Environmental Research 263 (2024) 119897

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Sleep problems mediate the association between outdoor nighttime light and symptoms of depression and anxiety: A cross-sectional, multi-city study in Bulgaria

Marco Helbich [a,b,c,*], Angel Burov [b,c,d], Donka Dimitrova [b,c,e], Iana Markevych [b,c,f], Mark J. Nieuwenhuijsen [b,c,g,h,i], Angel M. Dzhambov [b,c]

[a] Department of Human Geography and Spatial Planning, Faculty of Geosciences, Utrecht University, Utrecht, the Netherlands
[b] Health and Quality of Life in a Green and Sustainable Environment Research Group, Strategic Research and Innovation Program for the Development of MU – Plovdiv, Medical University of Plovdiv, Plovdiv, Bulgaria
[c] Environmental Health Division, Research Institute at Medical University of Plovdiv, Medical University of Plovdiv, Plovdiv, Bulgaria
[d] Department of Urban Planning, Faculty of Architecture, University of Architecture, Civil Engineering and Geodesy, Sofia, Bulgaria
[e] Department of Health Management and Health Economics, Faculty of Public Health, Medical University of Plovdiv, Plovdiv, Bulgaria
[f] Institute of Psychology, Jagiellonian University, Krakow, Poland
[g] Barcelona Institute for Global Health, Barcelona, Spain
[h] Universitat Pompeu Fabra, Barcelona, Spain
[i] CIBERESP, Madrid, Spain

ARTICLE INFO

Keywords:
Mental health
Anxiety
Depression
Insomnia
Light at night
Air pollution
Green space
Eastern Europe

ABSTRACT

Background: Nighttime light is a growing anthropogenic health threat, particularly in urban areas. Limited evidence suggests that exposure to outdoor artificial light at night (ALAN) may be associated with people's mental health by disrupting sleep-wake cycles.
Aims: We assessed 1) the association between ALAN exposure and adults' symptoms of depression and anxiety, 2) whether the association was modified by sex, age, and income, and 3) the mediating role of sleep problems.
Methods: We obtained cross-sectional data from 4,068 adults from the five largest Bulgarian cities. Depression and anxiety symptoms were measured using the 4-item Patient Health Questionnaire (PHQ-4). Sleep problems were self-reported based on three items. Outdoor ALAN at residential addresses was assessed using annual radiance levels obtained from satellite imagery. Regression models were adjusted for person-level characteristics, green space, and nitrogen dioxide (NO_2). We also assessed effect modification by sex, age, and income. Using mediation analyses, we tested sleep problems as a mediator of the ALAN-PHQ-4 association.
Results: Greater ALAN exposure in the fully adjusted model was marginally associated with higher PHQ-4 scores. We observed no effect modification. The mediator, sleep problems, was also positively associated with ALAN. The mediation of sleep problems was significantly positive. While the direct association was null, the total ALAN association was marginally and positively associated with PHQ-4 scores.
Conclusions: Our findings suggest a positive association between outdoor nighttime light pollution and mental health. Poor sleep quality is a possible pathway relating ALAN exposure to mental health. Considering the increasing ubiquity and intensity of urban nighttime illumination, light pollution-reducing policies may provide significant health benefits for urban populations.

1. Background

Nighttime light pollution (e.g., from street lamps and illumination of buildings and grounds) has become pervasive in cities. Current estimates suggest that 99% of Europeans live beneath light-polluted night skys (Falchi et al., 2016), with 10% increases in brightness occurring annually between 2011 and 2022 (Kyba et al., 2023). This escalating level of artificial light at night (ALAN) far outstrips natural nighttime light and

* Corresponding author. Department of Human Geography and Spatial Planning, Faculty of Geosciences, Utrecht University, Princetonlaan 8a, 3584 CB, Utrecht, the Netherlands.
E-mail address: m.helbich@uu.nl (M. Helbich).

https://doi.org/10.1016/j.envres.2024.119897
Received 18 June 2024; Received in revised form 21 August 2024; Accepted 29 August 2024
Available online 31 August 2024

appears to be an ever-growing potential anthropogenic environmental disruptor.

There is rising concern that prolonged exposure to excessive ALAN has ecological repercussions (Gaston and de Miguel, 2022) and adverse health effects (Zielinska-Dabkowska et al., 2023). Experimental animal studies have suggested physiological and behavioral alterations (LeGates et al., 2012). Findings in mice have shown that over-illumination evokes depressive-like (An et al., 2020) and anxiety-like responses (Borniger et al., 2014) and interferes with sleep behavior (Fonken and Nelson, 2013). These findings may also apply to some degree to human mental illness, in turn contributing to the global disease burden (GBD 2019 Mental Disorders Collaborators, 2022).

Epidemiological studies measuring bedroom light levels have suggested that greater nighttime light exposure may increase the risk for psychiatric disorders by disrupting the natural sleep-wake cycle (Burns et al., 2023). However, the evidence for how prolonged exposure to outdoor ALAN puts people at risk remains limited. Systematic reviews of population-based studies concluded that only a few studies dealt with outdoor ALAN, the available evidence is only of fair quality, and that results, especially for depressive symptoms, are controversial (Tancredi et al., 2022; Tongyu et al., 2023). The latter may be due to inadequate environmental co-exposure adjustment (McIsaac et al., 2021), including air pollution (Helbich et al., 2020) and green space (Stanhope et al., 2021). The evidence that ALAN-mental health associations vary by socio-demographics is also conflicting (Jin et al., 2023; Yu et al., 2022).

Another strand of research examined how ALAN is associated with sleep (Wang et al., 2023). A meta-analysis of seven heterogeneous studies revealed possible associations between ALAN and sleep problems, notably when ALAN levels exceeded 5.8 nW/sr/cm^2 (Xu et al., 2023). A not yet explored indirect pathway relating ALAN to mental health involves poor sleep (Tongyu et al., 2023; Wang et al., 2023). Insufficient restorative sleep contributes to reduced mental functioning and fatigue, which can increase levels of depression (Tsuno et al., 2005).

In response to uncertainties raised by prior scholarship, we had three objectives: 1) To assess the associations between outdoor ALAN, mental health, and sleep quality among adults in urban Bulgaria, 2) to assess whether the ALAN-mental health association is modified by sex, age, and income, and 3) to assess to what extent sleep problems mediate a possible ALAN-mental health association. For the first study of its kind in Eastern Europe, we recruited 4640 adults in urban Bulgaria, where approximately 13% of the population experienced mental health problems, typically anxiety and depression, in 2019 (the EU average was 17%) (OECD, 2023).

2. Materials and methods

2.1. Survey area and survey design

We conducted an omnibus cross-sectional study in the five largest Bulgarian cities (i.e., Sofia, Plovdiv, Varna, Burgas, and Ruse) (Supplementary Table S1). We used stratified sampling to acquire a sample representative of the cities' populations and socio-demographics while ensuring environmental variability related to green space, transport noise, air pollution, and housing types (Supplementary Table S2) (Dzhambov et al., 2023). A professional survey company, supervised by the research team, recruited 4,640 participants who were required to be 18+ years old and live in a private household to be eligible for study inclusion (Helbich et al., 2024).

We designed our survey items to capture a broad spectrum of physical and mental health outcomes and socio-demographics. Before commencing fieldwork, we trained interviewers. These interviewers then visited each participant at home to complete a tablet-assisted interview between August and October 2023. Due to the broad survey scope, we did not base the sample size on power calculations. Response rates varied across cities (Supplementary Table S1), with an overall value of 42.51%. Supplementary Table S3 provides a comparison between the sample and the respective source population obtained from the census 2021. We obtained participant consent before study inclusion. The study was approved by the Ethics Committee of the Medical University of Plovdiv (Protocol № 4/04.05.2023 and Opinion № P-1253/17.05.2023). We adhered to the STrengthening Reporting of OBservational studies in Epidemiology (STROBE) reporting guideline (Von Elm et al., 2007).

2.2. Depression and anxiety symptom scores as the outcome

We used the self-administered Patient Health Questionnaire-4 (PHQ-4) to screen adults' levels of anxiety and depression (Kroenke et al., 2009). The four-item instrument inquired about participants' experiences in the preceding two weeks. The statements examined whether people 'feel nervous, anxious or on edge,' were 'not being able to stop or control worrying,' had 'little interest or pleasure in doing things,' and were 'feeling down, depressed, or hopeless.' Respondents rated each item on a four-point Likert scale from 'not at all' (0) to 'nearly every day' (3).

We determined scores by summing the individual items. The PHQ-4 scores ranged between 0 and 12, with higher scores representing greater symptom severity. Higher PHQ-4 scores correlate well with higher levels of functional impairment, an increase in disability days, and heightened utilization of healthcare services (Kroenke et al., 2009). Validation studies certified that the PHQ-4 is a reliable instrument when applied to the general population (Löwe et al., 2010). The Cronbach's alpha in our sample was 0.897 (95% confidence interval [CI]: 0.887; 0.906), implying good internal item consistency.

2.3. Sleep problem score as the mediator

We anticipated that ALAN exposure might harm people's mental health either directly or by disrupting sleep quality. We identified sleep problems with survey items addressing the respondents' sleep patterns over the two weeks preceding (Dzhambov et al., 2024). Three items probed issues with falling asleep, waking up and remaining sleepless during the night, and feeling unrested the following morning. Responses were given on a four-point Likert scale (1 = never, 2 = several days, 3 = more than half the days, 4 = nearly every day). We summed the item scores to obtain an overall sleep problem score ranging from 0 to 9. Higher scores indicate more sleep problems. The internal item consistency was good (Cronbach's alpha = 0.856; 95% CI: 0.843; 0.867).

2.4. Space-borne assessment of outdoor nighttime light

We used satellite imagery to identify outdoor artificial nighttime luminance (Kocifaj et al., 2023). Due to ALAN uncertainties introduced by first-generation remote sensing platforms (i.e., the Defense Meteorological Satellite Program Operational Linescan System [DMSP-OLS]), we used globally calibrated data from the day/night band on the panchromatic Visible Infrared Imaging Radiometer Suite (VIIRS) sensor operating on the Suomi National Polar-orbiting Partnership satellite (Miller et al., 2012). We favored VIIRS data for its higher spatial resolution of ~464 m compared to ~1 km for DMSP-OLS (Levin et al., 2020), enhanced radiometric sensitivity, and in-flight sensor calibration (Elvidge et al., 2017; Levin et al., 2020).

To match our survey data as closely as possible while ensuring the exposure occurred before the survey took place and to mitigate seasonal variations, we used the twelve-month median radiance grid (in nW/cm^2/sr) corrected for stray light. Google Earth Engine provided scenes from the 2022 'VCMSLCFG' image collection sourced from the data archive hosted by the National Oceanic and Atmospheric Administration.

We estimated exposure to ALAN at respondents' residential addresses. We geocoded the address locations using global positioning system-based tracking devices. The spatial accuracy of the address coordinates was evaluated based on auxiliary data (e.g., cadaster) and, if needed, manually corrected on a case-by-case basis. Since it is possible for a respondent to reside at the boundary of a cell and be more affected by an adjacent cell, we resampled the grid to 10 m using bilinear interpolation to match the resolution of the co-exposures (see below). Given the original ALAN data resolution, we used 500 m circular buffers centered on address locations as our main contextual unit to delineate environmental exposures. Our buffer size was comparable to a buffer size used elsewhere (Helbich et al., 2020).

2.5. Covariates

We developed a directed acyclic graph (Textor et al., 2016) to select possible confounders for our statistical analysis based on the existing literature and plausible relationships among them (Supplementary Fig. S1). The following person-level confounders were obtained through the questionnaire: age (in years), sex (male, female), ethnicity (Bulgarian, other), marital status (single, married/partner, divorced/-separated, widowed), education (primary education not completed/completed, secondary education completed, higher education completed), employment status (unemployed, employed), difficulty to get along with the monthly household income grouped into easy, moderate, and difficult. For sensitivity analyses, we also used the respondents' bedroom orientation (a busy/noisy street, quiet street/inner courtyard, other), ALAN annoyance (not at all, slightly, very, extremely), and light sensitivity (i.e., the visual discomfort occurring in everyday light conditions; not at all, slightly, very, extremely), each measured by means of a single item.

We included environmental characteristics on the neighborhood level using 500 m circular buffers centered on respondents' residential addresses (Helbich et al., 2020; Stanhope et al., 2021). Because light emissions interact chemically with the atmospheric production of nitrogen dioxide (NO_2) radicals (Stark et al., 2011) and have been suggested to be more strongly associated with mental health than fine particulate matter (Gao et al., 2023), we included annual mean NO_2 concentrations (1 ppb = 1.88 μg/m^3) for 2020 (Larkin et al., 2023). Estimates on a 50 × 50 m grid were obtained from a global land use regression model calibrated from 8,250 monitoring stations with 11 predictors, including the presence of major and minor roads, ozone, population density, tree cover, and atmospheric pressure. The cross-validated model accuracy indicated that the annual mean NO_2 estimates correlated reasonably well with ground-based measurements ($R^2_{Europe} = 0.56$). Data on green space were retrieved from the pan-European Urban Atlas for 2018 (Copernicus, 2024). The Urban Atlas nomenclature distinguishes 17 land cover and land use classes with a minimum mapping unit of 0.25 ha. We aggregated multiple vegetation classes (e.g., forests, pastures, permanent crops) to obtain a binary green space measure following prior analyses (Supplementary Table S4) (Barboza et al., 2021). NO_2 and green space were resampled to a uniform 10 m grid before the mean NO_2 concentrations (μg/m^3), and the proportion of green space per buffer size was determined. Population density estimates for 2021 were included in a sensitivity test and determined by the gross floor area for buildings with residential functions from the cadaster linked to the number of people per address location.

2.6. Statistical analyses

2.6.1. Primary analyses

Descriptive statistics summarized the sample characteristics. We used non-parametric Spearman correlation coefficients to assess correlations between PHQ-4 scores, sleep problem scores, and exposures. Since multicollinearity causes unreliable associations, we calculated generalized variance inflation factors (GVIF). GVIF values exceeding five are indicative of multicollinearity (Craney and Surles, 2002).

We computed intraclass correlation coefficients of the null models to assess whether random-intercept multilevel models were warranted for the PHQ-4 and sleep problem scores. Intraclass correlations of 0.056 (95% CI: 0.029; 0.083) and 0.049 (95% CI: 0.031; 0.079) suggested negligible variability between cities. We then developed linear regressions to assess the associations between ALAN, PHQ-9 scores, and sleep problem scores, conditioned on differing adjustment levels.

Model 1 was minimally adjusted, regressing PHQ-4 and sleep problem scores separately on ALAN, including city-specific dummies. Model 2 additionally included the person-level covariates (i.e., age, sex, ethnicity, marital status, education, employment status, and income). Model 3 added NO_2. Model 4 replaced NO_2 with green space. Finally, Model 5 was fully adjusted for person-level and neighborhood-level confounders (i.e., NO_2 and green space).

We used E-values to quantify the magnitude of unobservable confounding required to explain the exposure-outcome association in Model 5 (VanderWeele and Ding, 2017). We also assessed the relative importance of the environmental exposures collectively and individually using relative weight analyses in Model 5 (Grömping, 2007). Regression coefficients were reported with 95% CIs based on White's heteroskedasticity-consistent standard errors, as suggested by Breusch-Pagen tests. We conducted the analyses using R-4.1.0 (R Core Team, 2024).

2.6.2. Sensitivity tests of the primary analyses

We conducted sensitivity tests to evaluate the robustness of Model 5. First, because different buffer sizes may affect the magnitude of the estimated associations (Tian et al., 2024), we refitted the models using 100 m and 800 m buffers for the exposure assignment (i.e., ALAN, NO_2, and green space) (Helbich et al., 2020). Second, we additionally adjusted Model 5 for estimated population density as a proxy of omitted urban characteristics, possibly confounding the ALAN association. Third, we refitted Model 5 after excluding those self-reporting extremely high ALAN annoyance and light sensitivity in the survey and ran stratified analyses depending on the bedroom orientation (busy/noisy street, quiet street/inner courtyard, other).

2.6.3. Secondary analyses

To assess the possible effect modification by sex, age, and income of the ALAN-PHQ-4 association in Model 5, we added interaction terms between ALAN and each modifier. We interpreted a significant interaction ($p < 0.05$) as effect modification. We applied likelihood ratio tests and the Akaike information criterion (AIC) to each model to compare goodness-of-fit with and without the interaction terms.

Because ALAN may be related to sleep problems and, in turn, possibly related to mental health, we did not adjust for sleep problems in the primary analyses, instead using mediation analysis based on the counterfactual framework (Imai et al., 2010). In addition to the outcome model regressing PHQ-4 on ALAN based on 500 m buffers and sleep problem scores, we regressed sleep problem scores on the fully adjusted covariates in the mediator model. The mediation analysis permits decomposing the total ALAN association into a mediation (i.e., part of the ALAN-PHQ-9 association transmitted via sleep problems) and a direct association (i.e., direct association between ALAN and PHQ-9 without considering sleep problems). We based the 95% CIs on 5,000 bootstrap simulations (Tingley et al., 2014). To evaluate the robustness of the mediation analysis using 500 m buffers, we refitted the model using 100 m and 800 m buffers.

3. Results

3.1. Sample description

We excluded respondents with missing survey data ($N = 567$) and those living at their residential addresses for less than a year, in the latter case, to avoid risking exposure misclassification due to residential mobility ($N = 5$). Our analytic sample comprised 4,068 respondents

(Supplementary Fig. S2) aged 18–90 years with a mean age of 50.5 (SD ± 17.4), of which 54.9% were female (Table 1). Respondents were predominantly Bulgarian (95.9%), 63.4% were married or lived with a partner, and 57.1% completed secondary education. The PHQ-4 score was, on average, 1.6 (SD ± 2.5; interquartile range: 2), and the mean sleep problem score was 1.7 (SD ± 2.2; an interquartile range: 3).

3.2. Exposure distribution and correlations

Unless otherwise noted, we reported the results for the 500 m buffer analyses. Supplementary Fig. S3 shows the geographical distribution of ALAN concentrations. The average ALAN exposure was 36.1 nW/cm^2/sr (SD ± 13.9) (Supplementary Table S5). Fig. 1 shows that the mean ALAN levels, except for Varna, were associated with higher PHQ-4 scores across the cities. Excepting Plovdiv, higher ALAN levels are related to higher sleep problem scores (Supplementary Fig. S4).

Supplementary Fig. S5 summarizes the pairwise Spearman correlations between the exposures, PHQ-4 scores, and sleep problem scores. Correlations between ALAN and the PHQ-4 scores were not statistically significant. We observed weak positive associations between ALAN and sleep problem scores (0.102; $p < 0.001$). The correlation between the PHQ-4 scores and sleep problem scores was moderately high, with a coefficient of 0.613 ($p < 0.001$). ALAN was inversely correlated with green space (−0.397; $p < 0.001$) and positively correlated with NO_2 (0.479; $p < 0.001$) for the 500 m buffers.

Table 1
Characteristics of the study sample (N = 4,068).

	Mean (SD)/%
PHQ-4 score (mean (SD))	1.569 (2.482)
Sleep problem score (mean (SD))	1.718 (2.209)
Sex (Female (%))	2233 (54.9)
Age (mean (SD))	50.466 (17.366)
Ethnicity (other (%))	167 (4.1)
Marital status (%)	
Single	659 (16.2)
Married/with partner	2,581 (63.4)
Divorced/separated	334 (8,2)
Widowed	494 (12,1)
Education (%)	
Primary education not completed/completed	203 (5.0)
Secondary education completed	2,323 (57.1)
Higher education completed	1,542 (37.9)
Unemployed (yes (%))	155 (3.8)
Income (%)	
Difficult	636 (15.6)
With some difficulty	1,784 (43.9)
Mostly easy	1,034 (25.4)
Easy	304 (7.5)
Very easy	79 (1.9)
ALAN annoyance (%)	
Not at all	2,174 (53.4)
Slightly	1,115 (27.4)
Moderately	634 (15.6)
Very	111 (2.7)
Extremely	34 (0.8)
Light sensitivity (%)	
Not at all	1,855 (45.6)
Slightly	1,430 (35.2)
Very	665 (16.3)
Extremely	118 (2.9)
City (%)	
Sofia	1,257 (30.9)
Varna	945 (23.2)
Plovdiv	901 (22.1)
Burgas	549 (13.5)
Ruse	416 (10.2)
Residence years (mean (SD))	27.201 (17.495)
Bedroom orientation (%)	
Busy/noisy street	994 (24.4)
Quiet street, inner courtyard	2,659 (65.4)
Other	415 (10.2)
$ALAN_{100m}$ (mean (SD))	36.768 (14.434)
$ALAN_{500m}$ (mean (SD))	36.064 (13.923)
$ALAN_{800m}$ (mean (SD))	35.132 (13.484)
$NO_{2\ 100m}$ (mean (SD))	20.110 (5.168)
$NO_{2\ 500m}$ (mean (SD))	20.036 (5.098)
$NO_{2\ 800m}$ (mean (SD))	19.805 (5.064)
Green $space_{100m}$ (mean (SD))	4.569 (9.040)
Green $space_{500m}$ (mean (SD))	14.151 (12.580)
Green $space_{800m}$ (mean (SD))	17.471 (13.608)
Population $density_{100m}$ (mean (SD))	520.344 (269.519)
Population $density_{500m}$ (mean (SD))	8,669.759 (4,236.828)
Population $density_{800m}$ (mean (SD))	19,228.332 (9,490.782)

3.3. Associations between ALAN, PHQ-4 scores, and sleep problem scores

We observed no multicollinearity in the fully adjusted models, with the highest GVIF being 1.978. Fig. 2 and Supplementary Tables S6–S7 summarize the associations between ALAN levels, PHQ-4 scores, and sleep problem scores for different adjustment levels. Incrementally adjusting the model amplified the magnitude of the associations of ALAN with PHQ-4 and sleep problem scores, especially when adding green space but not when including NO_2 alone. In Model 5, considering the combined exposures, ALAN was positively associated with the PHQ-4 scores but only attained borderline significance (β = 0.007; 95% CI: −0.000; 0.013). ALAN was positively and significantly associated with sleep problem scores (Model 5) (β = 0.012; 95% CI: 0.006; 0.019). Given an E-value of 1.055 for PHQ-4 and 1.082 for sleep problems in Model 5, some residual confounding cannot be ruled out. The environmental exposures collectively explained a small proportion of the PHQ-4 scores (0.92%), with ALAN representing approximately 0.23% (Supplementary Fig. S6).

3.4. Sensitivity analyses

Most sensitivity analyses yielded similar results, suggesting the robustness of our primary results. ALAN estimates for the 100 m (β = 0.007; 95% CI: 0.001; 0.012) and 800 m buffer sizes (β = 0.003; 95% CI: −0.004; 0.011) were generally similar to those of the 500 m buffers (Fig. 2). Further adjusting Model 5 with 500 m buffers for population density attenuated the estimated ALAN association (β = 0.003; 95% CI: −0.004; 0.010), possibly due to an over-adjustment. We observed comparable and borderline significant ALAN associations using 500 m buffers when excluding those with extremely high ALAN annoyance ($N = 34$) (β = 0.007; 95% CI: 0.000; 0.014) and extremely high light sensitivity ($N = 118$) (β = 0.007; 95% CI: 0.000; 0.013). Stratifying by bedroom orientation rendered the associations insignificant and possibly lacking statistical power for busy/noisy streets ($N = 994$) (β = 0.004; 95% CI: −0.004; 0.011) and for quiet streets/inner courtyards ($N = 2,659$) (β = 0.005; 95% CI: −0.003; 0.013).

3.5. Effect modification by sex, age, and income

We did not observe effect modifications by sex, age, or income of the ALAN-PHQ-4 association for the 500 m buffers (Model 5) (Supplementary Table S8). The likelihood ratio test comparing Model 5 with and without an interaction term was null for income ($p = 0.328$), sex ($p = 0.280$), and age ($p = 0.488$). Likewise, model comparisons via AIC scores rendered stratified analyses unnecessary. Other buffer sizes yielded comparable results.

3.6. Mediating role of sleep problems

Fig. 3 and Supplementary Table S9 summarize the results of the mediation analyses based on Model 5. Assuming that the unverifiable mediation assumptions held, our results suggested that the ALAN-mental health association was largely mediated by sleep problems, regardless of the buffer size. The mediation of the 500 m buffers was 0.009 ($p = 0.000$), while the direct association of −0.002 was

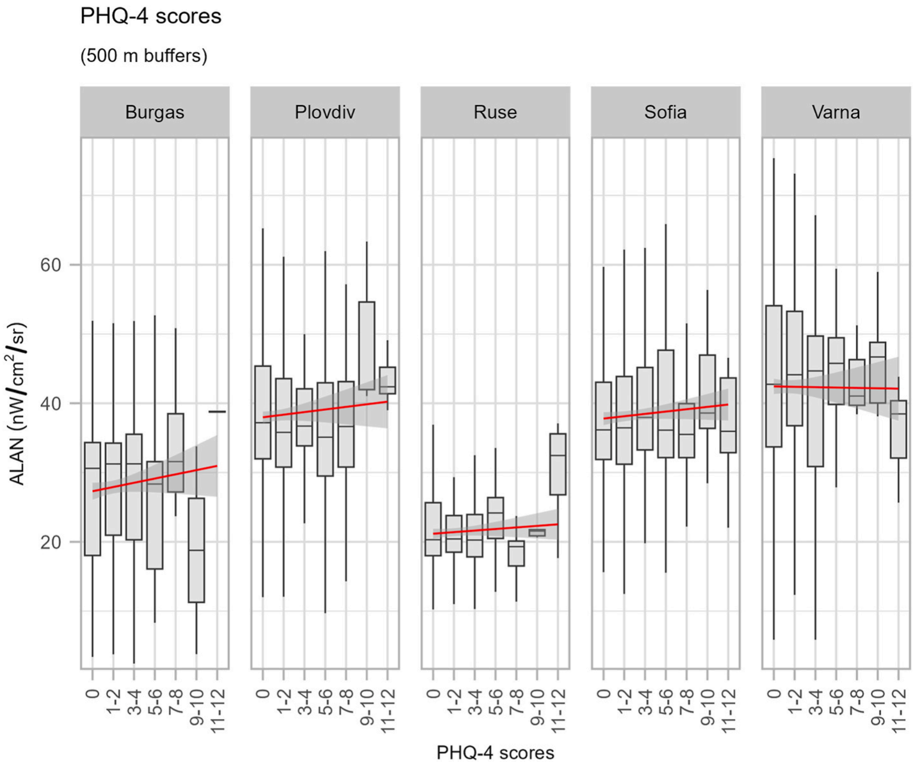

Fig. 1. Exposure to ALAN by PHQ-4 scores stratified by city. Boxplots are based on 500 m buffers. Regression lines and the 95% CIs are superimposed to illustrate the associations between ALAN and the PHQ-4 scores.

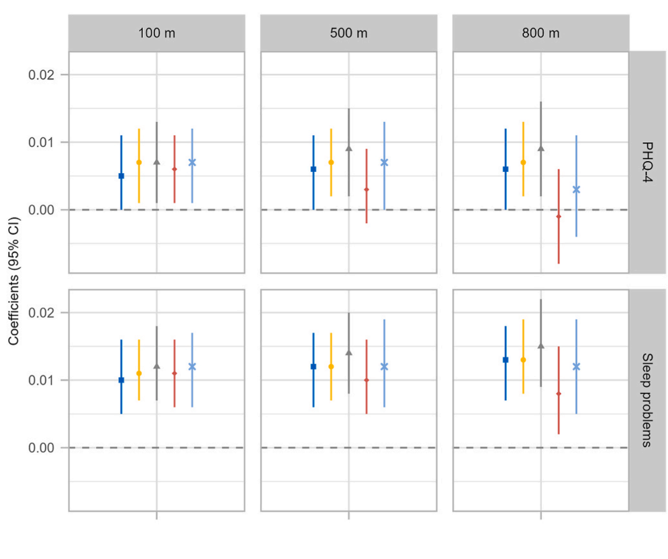

Fig. 2. Associations between outdoor ALAN at residential addresses and PHQ-4 scores and sleep problem scores using 100 m, 500 m, and 800 m buffers with 95% CIs. Model 1 included ALAN and city-specific regional dummies, Model 2 added person-level characteristics (i.e., age, sex, ethnicity, marital status, education, employment status, and income), in Model 3 adjustments for NO_2 were added, Model 4 replaced NO_2 with green space, and Model 5 was fully adjusted for person-level characteristics, NO_2, and green space.

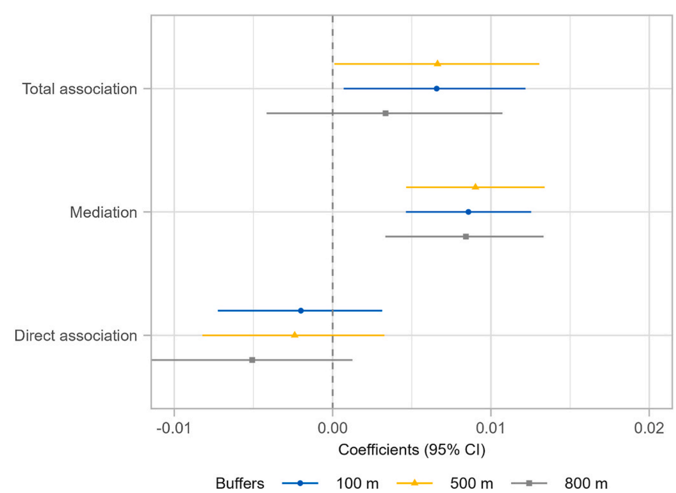

Fig. 3. Mediation of sleep problems on the ALAN-mental health association using 100 m, 500 m, and 800 m buffers. The outcome and mediation model were fully covariate-adjusted (Model 5).

statistically insignificant ($p = 0.416$). Considering both the direct and indirect associations, we observed a total ALAN association of 0.007 with borderline statistical significance ($p = 0.048$). Results for the 100 and 500 m buffers were roughly similar in contrast to the 800 m buffers, perhaps because ALAN exposure contrasts were attenuated over the 800 m buffers.

4. Discussion

4.1. Principal findings and available evidence

We advanced the limited state-of-the-art on nighttime light pollution by assessing how outdoor ALAN in the residential environment was associated with adults' mental health in the context of sleep problems in urban Bulgaria. Our findings suggested a potentially harmful association between greater ALAN exposure and increases in depressive and anxiety-related symptoms. This result is congruent with previous studies on indoor and outdoor ALAN exposure and mental health (Tancredi et al., 2022; Tongyu et al., 2023). For example, a study of 113,119 South Korean adults found that those living in more light-polluted areas were more prone to depressive symptoms (Min and Min, 2018). However, the Korean study used lower resolution DMSP-OLS ALAN data, possibly biasing the association as simulation experiments suggested, and assigned exposures at the district level, eliminating heterogeneity in light pollution (Levin et al., 2020). Moreover, the estimated ALAN associations were possibly overestimated as the hierarchical structure of the data was not addressed (McIsaac et al., 2021). Another ecological study employing VIIRS data conducted among 21,036 Chinese adults found that greater ALAN exposure was associated with poorer mental health, even after adjusting for fine particulate matter (Yu et al., 2022). Elsewhere (Helbich et al., 2020; Stanhope et al., 2021), criticism was directed at inadequate environmental co-exposure adjustments in some ALAN analyses (Min and Min, 2018; Paksarian et al., 2020). On adjusting for green space, we observed that ALAN risk estimates increased while adjusting for NO_2 attenuated the ALAN association. Such attenuation mirrored Dutch results in which positive associations between ALAN and depressive symptoms turned insignificant after considering greenness and fine particulate matter within 600 m residential buffers, though not for those of 100 m (Helbich et al., 2020).

Evidence of effect modification of the ALAN-mental health association is controversial. Our results did not support such effect modification; neither were low-incomers more susceptible to ALAN exposure nor were there sex or age inequalities. With results partially similar to ours, a UK study among 298,283 middle-aged and older adults reported that sex and education levels did not qualify as effect modifiers, although outdoor ALAN was related to increased risk for depression and anxiety disorders (Jin et al., 2023). By contrast, the strength of the associations varied across population strata, including sex, in a Chinese analysis (Yu et al., 2022). Given ongoing debates about disproportionate exposures of underprivileged populations to environmental threats (Mohai et al., 2009), these possible discrepancies warrant further investigation (Helbich et al., 2024).

Corroborating our results, other population-based studies analyzing sleep as an outcome are suggestive that increased ALAN exposure was associated with sleep-related issues (Xu et al., 2023; Zhong et al., 2022). For example, in a cross-sectional sample of 19,136 US adults, elevated ALAN levels were associated with an increased probability of reporting less than 6 h of sleep, which persisted after accounting for individual-level and other environmental exposures (Ohayon and Milesi, 2016). Similarly, findings from US adolescents also revealed that greater ALAN exposure was associated with later weeknight bedtimes and higher odds of mood and anxiety disorders (Paksarian et al., 2020), echoing estimates among middle-to-older aged males from six US states in which long sleep became cross-sectionally less likely with greater exposure to ALAN (Xiao et al., 2020). Based on this evidence, we assessed the possible mediating role of sleep on the ALAN-mental health association, as speculated elsewhere (Wang et al., 2023). Decomposing the positive total association revealed that the direct association between ALAN and mental health was almost null and statistically insignificant. By contrast, we found a notable positive mediation by sleep problems on mental health. Since Bulgaria's ALAN levels are lower than the European average (Falchi et al., 2019), the mental health associations may be more distinctive in areas with increased light pollution.

4.2. Possible biological mechanisms

The biological pathways underlying our observed associations remain uncertain and are not fully elucidated. Excessive exposure to nighttime light possibly misaligns the circadian rhythm (i.e., the 24-h sleep-wake cycle) in humans (Walker et al., 2020). Mood alterations and an increased risk of mental health disorders could be the consequence; however, our physiological responses depend on such factors as light spectrum values, exposure, and duration (Vetter et al., 2022; Zielinska-Dabkowska et al., 2023).

An alternate pathway might be via the disruption of melatonin secretion. Exposure to excessive nighttime light and potentially specific wavelengths (e.g., blue light) may suppress nocturnal melatonin production, a sleep-regulating hormone that appears to be associated with mood regulation. Reduced melatonin levels can contribute to sleep disturbances (e.g., shortage of sleep time and impaired sleep quality) (Bedrosian and Nelson, 2017). In turn, chronic sleep disturbances have been related to exacerbated changes in mood and an increased risk of mental disorders (Tsuno et al., 2005).

4.3. Strengths and limitations

Our study is among the few examining ALAN-mental health associations and a first in Eastern Europe. Unlike earlier studies that relied on lower resolution nighttime illuminance data (Min and Min, 2018; Paksarian et al., 2020; Xiao et al., 2020), ours took advantage of VIIRS imagery with enhanced resolution, also allowing avoidance of saturation effects in brightly illuminated areas (Levin et al., 2020). Another strength was using residential addresses to assign the exposures rather than administrative units, as done previously (Min and Min, 2018), making exposure misclassification less likely. However, despite rigorously examining different buffer sizes, we cannot exclude the possibility that the buffers chosen do not deflate the estimated associations (Tian et al., 2024). Eschewing self-administered questionnaires, our survey capitalized on direct questioning by trained interviewers. Such direct questioning mitigated non-responses.

Although setting new frontiers, some limitations are acknowledged. The assumption that outdoor light penetrates indoors, a premise questioned elsewhere, could also have introduced exposure measurement errors (Huss et al., 2019). Furthermore, the current generation of earth observation satellites cannot detect blue light emitted from LED lighting (Kocifaj et al., 2023), possibly causing an underestimation of people's actual ALAN exposure. Albeit applicable to other studies (Helbich et al., 2020), VIIRS data lacked sufficient resolution to resolve small-scale variations in nighttime light (Levin et al., 2020). High-resolution (~1 m) nighttime light images from the Jilin-1 satellite will become a feasible alternative as coverage increases (Cheng et al., 2020). Another consideration is the temporal misalignment between the survey and ALAN data, possibly weakening the estimated associations; however, a one-year mismatch likely represents only a negligible discrepancy. For comparative purposes with previous Bulgarian studies (Dzhambov et al., 2023), we employed a three-item measure of sleep problems. Nevertheless, to encompass various dimensions of sleep quality and disturbances, other instruments might be more appropriate (e.g., the Pittsburgh Sleep Quality Index) (Buysse et al., 1989). Despite our efforts at confounder adjustment, it was unlikely that we eliminated residual confounding. Other non-measured factors could have also influenced our findings. For example, although NO_2 may correlate better with ALAN than fine particulate matter (Helbich et al., 2020), we cannot exclude some confounding. However, exposure data on fine particulate matter were not available across the cities. As is the case for most cross-sectional ALAN studies (Tancredi et al., 2022), results preclude inference on the causality of the presented associations and are vulnerable to reverse causality, especially the mediation pathway. We assumed that poor sleep worsens mental health, but the opposite is also conceivable. Finally, the reliance on cross-sectional data limited our ability to establish causalities.

5. Conclusions

Our multi-city study provided novel evidence that higher levels of nighttime light pollution in the residential environment were associated with increased symptoms of depression, anxiety, and sleep problems. Nighttime light exposure may affect the sleep disturbance pathway while appearing not to affect mental health directly. Given the continuing rise in light pollution levels and the ongoing changes in their spectral composition, our findings emphasize the importance of policies targeting nighttime lighting mitigation. In light of the European Union's Environment Action Programme 2030 goal of zero pollution (European Commission, 2024), our analyses contribute a timely assessment of how light pollution may interfere with mental health. Our findings warrant longitudinal replication as our tentative results support the notion that ALAN exposure is a mental health and behavioral risk factor.

Funding

The research leading to this work was supported by the "Strategic research and innovation program for the development of Medical University – Plovdiv" No. BG-RRP-2.004-0007-C01, Establishment of a network of research higher schools, National plan for recovery and resilience, financed by the European Union – NextGenerationEU. The funder did not influence the study design, data collection and analysis, interpretation, or article drafting. All authors had data access. The first and last authors were responsible for submitting the article for publication.

Declaration of generative AI in scientific writing

No generative AI and AI-assisted technologies were used during the preparation of this work.

CRediT authorship contribution statement

Marco Helbich: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Angel Burov:** Writing – review & editing, Data curation. **Donka Dimitrova:** Writing – review & editing, Data curation. **Iana Markevych:** Writing – review & editing, Data curation. **Mark J. Nieuwenhuijsen:** Writing – review & editing, Data curation. **Angel M. Dzhambov:** Writing – review & editing, Project administration, Funding acquisition, Data curation.

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.

Data availability

The exposure data presented in this study can be made available to researchers upon reasonable request directed to the corresponding author. The survey data used in our study cannot be made publicly available due to ethical and privacy reasons. Survey data requests can be sent to the last author.

Acknowledgments

We thank the survey participants whose contributions made this study possible. We also express our gratitude to the reviewers for their constructive comments that have enhanced the quality of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.119897.

References

An, K., Zhao, H., Miao, Y., Xu, Q., Li, Y.-F., Ma, Y.-Q., Shi, Y.-M., Shen, J.-W., Meng, J.-J., Yao, Y.-G., others, 2020. A circadian rhythm-gated subcortical pathway for nighttime-light-induced depressive-like behaviors in mice. Nat. Neurosci. 23 (7), 869–880.

Barboza, E.P., Cirach, M., Khomenko, S., Iungman, T., Mueller, N., Barrera-Gómez, J., Rojas-Rueda, D., Kondo, M., Nieuwenhuijsen, M., 2021. Green space and mortality in European cities: a health impact assessment study. Lancet Planet. Health 5 (10), e718–e730.

Bedrosian, T.A., Nelson, R.J., 2017. Timing of light exposure affects mood and brain circuits. Transl. Psychiatry 7 (1), e1017.

Borniger, J.C., McHenry, Z.D., Abi Salloum, B.A., Nelson, R.J., 2014. Exposure to dim light at night during early development increases adult anxiety-like responses. Physiol. Behav. 133, 99–106.

Burns, A.C., Windred, D.P., Rutter, M.K., Olivier, P., Vetter, C., Saxena, R., Lane, J.M., Phillips, A.J.K., Cain, S.W., 2023. Day and night light exposure are associated with psychiatric disorders: an objective light study in> 85,000 people. Nature Mental Health 1 (11), 853–862.

Buysse, D.J., Reynolds III, C.F., Monk, T.H., Berman, S.R., Kupfer, D.J., 1989. The Pittsburgh Sleep Quality Index: a new instrument for psychiatric practice and research. Psychiatr. Res. 28 (2), 193–213.

Cheng, B., Chen, Z., Yu, B., Li, Q., Wang, C., Li, B., Wu, B., Li, Y., Wu, J., 2020. Automated extraction of street lights from JL1-3B nighttime light data and assessment of their solar energy potential. IEEE J. Sel. Top. Appl. Earth Obs. Rem. Sens. 13, 675–684.

Copernicus, 2024. Urban atlas 2018. https://Land.Copernicus.Eu/En/Products/Urban-Atlas.

Craney, T.A., Surles, J.G., 2002. Model-dependent variance inflation factor cutoff values. Qual. Eng. 14 (3), 391–403.

Dzhambov, A.M., Dimitrova, V., Germanova, N., Burov, A., Brezov, D., Hlebarov, I., Dimitrova, R., 2023. Joint associations and pathways from greenspace, traffic-related air pollution, and noise to poor self-rated general health: a population-based study in Sofia, Bulgaria. Environ. Res. 231, 116087.

Dzhambov, A.M., Lercher, P., Botteldooren, D., 2024. Childhood sound disturbance and sleep problems in Alpine valleys with high levels of traffic exposures and greenspace. Environ. Res. 242, 117642.

Elvidge, C.D., Baugh, K., Zhizhin, M., Hsu, F.C., Ghosh, T., 2017. VIIRS night-time lights. Int. J. Rem. Sens. 38 (21), 5860–5879.

European Commission, 2024. Environment Action Programme to 2030.

Falchi, F., Cinzano, P., Duriscoe, D., Kyba, C.C.M., Elvidge, C.D., Baugh, K., Portnov, B.A., Rybnikova, N.A., Furgoni, R., 2016. The new world atlas of artificial night sky brightness. Sci. Adv. 2 (6), e1600377.

Falchi, F., Furgoni, R., Gallaway, T.A., Rybnikova, N.A., Portnov, B.A., Baugh, K., Cinzano, P., Elvidge, C.D., 2019. Light pollution in USA and Europe: the good, the bad and the ugly. J. Environ. Manag. 248, 109227.

Fonken, L.K., Nelson, R.J., 2013. Dim light at night increases depressive-like responses in male C3H/HeNHsd mice. Behav. Brain Res. 243, 74–78.

Gao, X., Jiang, M., Huang, N., Guo, X., Huang, T., 2023. Long-term air pollution, genetic susceptibility, and the risk of depression and anxiety: a prospective study in the UK Biobank cohort. Environ. Health Perspect. 131 (1), 17002.

Gaston, K.J., de Miguel, A., 2022. Environmental impacts of artificial light at night. Annu. Rev. Environ. Resour. 47, 373–398.

GBD 2019 Mental Disorders Collaborators, 2022. Global, regional, and national burden of 12 mental disorders in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. Lancet Psychiatr. 9 (2), 137–150.

Grömping, U., 2007. Relative importance for linear regression in R: the package relaimpo. J. Stat. Software 17, 1–27.

Helbich, M., Browning, M.H.E.M., Huss, A., 2020. Outdoor light at night, air pollution and depressive symptoms: a cross-sectional study in The Netherlands. Sci. Total Environ. 744, 140914.

Helbich, M., Burov, A., Dimitrova, D., Markevych, I., Nieuwenhuijsen, M., Dzhambov, A., 2024. Sociodemographic inequalities in residential nighttime light pollution in urban Bulgaria: an environmental justice analysis. Environ. Res. 262, 119803.

Huss, A., van Wel, L., Bogaards, L., Vrijkotte, T., Wolf, L., Hoek, G., Vermeulen, R., 2019. Shedding some light in the dark—a comparison of personal measurements with satellite-based estimates of exposure to light at night among children in The Netherlands. Environ. Health Perspect. 127 (6), 67001.

Imai, K., Keele, L., Tingley, D., 2010. A general approach to causal mediation analysis. Psychol. Methods 15 (4), 309.

Jin, J., Han, W., Yang, T., Xu, Z., Zhang, J., Cao, R., Wang, Y., Wang, J., Hu, X., Gu, T., others, 2023. Artificial light at night, MRI-based measures of brain iron deposition and incidence of multiple mental disorders. Sci. Total Environ. 902, 166004.

Kocifaj, M., Wallner, S., Barentine, J.C., 2023. Measuring and monitoring light pollution: current approaches and challenges. Science 380 (6650), 1121–1124.

Kroenke, K., Spitzer, R.L., Williams, J.B.W., Löwe, B., 2009. An ultra-brief screening scale for anxiety and depression: the PHQ–4. Psychosomatics 50 (6), 613–621.

Kyba, C.C.M., Altıntaş, Y.Ö., Walker, C.E., Newhouse, M., 2023. Citizen scientists report global rapid reductions in the visibility of stars from 2011 to 2022. Science 379 (6629), 265–268.

Larkin, A., Anenberg, S., Goldberg, D.L., Mohegh, A., Brauer, M., Hystad, P., 2023. A global spatial-temporal land use regression model for nitrogen dioxide air pollution. Front. Environ. Sci. 11, 1125979.

LeGates, T.A., Altimus, C.M., Wang, H., Lee, H.-K., Yang, S., Zhao, H., Kirkwood, A., Weber, E.T., Hattar, S., 2012. Aberrant light directly impairs mood and learning through melanopsin-expressing neurons. Nature 491 (7425), 594.

Levin, N., Kyba, C.C.M., Zhang, Q., de Miguel, A.S., Román, M.O., Li, X., Portnov, B.A., Molthan, A.L., Jechow, A., Miller, S.D., others, 2020. Remote sensing of night lights: a review and an outlook for the future. Rem. Sens. Environ. 237, 111443.

Löwe, B., Wahl, I., Rose, M., Spitzer, C., Glaesmer, H., Wingenfeld, K., Schneider, A., Brähler, E., 2010. A 4-item measure of depression and anxiety: validation and standardization of the Patient Health Questionnaire-4 (PHQ-4) in the general population. J. Affect. Disord. 122 (1–2), 86–95.

McIsaac, M.A., Sanders, E., Kuester, T., Aronson, K.J., Kyba, C.C.M., 2021. The impact of image resolution on power, bias, and confounding: a simulation study of ambient light at night exposure. Environ. Epidemiol. 5 (2).

Miller, S.D., Mills, S.P., Elvidge, C.D., Lindsey, D.T., Lee, T.F., Hawkins, J.D., 2012. Suomi satellite brings to light a unique frontier of nighttime environmental sensing capabilities. Proc. Natl. Acad. Sci. USA 109 (39), 15706–15711.

Min, J., Min, K., 2018. Outdoor light at night and the prevalence of depressive symptoms and suicidal behaviors: a cross-sectional study in a nationally representative sample of Korean adults. J. Affect. Disord. 227, 199–205.

Mohai, P., Pellow, D., Roberts, J.T., 2009. Environmental justice. Annu. Rev. Environ. Resour. 34, 405–430.

OECD, 2023. Bulgaria: Country Health Profile 2023, State of Health in the EU.

Ohayon, M.M., Milesi, C., 2016. Artificial outdoor nighttime lights associate with altered sleep behavior in the American general population. Sleep 39 (6), 1311–1320.

Paksarian, D., Rudolph, K.E., Stapp, E.K., Dunster, G.P., He, J., Mennitt, D., Hattar, S., Casey, J.A., James, P., Merikangas, K.R., 2020. Association of outdoor artificial light at night with mental disorders and sleep patterns among US adolescents. JAMA Psychiatr. 77 (12), 1266–1275.

R Core Team, 2024. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Stanhope, J., Liddicoat, C., Weinstein, P., 2021. Outdoor artificial light at night: a forgotten factor in green space and health research. Environ. Res. 197, 111012.

Stark, H., Brown, S.S., Wong, K.W., Stutz, J., Elvidge, C.D., Pollack, I.B., Ryerson, T.B., Dube, W.P., Wagner, N.L., Parrish, D.D., 2011. City lights and urban air. Nat. Geosci. 4 (11), 730–731.

Tancredi, S., Urbano, T., Vinceti, M., Filippini, T., 2022. Artificial light at night and risk of mental disorders: a systematic review. Sci. Total Environ. 833, 155185.

Textor, J., der Zander, B., Gilthorpe, M.S., Liśkiewicz, M., Ellison, G.T.H., 2016. Robust causal inference using directed acyclic graphs: the R package 'dagitty.'. Int. J. Epidemiol. 45 (6), 1887–1894.

Tian, T., Kwan, M.-P., Vermeulen, R., Helbich, M., 2024. Geographic uncertainties in external exposome studies: a multi-scale approach to reduce exposure misclassification. Sci. Total Environ. 906, 167637.

Tingley, D., Yamamoto, T., Hirose, K., Keele, L., Imai, K., 2014. Mediation: R package for causal mediation analysis. J. Stat. Software 59 (5), 1–38.

Tongyu, W., Kaida, N., Kaida, K., 2023. Effects of outdoor artificial light at night on human health and behavior: a literature review. Environ. Pollut., 121321

Tsuno, N., Besset, A., Ritchie, K., others, 2005. Sleep and depression. J. Clin. Psychiatr. 66 (10), 1254–1269.

VanderWeele, T.J., Ding, P., 2017. Sensitivity analysis in observational research: introducing the E-value. Ann. Intern. Med. 167 (4), 268–274.

Vetter, C., Pattison, P.M., Houser, K., Herf, M., Phillips, A.J.K., Wright, K.P., Skene, D.J., Brainard, G.C., Boivin, D.B., Glickman, G., 2022. A review of human physiological responses to light: implications for the development of integrative lighting solutions. Leukos 18 (3), 387–414.

Von Elm, E., Altman, D.G., Egger, M., Pocock, S.J., Gøtzsche, P.C., Vandenbroucke, J.P., 2007. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. Lancet 370 (9596), 1453–1457.

Walker, W.H., Walton, J.C., DeVries, A.C., Nelson, R.J., 2020. Circadian rhythm disruption and mental health. Transl. Psychiatry 10 (1), 28.

Wang, T., Kaida, N., Kaida, K., 2023. Effects of outdoor artificial light at night on human health and behavior: a literature review. Environ. Pollut. 323, 121321.

Xiao, Q., Gee, G., Jones, R.R., Jia, P., James, P., Hale, L., 2020. Cross-sectional association between outdoor artificial light at night and sleep duration in middle-to-older aged adults: the NIH-AARP Diet and Health Study. Environ. Res. 180, 108823.

Xu, Y.-X., Zhang, J.-H., Tao, F.-B., Sun, Y., 2023. Association between exposure to light at night (LAN) and sleep problems: a systematic review and meta-analysis of observational studies. Sci. Total Environ. 857, 159303.

Yu, Z., Hu, N., Du, Y., Wang, H., Pu, L., Zhang, X., Pan, D., He, X., Li, J., 2022. Association of outdoor artificial light at night with mental health among China adults: a prospective ecology study. Environ. Sci. Pollut. Control Ser. 29 (54), 82286–82296.

Zhong, C., Longcore, T., Benbow, J., Chung, N.T., Chau, K., Wang, S.S., Lacey Jr, J.V., Franklin, M., 2022. Environmental influences on sleep in the California teachers study cohort. Am. J. Epidemiol. 191 (9), 1532–1539.

Zielinska-Dabkowska, K.M., Schernhammer, E.S., Hanifin, J.P., Brainard, G.C., 2023. Reducing nighttime light exposure in the urban environment to benefit human health and society. Science 380 (6650), 1130–1135.