depending on sex, physical activity, residence, or lifestyle (e.g., smoking, drinking). Dopamine levels in men and women are different. Dopamine is involved in controlling the retina's sensitivity to light, which results in men being more sensitive to light than women (Chellappa et al. 2017). Regular exercise can improve immune function and reduce sensitivity to ALAN. Our stratified research demonstrated that, while assessing the harmful effect of ALAN, individual variations in photosensitivity must also be considered.

Our study had five main limitations. First, the CFPS database contains information only within the provinces of China. We used ALAN-exposure levels within provinces, which may not reflect an individual's true exposure accurately. However, measurement of outdoor ALAN exposure for individuals is very difficult (especially for such a large study cohort) and would be time-consuming and labor intensive. Second, despite our efforts to incorporate as many variables as possible, certain factors were unavoidably missing. Hence, we adjusted for variables that could not be measured (e.g., genetic variables) using comparing each respondent with himself/herself. Third, though our findings are congruent with those of certain cross-sectional studies (Helbich et al. 2020; Paksarian et al. 2020), like those studies, we could not demonstrate a causal relationship between ALAN and mental health. Even though we used a difference-in-differences design with stronger causal associations than those in cross-sectional studies, longitudinal studies are needed to support our conclusions. Fourth, we used a self-reported questionnaire to assess mental health, but a recall bias was inevitable. Fifth, we controlled for the impact of two well-studied environmental factors on mental health. However, we cannot be sure that the impact of ALAN on mental health did not suffer interference by other environmental factors, such as the level of nitric dioxide (Helbich et al. 2020) or greenness (Perrino et al. 2019).

Conclusions

Exposure to brighter ALAN was associated with worse mental health among Chinese adults. For ALAN (a preventable and modifiable exposure), our results support better mental-health public-health interventions in China. We also revealed the complexity of the epidemiological relationship between mental health and ALAN changes, including confounding factors with other environmental factors, and individual susceptibility, which should be investigated in future studies.

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Data availability statement The population data (CFPS) that support findings of this study are available from https://opendata.pku.edu.cn. The ALAN data that support the findings of this study are available from https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/YGIVCD. The PM2.5 data that support the findings of this study are available from https://sites.wustl.edu/acag/datasets/surface-pm2-5/. The temperature data that support the findings of this study are available from http://data.cma.cn

Code availability statement The code that supports the findings of this study is available from the corresponding author upon reasonable request.

Author's contributions Zhenfan Yu: Data curation, Methodology, and Writing—original draft. Naifan Hu: Conceptualization, Data curation, and Writing—review & editing. Yurun Du: Software and Writing—review & editing. Huihui Wang: Formal analysis and Writing—review

& editing. Lining Pu: Data curation and Writing—review& editing. Xue Zhang: Data curation. Degong Pan: Writing—review & editing. Xiaoxue He: Writing—review & editing. Jiangping Li: Supervision, Resources, Writing—review & editing, Project administration, and Funding acquisition

Declarations

Ethics approval and consent to participate The CFPS is a nationally representative, the biennial household survey that has been performed since 2010, organized by the Institute of Social Science Survey, Peking University. The Peking University Biomedical Ethics Review Committee provided ethical approval for the survey (Approval number: IRB00001052-14010).

Conflicts of interest The authors have no conflicts of interest to disclose.

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