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Research article

Association of perceptions of artificial light-at-night, light-emitting device usage and environmental noise appraisal with psychological distress, sleep quality and chronotype: A cross sectional study

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ABSTRACT

Exposure to artificial light-at-night (ALAN) is increasing globally, and there are concerns around how ALAN may impact sleep, psychological and physical health. However, there is a lack of evidence in the literature on how individuals perceive ALAN relative to their sleeping environment and habits, and how such perceptions correspond to objectively assessed night-time illuminance at the level of the residence. This cross-sectional study examined how such perceptions associate with sleep quality, sleep timing, psychological distress and cognitive failures. Further we examined the association between illuminance levels calculated as the biologically-relevant melatonin-suppression index (MSI) and the self-report of perception of ALAN. Five hundred and fifty two adult participants completed a survey addressing perception of ALAN in sleep environment along with the Pittsburgh Sleep Quality Index, Munich Chronotype Questionnaire, Cognitive Failure Questionnaire and the General Health Questionnaire. We report that perception of external ALAN in the sleeping environment was associated with poorer sleep quality, more cognitive failures and greater psychological distress, when controlling for age, sex, house location and MSI. No associations were found between the perception of external ALAN and MSI scores, and MSI scores were not associated with scores on any of the self-report measures. Internal lighting passing into the sleeping environment was associated with poorer sleep quality but not with psychological wellbeing. Habitual use of light-emitting devices was associated with poorer psychological wellbeing but not with sleep quality and sleep timing. Perception of environmental noise annoyance at night was associated with higher psychological distress and poorer quality sleep, and the perception of noise annoyance was associated with perception of ALAN. These results may suggest heightened attentional bias towards ALAN associated with poor sleep quality and higher levels of psychological distress, and highlight the need for more granular approaches in the study of ALAN and sleep and psychological health in terms of levels individual ALAN exposure, and an interpretation that seeks to integrate biological and psychological perspectives.

1. Introduction

Exposure to artificial light-at-night (ALAN) has become part of everyday life, with individuals routinely exposed to ALAN through the use of electronic devices, indoor electric lighting and environmental light pollution (Falchi et al., 2016). Whilst ALAN brings many societal benefits such as extending the length of productive days and recreational activities (Fonken and Nelson, 2011), ALAN may also disrupt both the internal biological circadian clock and sleep by artificially extending the biological day leading to desynchrony of the circadian timing system and impaired sleep (Zeitzer et al., 2000). Such effects may contribute to a number of adverse health outcomes at a metabolic (Park et al., 2019), psychiatric (Wulff et al., 2010) and neurological level (Musiek and Holtzman, 2016), as well as potentially elevating the risk of some hormone-dependent cancers (Davis, Mirick & Stevens, 2001). Circadian rhythms are the product of endogenous oscillators which are responsible for the regulation of our physiology and behaviour with a near 24-h period (Dijk and von Schantz, 2005). The core pacemaker is located in the suprachiasmatic nucleus (SCN) of the hypothalamus and is entrained to the 24-h day, with light being the major synchronising cue (Hughes et al., 2015). The primary neural mechanism of such photic entrainment is via a pathway involving intrinsically photosensitive retinal ganglion

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cells which direct neural projections to the SCN allowing for non-visual synchronisation of circadian rhythms to cycles in environmental light (Hughes et al., 2015).

Through industrialisation and modernisation the natural pattern of light and dark has been altered by the lengthening of the period of daily light exposure resulting from man-made lighting (Lunn et al., 2017). Exposure to ALAN at sufficient intensity, duration, wavelength and timing impacts on the circadian timing system (Gooley et al., 2003; Cajochen et al., 2000; 2005; Lockley et al., 2006). ALAN may also suppress the sleep-promoting hormone melatonin (Gooley et al., 2011) and alter the expression of the molecular components of the circadian clockworks in the SCN (Bedrosian and Nelson, 2017). Through the advancement of technology, individuals may now be routinely exposed to low level ALAN in their sleeping environments through the use of computer screens, tablets and smartphones which emit short wavelength visible light to which the circadian clock is most sensitive (Hughes et al., 2015). Dim light at night (dLAN) emitted from may increase both alertness and heart rate and a reduced propensity to sleep (Cajochen et al., 2005) and alter clock gene expression (Cajochen et al., 2016).

Bedroom lights left on during sleep is associated with more shallow sleep, frequent arousals and negative impacts on brain oscillations essential to sleep depth and stability (Cho et al., 2013). dLAN exposure during sleep has been reported in increased number of awakenings, shallow sleep (Cho et al., 2016), poorer sleep quality and increased risk of insomnia in older adults (Obeyashi, Saeki & Kurumatani, 2014). Observational and longitudinal studies in older adults have found ALAN exposure in sleeping environments is associated with greater risk of depression (Obeyashi, Saeki, Iwamoto, Ikada & Kurumatani, 2013; Obeyashi, Saeki & Kurumatani, 2018). Similar findings have also been reported from animal studies, with ALAN perturbing circadian rhythms (Stenvers et al., 2016; Panagiotou et al., 2020) and associating with depressive-like behaviour (Bedrosian et al., 2014; Borniger et al., 2014; although such findings are not ubiquitous and may vary according to the animal model (Cleary-Gaffney and Coogan, 2018)).

Outdoor street lighting is common in industrialised countries, with outdoor ALAN increasing annually by 5–10% (Hölker et al., 2010) resulting in around 80% of USA citizens living in areas where the natural appearance of the night sky cannot be observed, and up to 40% living in areas where night adaptation of human eyes is inhibited by light (Falchi et al., 2016). The recommended mean lighting level along residential roads has surface illuminance levels of 2–15 lux, with lighting levels along busier routes or in city centres being higher (BSI, 2015). However, lighting from other sources such as private dwelling and commercial outdoor lighting may result in the maximum permitted level being exceeded in urban settings. Such light may also trespass into individual's sleeping environments, particularly in urban environments where there is closer proximity between public lighting and house windows both in horizontal and vertical alignment. A number of studies have associated outdoor ALAN with poorer sleep quality, reduced night time sleep, and delays in both bedtime and waking-up time (Koo et al., 2016; Ohayon and Milesi, 2016). Living in areas with high outdoor light may result in greater risk of depressive symptoms and suicidal behaviours in adults (Min and Min, 2018) and increased risk of mood and anxiety disorders in adolescents (Paksarian et al., 2020). In addition, individuals over 60 years old living in areas with high external ALAN had greater hypnotic medication use (Ohayon and Milesi, 2016).

There are a number of important limitations in the current literature relating ALAN to real-world effects. Although previous studies in older adults have indicated negative associations between indoor ALAN and sleep, physical and psychological health, the results of these studies may not be generalizable to the general population as around 40% of older adults would be expected to report insomnia symptoms such as delayed sleep onset and difficulty maintaining sleep (Calem et al., 2010; Walsh et al., 2011), and as such the additional impact of ALAN on top of normal age-related changes in sleep and circadian function is not clear. Another important limitation is the level at which ALAN is assessed; ecological studies have provided evidence that high levels of outdoor LAN measured via satellite data are associated with sleep disturbances, poor sleep quality and poor psychological well-being (Paksarian et al., 2020; Xiao et al., 2020). Because of the use of low-resolution external estimates of ALAN, these studies potentially under- or overestimate personal experience of ALAN in the sleeping environment. Evidence for this emerges from studies which suggests there is a lack of association between external ALAN and the ALAN measured in the bedroom (Huss et al., 2019; Rea et al., 2011) and the subjective perception of external ALAN and satellite measurements of ALAN (Garcia-Saenz et al., 2018); as such, it is unclear whether outdoor ALAN directly impacts sleep and general psychological well-being. Another caveat for the use of satellite image data is that it provides an average light intensity of a region and may not reflect the true nature of individuals' ALAN exposure; as an example, Katz and Levin (2016) found only a low to moderate correlation between ALAN measured at ground level and satellite measured ALAN.

No studies to date have investigated how the *perception* of ALAN exposure is associated with sleep and psychological well-being. The current study aims to examine how individuals perceive ALAN exposure in their sleeping environment, how subjective perceptions of ALAN correlate with estimates of outdoor illuminance due to public lighting at the level of individual residences, and how subjective perceptions of ALAN as well as objectively-measured household illuminance levels associate with measures of psychological distress, cognitive failures, sleep duration quality and chronotype. Our *a priori* hypotheses were: 1) That the perception of ALAN trespassing into the sleeping environment will associate with poorer sleep quality, delayed circadian timing, and higher levels of psychological distress; 2) The self-reported use of light-emitting technology at night will associate with poorer sleep quality and more psychological distress; and 3) There will be an association between objective measure of external lighting and subjective perception of external lighting.

2. Methods

2.1. Participants

Recruitment of participants was through a mixture of snowball and convenience sampling via flyers, emails, personal contacts and tradeshows. A total of 552 of participants in Ireland completed the questionnaires. Participation was not limited to any particular geographical region within Ireland, although the majority of respondents were resident in Leinster, the province that includes Dublin and its metropolitan region. Data were collected between March 2017 and June 2019. Both pencil and paper and online versions of the questionnaires were used. The inclusion criteria were that participants were aged 18 years and above who were not current shift workers. All participants gave their electronic informed consent before participating in this study and were informed that all data collected would be stored anonymously and participation was voluntary and unpaid. Ethical approval was obtained from Maynooth University Research Ethics Committee.

2.2. Questionnaires

Participants provided demographic information, including age gender, location of house (city, suburb, town, semi-rural, rural), type of residence (detached house, semi-detached house, bungalow, apartment) the exact GPS of the residence (expressed as the Irish Eircode, a residence-specific geolocation identifier), and whether the respondent's bedroom located at the front or back of their premises.

Light at Night Questionnaire: we developed a questionnaire asking about perceptions of ALAN, its potential sources, and its perceived impact on sleep (questionnaire detailed in Supplementary Materials Table 1). The nature of most response items were dichotomous (yes/no), and as such the questionnaire generated categorical data. Specifically, there were items relating to the perception of whether outside ALAN

Table 1. Key demographics of the responding sample.

Variable	N	Valid Percentage
Gender		
Male	175	31.7%
Female	366	66.3%
Prefer not to say	11	2%
Location of residence		
City	115	20.8%
Suburb	134	24.3%
Town	139	25.2%
Semi-Rural	60	11.8%
Rural Environment	99	17.9%
Bedroom Location		
Front of premises	152	28.7%
Back of premises	131	24.8%
Residence type		
Detached house	73	13.2%
Semi-detached house	94	17%
Terraced house	45	8.2%
Apartment	68	12.3%
Bungalow	29	5.3%

enters the bedroom at night, if outside ALAN impacts on sleep, whether there are indoor sources of ALAN that enter the bedroom at night and whether such ALAN impacts on sleep, a question rating the brightness of bedroom with no bedroom lighting, and questions pertaining to electronic device usage in the run-up to, and after, sleep onset and the perceived impacts of device usage on sleep. Furthermore, there were questions relating to noise pollution, asking whether noise pollution at night is a nuisance in the bedroom and whether it impacts on sleep.

Pittsburgh Sleep Quality Index (PSQI; Buysse et al., 1989). The PSQI is a retrospective self-report questionnaire on sleep quality over the previous 4 weeks. It is a 19 item measure which is divided into 7 domains called component scores (subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleep medications and daytime dysfunction). Each component score ranges from 0 (no difficulty) to 3 (severe difficulty) and is summed to produce a global score which ranges from 0 to 21. Scores of 5 and above categorise poor sleep quality. In our study, the Cronbach's alpha for the PSQI was 0.73.

Munich Chronotype Questionnaire (MCTQ; Roenneberg et al., 2003) is a self-report measure which investigates sleep–wake behaviour by asking participants to indicate their sleep and wake times on both "work" and "free" days resulting in the calculation of the mid-point of sleep on each of these types of days. The average sleep duration over the course of a week was calculated using a formula which weighted the amount of self-reported sleep on "work" and "free" days (Roenneberg et al., 2012). Mid-sleep on free days (the midpoint between sleep onset and wake time), corrected for sleep debt accumulated during the week and provided a measure of chronotype as sleep timing without social constraint provides an indication of the underlying phase of circadian entrainment (MSFsc) (Roenneberg et al., 2003)]. Social Jetlag (SJL) was measured by subtracting mid-sleep on workdays from mid-sleep on free days and presenting this as an absolute value (Wittmann et al., 2006). The numbers of work and free days were also assessed through this instrument, as was whether there was any meaningful distinction between "work" and "free" days for the participant.

Cognitive Failures Questionnaire (CFQ; Broadbent et al., 1982) is a 25-item self-report instrument which assesses the frequency of everyday slips and errors an individual has in the domains of memory, perception, and motor function. Scores for the CFQ can range from 0 to 100 with the total CFQ score being simply the sum of all the individual responses on for the 25 items. In our study, the Cronbach's alpha for the CFQ was 0.91.

General Health Questionnaire (GHQ; Goldberg, 1978) is 28-item self-report questionnaire which assesses how participants rate their general psychological health over the past weeks. The questionnaire is divided into four specific subscales which are somatic symptoms, anxiety/insomnia, social dysfunction and severe depression. Global scores range from 0-84 with higher scores indicate greater levels of psychological distress. In our study, the Cronbach's alpha for the GHQ was 0.94.

2.3. Address geocoding and residence-level melatonin suppression index

Each participant provided their Eircode; unlike postcodes in other jurisdictions which define clusters of residences, an Eircode is specifically unique and assigned to each residential address. After Eircodes were collated each address was geocoded to the corresponding geographic position using the Google Geocoding API service through Python. A randomly-selected subsample was used to verify the positions by comparing our derived locations with those obtained using Google Earth's location based solely on the of the address location and, additionally, using the Eircode map positions.

2.4. Melatonin suppression index (MSI)

The contribution of street lighting to sleep disruption was calculated using the Melatonin Suppression Index (MSI) for a range of lamp types as discussed in Aubé et al. (2013). MSI provides an estimate of the potential impact of each lamp type on humans based on its blue content and is normalised such that the spectrum of daylight–represented by the International Commission of Illumination (CIE) illuminant D65–has a value of unity. On this scale, low pressure sodium light has a MSI of 0.017, while LED white light with a colour temperature of 4000 K has a MSI of 0.465.

2.5. Application to individual addresses

The methodology in generating these values was as follows:

1. For each location, a list of the public lights within one km of the residence was generated, ranked in increasing distance. This list was generated using inventories of public lighting from public authorities (county councils) which included precise location of such lighting and the lamp specifications.
2. The expected illuminance at each residence's location was calculated by scaling the wattage by the typical lumens/watt for that lamp type, and weighted by the inverse distance between the lantern and the residence;
3. The estimated human health impact of the light was estimated by multiplying by the Melatonin Suppression Index (MSI) for each lamp type (Aubé et al., 2013).
4. The impact for each streetlight was calculated, and stopped including further lights when the additional contribution to the cumulative total is smaller than the selected cut-off or no further lights are available within the 1 km limit.

2.6. Code output

For each location a series of metrics were produced by the software: the total lux at the nominal location; the summed light weighted in terms of both lux and MSI value; similar values for those sources closer than 30m, and the distance to the nearest public light, irrespective of spectrum or light output. Missing data were recorded for 23% (N = 127) of the sample, due to either incorrect Eircode, an address provided which was outside a jurisdiction, incomplete data and, in a small number of cases, no data being available.

2.7. Statistical analyses

For statistical analysis of time-based variables from the MCTQ (MSFsc, average sleep duration and SJL) were decimalised (i.e. 6:30 become 6.5, 45 min became 0.75). Data was assessed for normality via Kolmogarov-Smirnov tests, and all variables to be treated as dependent variables were found to be not normally distributed, and non-parametric inferential testing was employed for initial unadjusted analysis (Mann-Whitney U and Kruskall-Wallis tests), Chi Square tests for independence were employed on to investigate associations between categorical variables. When bivariate unadjusted analysis revealed statistically significant results, associations were retested using ANCOVA adjusting for the relevant covariates of age, sex, house location MSI. For this analysis the variables of CFQ, GHB and MSI scores were log-transformed and age and PSQI were centred, and partial eta-squared statistics were reported as indicators of effect sizes.

The study sample size was estimated using a-priori power calculations based on it being important to detect effect sizes of moderate size (d = 0.5) with anticipated variance in dependent variables based on standard deviations from previous studies in our group in similar populations with the psychometric instruments used; these calculations indicated a required study sample of approximately 500 would be required to detect differences of a likely-to-be-meaningful magnitude. All statistical analysis was conducted using IBM SPSS (V25, IBM Corporation) or JASP (V 0.9.1.0, https://jasp-stats.org/).

3. Results

3.1. Demographics of the study sample

Key demographic features of the study sample are presented in Table 1. The mean age of respondents was 36.7 years. There were significantly more female than male respondents (66% vs 32%) and a reasonably even distribution of residence location across cities, suburbs, towns, semi-rural and rural locales. Most respondents reported living in a house of some type, with only 12% of respondents reporting living in an apartment. The mean, median and standard deviation scores for the chronometric and psychometric data is presented in Table 2.

3.2. Perceptions of ALAN and sleep and psychological health indicators

42.2% of respondents reported that external lighting entered into their sleeping environment during sleep. Compared to those who did not perceive external ALAN entering into the sleeping environment, respondents who perceived outdoor ALAN entering into the sleeping environment had poorer sleep quality (median PSQI total score 7, 95% CI [6; 7] vs 6, 95% CI [5; 6], P = 0.002, r = .11), more cognitive failures (median CFQ total 37, 95% CI [34; 40] vs 33, 95% CI [31.51; 35], P = 0.001, r = −.15) and higher GHQ scores (median GHQ total 25, 95% CI [22; 27] vs 18, 95% CI [17; 20], P = 0.001, r = −0.18, Figure 1). When adjusting these associations for the potential confounders of age, sex, house location and MSI at residence level, the perception of external ALAN was associated with higher GHQ score (F (1, 336) = 14.2, P < 0.001, partial eta squared = 0.043), higher PSQI scores ((F (1, 336) = 11.23, P = 0.001, partial eta squared = 0.035; adjusted R^2 for the model = 0.014) and with higher CFQ score (F (1, 336) = 8.72, P = 0.003, partial eta squared = 0.026). Participants did not vary on average sleep duration (P = 0.48), MSFsc (P = 0.62) or SJL (P = 0.46) according to their perception of external ALAN entering their bedroom (Figure 1). When participants rated the brightness of their bedroom at night when the internal lights were switched off (on a five point scale from very bright to very dark), after adjusting for covariates there were no effects of rating of brightness on GHQ scores (P = 0.221), CFQ (P = 0.054), PSQI (P = 0.061), sleep duration (P = 0.371), MSFsc (P = 0.508) and SJL (P = 0.119; Supplementary Figure 1). The perception of ALAN did not interact with chronotype (operationalised as three levels: MSFsc before 4am, between 4am and 5:30am and later than 5:30am) on the outcomes of GHQ, PSQI or CFQ scores (P = 0.107, P = 0.130 and P = 0.916 respectively). Further, Chi-square analysis did not show an association between chronotype and perception of ALAN (P = 0.345).

Table 2. Mean, median and standard deviations for scores on the psychometric instruments used to assess psychological health, subjective sleep quality, daily cognitive failures and sleep timing and descriptives on objective MSI data. CFQ = cognitive failures questionnaire; GHQ = general health questionnaire; PSQI = Pittsburgh sleep quality questionnaire; MSFsc = mid sleep on free days, sleep debt corrected; SJL = social jetlag; MSI = melatonin suppression index.

	Mean	95% CI	Median	SD	Range
Age (yrs)	36.82	[34.86–38.68]	35	13.01	18–71
Total CFQ	35.46	[33.45–37.41]	33	14.41	2–91
Total Score GHQ	23.31	[21.62–25.09]	20	12.99	2–64
GHQ A–Somatic Symptoms	5.75	[5.17–6.30]	5	4.07	0–19
GHQ B–Anxiety & Depression	6.70	[6.06–7.35]	6	4.74	0–21
GHQ C–Social Dysfunction	7.83	[7.44–8.24]	7	2.97	0–17
GHQ D–Severe Depression	3.02	[2.50–3.59]	1	4.10	0–18
Global PSQI	6.45	[6.00–6.88]	6	3.26	1–17
Average Sleep Duration (h)	7.50	[7.35–7.67]	7.54	1.11	3.86–10.71
MSFsc (hh::mm)	4.36	[4.18–4.53]	4.17	1.29	1.00–7.61
Social Jetlag (h)	1.16	[1.04–1.30]	1.00	.91	0–4.79
MSI	.05	[.04–.07]	.01	.14	.0–1.56

When the subscales of the GHQ were examined, participants who perceived external ALAN entering their bedroom had higher scores in unadjusted analyses on the GHQ-A Somatic Symptoms (median GHQ-A total score 7, 95% CI [6; 7] vs 5, 95% CI [4; 6], P < 0.001), GHQ-B Anxiety/Insomnia symptoms (median GHQ-B total score 8, 95% CI [7; 9] vs 6, 95% CI [5; 6.48],P < 0.001) and GHQ-D severe depression (median GHQ-D total score 1, 95% CI [1; 2] vs 1, 95% CI [0; 1], P = 0.002), but not GHQ-C social dysfunction (P = 0.121); Figure 2. The associations between ALAN perception and GHQ-A and GHQ-B remained after adjusting for the covariates of sex, age, residence location and MSI (F (1, 336) = 14.8, P < 0.001, partial eta square = 0.043 for GHQ-A; F (1, 336) = 13.3, P < 0.001, partial eta square = 0.039 for GHQ-B), but the association of ALAN perception with GHQ-D was not significant in ANCOVA (F (1, 336) = 2.9, P = 0.089).

63.4% of participants perceived that exposure to external ALAN before sleep was disruptive to their sleep. Participants who reported this perception, when compared to those that did not in unadjusted analysis, had poorer sleep quality (median PSQI total 7, 95% CI [6; 7] vs 5, 95% CI [4; 6]; P = 0.001), more cognitive failures (median CFQ score 37, 95% CI [33; 40] vs 29.5 95%, CI [27; 32], P = 0.001, r = 0.22) and higher GHQ total scores (median total GHQ score 22, 95% CI [20; 25] vs. 17, 95% CI [14; 19], P = 0.001, r = 0.16; Supplementary Figure 2). when controlling for age, sex, MSI and residence location, the association between the perception of ALAN disrupting sleep and GHQ, PSQI and CFQ remained statistically significant (P = 0.016, partial eta square = 0.018; P = 0.007, partial eta square = 0.024; P = 0.049, partial eta square = 0.012). Those endorsing a perception of external ALAN disrupting sleep also reported later MSFsc (median MSFsc 04:50, 95% CI [4.23; 4.67] vs 04:01, 95% CI [3.79; 4.21) and greater levels of social jetlag (median SJL of 1.25h 95% CI [1.00; 1.33] vs. 0.79, 95% CI [.58; 1.15], although these differences were not shown to be statistically significant in ANCOVAs when age, sex, house location and MSI were controlled for (Supplementary Figure 1). Examining the subscales of the GHQ, participants reporting perception of external ALAN disrupting sleep displayed statistically significant higher scores when controlling for age, sex, MSI and residence location on GHQ-B anxiety and insomnia (median GHQ-B total score 7, 95% CI [6; 8] vs 6,

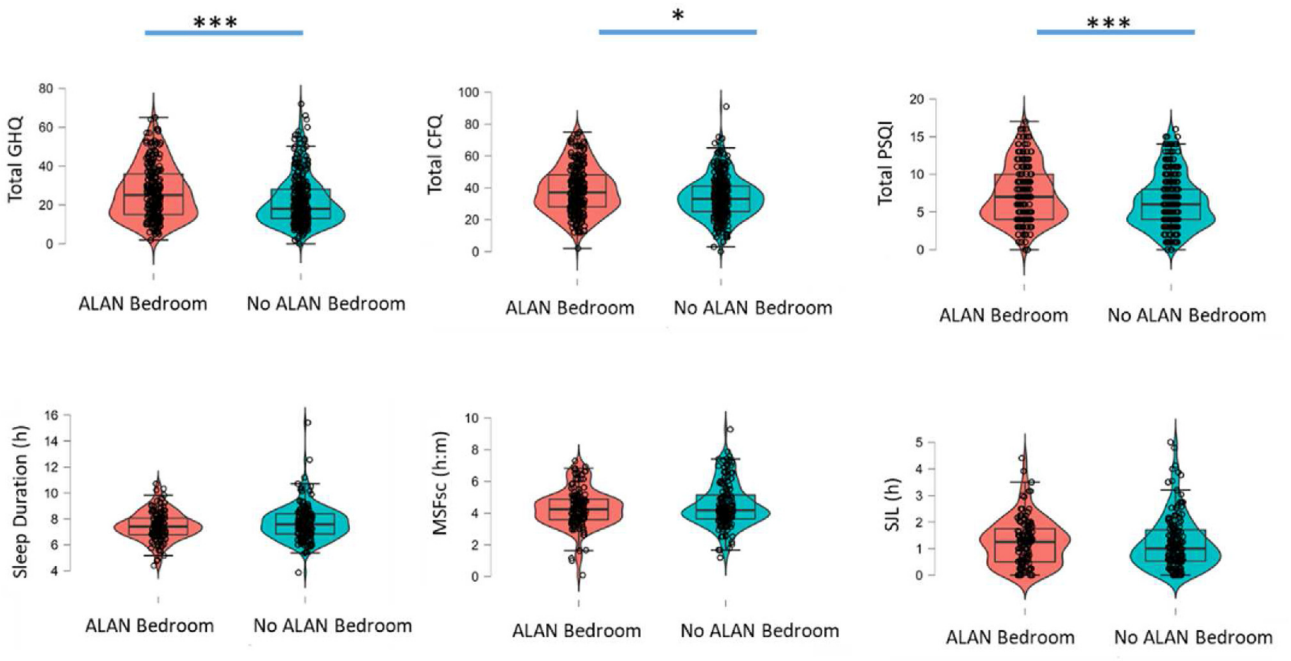

Figure 1. Box-and-violin plots of scores on the General Health Questionnaire (GHQ), Cognitive Failures Questionnaire (CFQ), Pittsburgh Sleep Questionnaire (PSQI) and sleep duration, Mid-Sleep on free days, sleep corrected (MSFsc) and Social Jetlag (SJL) from the Munich Chronotype Questionnaire, split by responding on the question "Does artificial outside light (i.e. street lights, traffic lights, headlights etc.) enter the bedroom when you are sleeping?". *** indicates $P < 0.01$ and * indicates $P < 0.05$ by ANCOVA controlling for age, sex, house location and MSI.

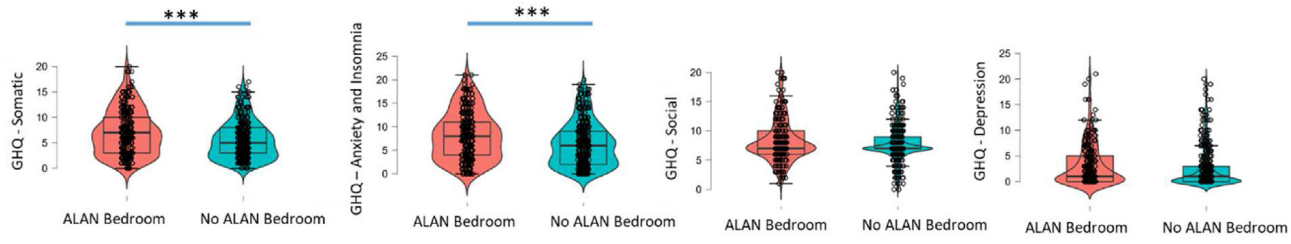

Figure 2. Box-and-violin plots of scores on the subscales of the GHQ split by responding on the question "Does artificial outside light (i.e. street lights, traffic lights, headlights etc.) enter the bedroom when you are sleeping?". *** indicates $P < 0.01$ by ANCOVA controlling for age, sex, house location and MSI.

95% CI [4; 6], P = 0.034, partial eta square = 0.014), GHQ-C social dysfunction (median GHQ-C total score 7, 95% CI [7; 7] vs 7, 95% CI [7; 7], P = 0.011, partial eta square = 0.020 and GHQ-D severe depression (median GHQ-D total score 1, 95% CI [1; 2] vs 0, 95% CI [0; 1], P = 0.035, partial eta square = 0.013) compared with those who do not perceive ALAN exposure to be disruptive to sleep.

Regarding perception of indoor ALAN, 27.4% of respondents endorsed that indoor lighting (e.g. from the bathroom or landing) intruded into their sleeping environment (42% of these respondents also reported intrusion of external ALAN). Respondents reporting internal lighting intruding into the bedroom reported no statistically significant differences, after controlling for covariates, in GHQ score (P = 0.449), sleep quality (P = 0.073), cognitive failures (P = 0.069), MSFsc (P = 0.90), sleep duration (P = 0.193) or SJL (0.298; Figure 3).

3.3. Residence location, illumination levels and sleep and psychological health indicators

When GHQ, CFQ, PSQI, sleep duration, MSFsc and SJL were analysed against residence location type, there were no significant effects (Supplementary Figure 3). MSI varied by location of the residence (F (4,342) = 6.71, P < 0.001, eta square = 0.074), with city location associated with highest MSI and countryside with the lowest; Supplementary Figure 4). When logMSI was correlated against GHQ, PSQI, CFQ, MSFsc, SJL and sleep duration, no significant associations were detected (Figure 4). 4). Further, when logMSI was used to assign participants into four groups based on MSI quartiles, PSQI, CFQ, GHQ, MSFsc, SJL and sleep duration did not significantly differ across these groups (Supplementary Figure 5). When Chi-Square tests for independence were carried out between the logMSI quartiles and self-report of external ALAN disrupting sleep, no significant associations were detected (P = 0.66), nor was there a statistically-significant association between logMSI quartile with perception of ALAN entering the bedroom (P = 0.536; Supplementary Figure 6). When assessed as a continuous variable, logMSI did not vary according to perception of external ALAN entering the bedroom (P = 0.911), or subjective ratings of the darkness of the bedroom (P = 0.097), or according to perception of external ALAN being disruptive to sleep (P = 0.827; Figure 5A). Further, when a possible interaction was examined between those classified as good or bad sleepers on the PSQI (PSQI score of five or greater classified as bad sleepers) and the perception of LAN entering the bedroom, there was no statistically significant interaction found (P = 0.991 for the interaction term), indicating that the disconnect between ALAN perception and MSI at the residence level was not influenced by sleep quality (Figure 5B). Further, there was no significant

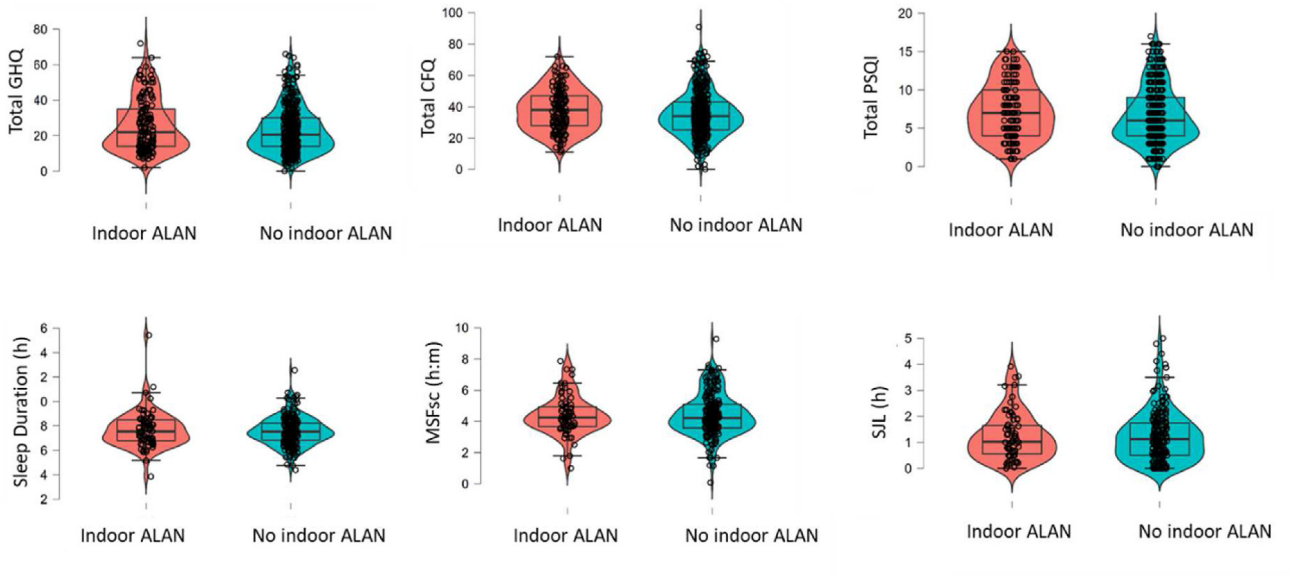

Figure 3. Figure 1: Box-and-violin plots of scores on the GHQ, CFQ, PSQI and sleep duration, MSFsc and SJL from the Munich Chronotype Questionnaire, split by perception of ALAN from within the residence assessed by the question "Do you usually have lights on outside your bedroom door which illuminate your bedroom (i.e. bathroom or landing. There were no statistical significant differences by ANCOVA.

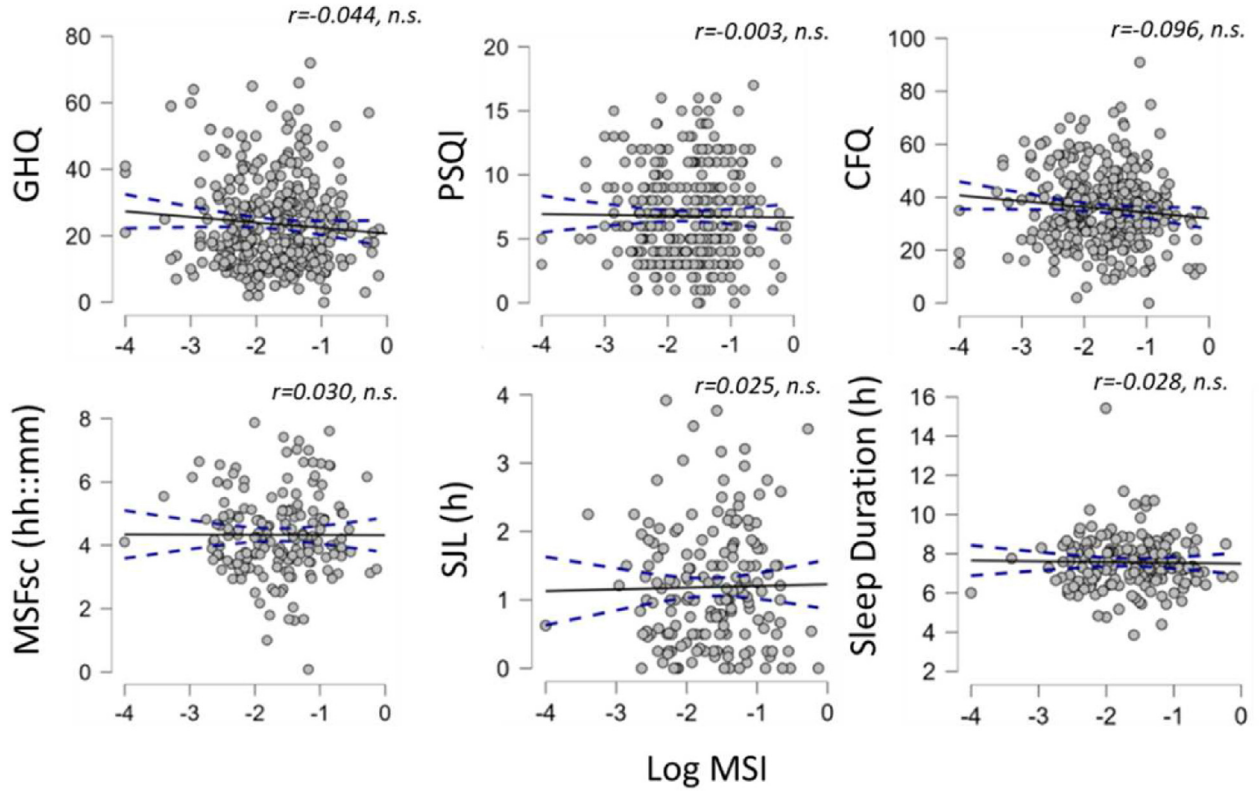

Figure 4. Scatter plots showing the lack of significant correlations between log transformed MSI scores and GHQ, PSQI, CFQ, MSFsc, SJL and Sleep Duration. Correlation coefficients indicated are Spearman's rho.

interaction between ALAN perception and chronotype on MSI (P = 0.991).

3.4. Perception of the effect of electronic devices affecting sleep

41% of participants perceived disruption to sleep by the use of electronic devices. Compared with those who reported no such effects (34% of respondents, the rest endorsing "Don't Know"), those who perceive negative sleep impacts of night-time device usage displayed poorer sleep quality after controlling for covariates of age, sex, house location and MSI (median PSQI scores 7, 95% CI [6; 8] vs 4.5, 95% CI [4; 5], P < 0.001, partial eta square = 0.053), higher cognitive failures (median CFQ scores 35.5, 95% CI [32; 40] vs 28 95% CI [26; 31], P < 0.001, partial eta square = 0.55), higher scores on the GHQ (median scores 23, 95% CI [20; 27] vs.

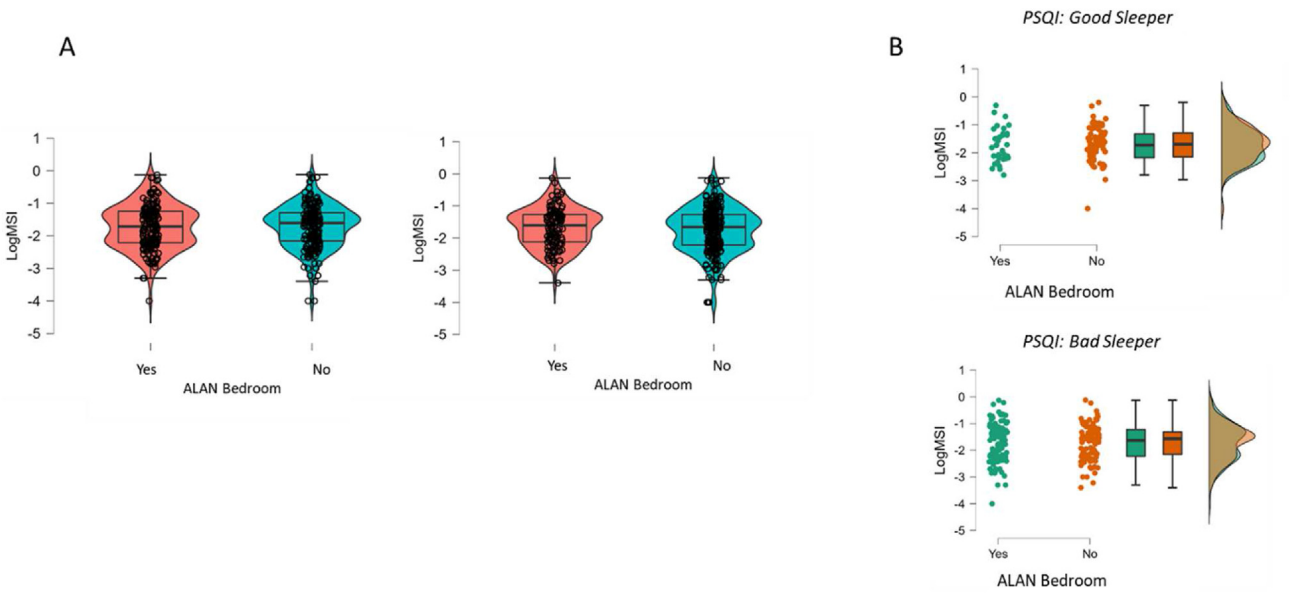

Figure 5. (A) Box and violin plots showing that logMSI at residence level does not vary between participants who report external ALAN entering the bedroom or that ALAN impacts on the quality of their sleep.(B) Scatter, box and raincloud plots showing the lack of difference in the association between MSI and LAN perception in good and bad sleepers based on PSQI scores.

15, 95% CI [13; 19], P = 0.016, partial eta square = 0.025). There were no effects of perceived sleep effects of device usage on MSFsc or sleep duration, and the unadjusted association with higher levels of social jetlag did not survive adjustment for covariates (median SJL 1.31 h, 95% CI [1; 1.46] vs 0.73 h, 95% CI [.58; .99] P = 0.219; Figure 6). 80.8% of respondents reported using electronic devices 1 h before bed. Respondents who used light-emitting technology before sleep reported more cognitive failures (median score 35, 95% CI [31; 38] vs 27, 95% CI [24; 33]) and higher scores on the GHQ (median scores 22, 95% CI [18; 25] vs 16, 95% CI [13; 20]), but these differences were not statistically significant after adjustment for the covariates of age, sex, house location and MSI (P = 0.488 and P = 0.272 respectively). There were no unadjusted statistically significant differences between those that used devices in the run-up to sleep on PSQI (median scores 6 vs 5, P = 0.091), sleep duration (7.54 h vs 7.47 h, P = 0.83), MSFsc (4.29 vs 4.10, P = 0.361) and SJL (1.13 h vs 1 h, P = 0.205).

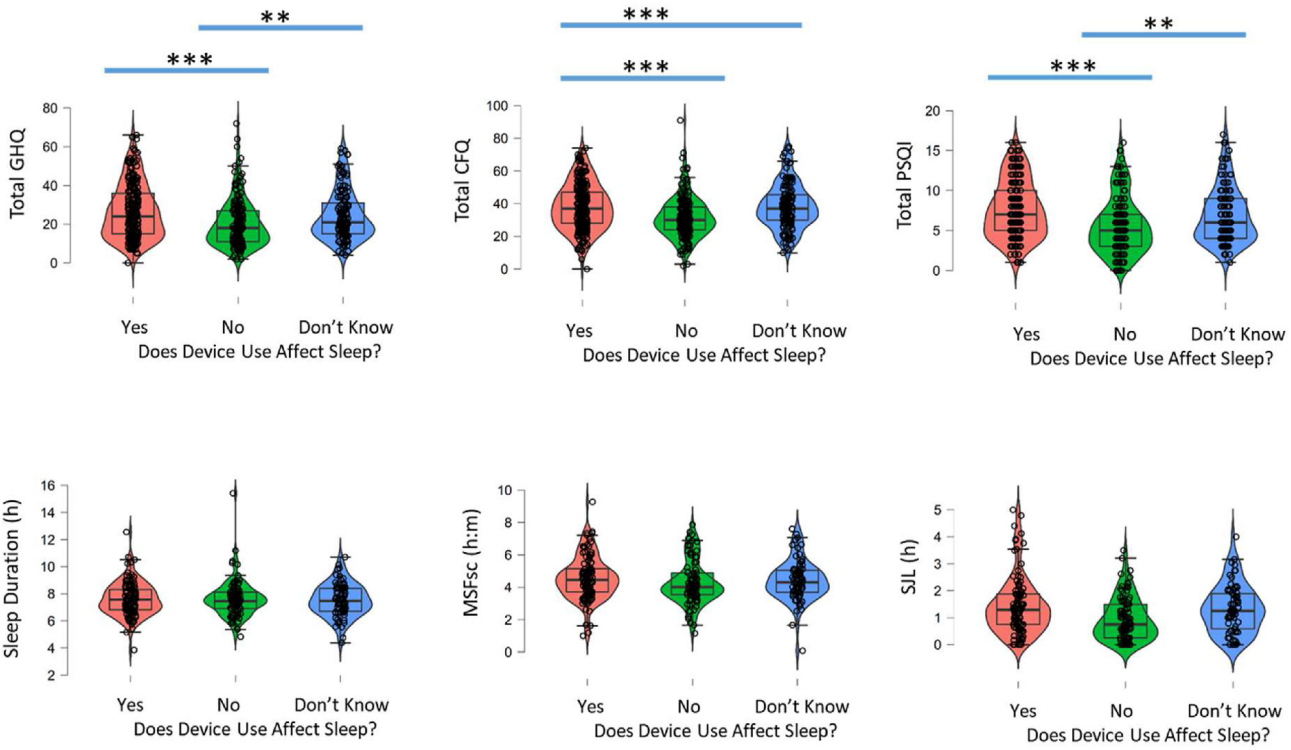

Figure 6. Box-and-violin plots of scores on the GHQ, CFQ, PSQI and sleep duration, MSFsc and SJL from the Munich Chronotype Questionnaire, split by responses to the question about electronic device usage impact on sleep ("Do you feel that use of these devices affect your sleepiness/quality of sleep in a negative manner?"). *** indicates P < 0.001 and **P < 0.01 by ANCOVA, adjusting for the covariates of sex, age, MSI and house location.

3.5. Perception of noise pollution in the bedroom

46% of respondents reported being sensitive to external noise intruding into the bedroom. Those who endorsed noise sensitivity scores significantly higher on the GHQ (median score 25, 95% CI [22; 28] vs 18, 95% CI [16; 20], P < 0.001 by ANCOVA controlling for age, sex and house location) and PSQI (median score 7, 95% CI [5; 7] vs 6, 95% CI [5; 6], P = .018 by ANCOVA; Figure 7). CFQ showed a difference on adjusted analysis (median score 38, 95% CI [33; 42] vs 31, 95% CI [29; 34]) but this did not persist after adjustment for covariates (P = 0.367). There were no significant differences, sleep duration, MSFsc or SJL (Figure 7). Similarly, respondents who endorsed that noise pollution negatively impacted on sleep quality scored significantly higher on the GHQ (median 26, 95% CI [20; 28] vs 17, 95% CI [16; 20]; P < 0.001 by ANCOVA) and also scored higher on the PSQI (median 7, 95% CI [6; 8] vs 5, 95% CI [5; 6] P < 0.001 by ANCOVA). After adjusting for covariates, there was no significant difference on CFQ (median 36, 95% CI [30; 40] vs 32, 95% CI [30; 36], P = 0.051), SJL (median .96 h, 95% CI [.79; 1.25 h] vs 1.25 h, 95% CI [1.00; 1.38 h], P = 0.572), on sleep duration (median 7.48 h vs 7.57 h, P = 0.914) or on MSFsc (median 4.18 vs 4.36, P = 0.126). There was a statistically significant association between external outdoor ALAN entering the bedroom and whether individuals perceived noise pollution during the night ($x^2 = 9.51$, P = 0.002, phi = 0.183) with those reporting no noise during the night also typically reporting no outdoor LAN entering into their sleeping environment (57% of participants who perceive ALAN intruding into their bedrooms also reported noise annoyance at night, whilst 61% of participants who did not report ALAN intrusion also did not report night-time noise annoyance).

4. Discussion

The current results indicate that perceptions of ALAN in the bedroom associate with psychological distress, cognitive failures and subjective sleep quality. Interestingly, the perception of ALAN in the bedroom appears to be independent of the level of external illuminance at the level of the individual residence as quantitated as MSI emerging from public lighting. Subjective perception of ALAN affecting sleep quality is consistent with previous studies reporting that exposure to ALAN in the sleeping environment is associated with shallow sleep, more frequent arousals and sustained effects on EEG oscillations implicated in sleep depth and stability (Cho et al., 2013, 2016) and with poorer sleep and shorter sleep duration (Ohayon and Milesi, 2016). Obayashi et al. (204a; 2014b) reported that in older adults, higher levels of photometer measured LAN exposure in the home setting was associated with a higher chance of self-reported insomnia, delayed sleep-onset latency and poorer objectively measured sleep quality. Our findings that perception of ALAN is associated with poorer psychological wellbeing is consistent with community-setting observational studies (Obayashi et al., 2013) and longitudinal studies wherein higher level ALAN exposure was a predictor of subsequent diagnosis of depression (Obayashi, Saeki & Kurumatani, 2018). However, given the cross-sectional design of this study, causality in demonstrating that ALAN exposure affects sleep quality and psychological well-being cannot be provided. Furthermore, as luminance levels in the bedroom were not objectively assessed in the current study, it is not clear what the relationship between external ALAN, in-bedroom ALAN and subjective perceptions of the same are; future studies should address these relationships.

Previous studies have reported associations between ALAN (measured at the ecological level) and levels of subjective sleep quality. Such studies have reported that participants residing in areas with high external ALAN have delayed bedtime, shorter sleep duration, increased daytime sleepiness and increased daytime sleepiness (Koo et al., 2020; Patel et al., 2018). Such associations are reported to persist after controlling for population density and environmental noise (Xiao et al., 2020), although recently Helbich et al. (2020) have reported that ALAN associations with depression are highly confounded by factors such as socioeconomic status and air pollution. Koo et al. (2020) report that outdoor light was associated with insomnia in middle age (47–58 years) and older (59–70 years) adults, but not in younger adults. Min & Min (2017) report that high outdoor ALAN was associated with increased rates of depression and suicidality, and another recent study also reported an association of ALAN with increased risk of depression and specific anxieties in adolescents (Paksarian et al., 2020). A number of studies have found no association between photometer measured LAN inside the sleeping environment and satellite image data (Huss et al., 2019; Rea et al., 2011). In addition, Garcia-Saenz et al. (2018) reported

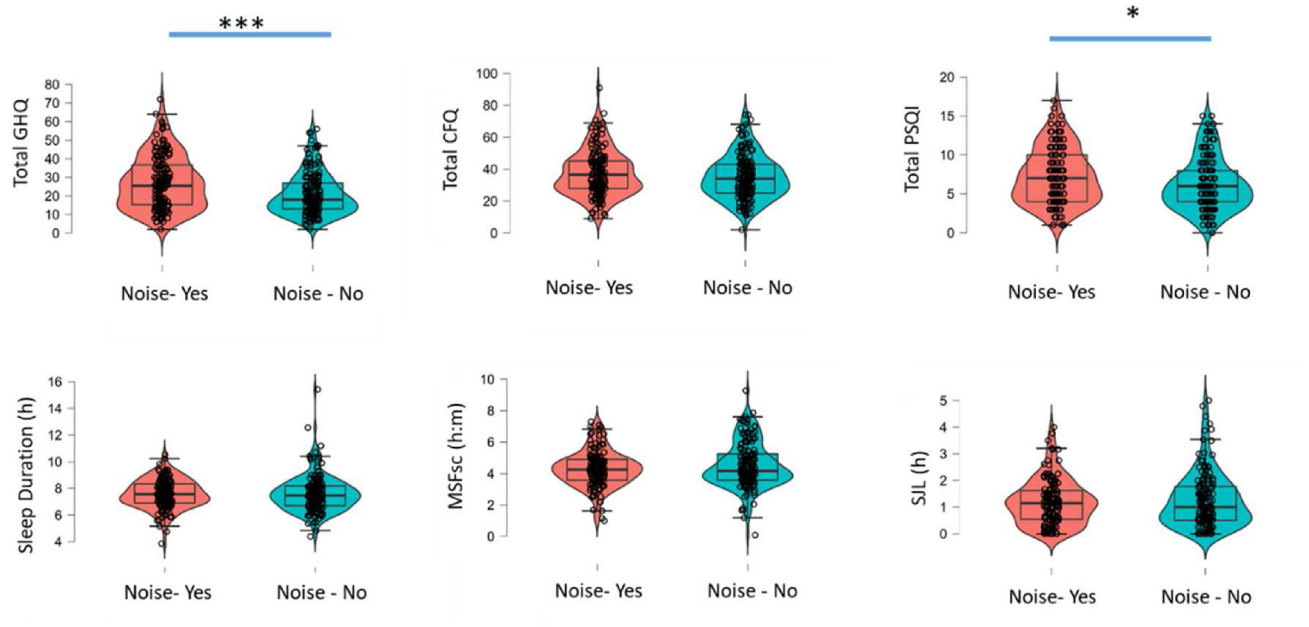

Figure 7. Box-and-violin plots of scores on the GHQ, CFQ, PSQI and sleep duration, MSFsc and SJL from the Munich Chronotype Questionnaire, split by perception of noise pollution in the bedroom assessed by the question "Does any particular noise annoy you during the night?". *** indicates P < 0.001, * indicates P < 0.05 assessed by ANCOVA, adjusting for age, sex and house location.

no association between the subjective perception of indoor LAN and outdoor satellite measures of LAN.

The majority of extant studies to date have measured ecological ALAN by using satellite imaging with the main sources of satellite image data coming from the Defense Meteorological Satellite Program (DMSP) or the Day-Night Band instrument in the Visible Infrared Imaging Radiometer Suite (VIIRS) on the SUOMI satellite (Koo et al., 2016; Ohayon and Milesi, 2016; Paksarian et al., 2020; Xiao et al., 2020). There are three important limitations which affect the use of their data as true proxies for ALAN in such studies which should be borne in mind. Firstly, the data from these sensors provides a measure of the radiance in the general environment at relatively coarse resolution of approximately 2.7 km for DMSP and 750 m resolution for the VIIRS DNB instrument; secondly, the timing of the satellite data varied between approximately 7 pm local time for the DMSP series of satellites and approximately 3am local time for the SUOMI satellite; thirdly, both instruments are panchromatic detectors and hence the spectral wavelength of the light and the response of the instruments differ (Gatson et al., 2015). The identification of the spectral composition of light is of critical importance given that short wavelength visible light has more potent effects on the circadian system by reducing melatonin secretion, delaying the latency/onset of sleep and blood pressure regulation compared with long wavelength light (Brainard et al., 2011). The relatively coarse resolution of satellite data limits it as a proxy for an individual's exposure to light as it is based on the average light intensity of a region of interest as defined by the resolution available, typically with pixel sizes of the order of a square km (e.g. Paksarian et al. (2020)) and may not reflect the true values, amounts, and patterns of ALAN at the levels of individual residences. Furthermore, a number of studies have found no associations between photometer measured ALAN inside the sleeping environment and satellite image data (Huss et al., 2019; Rea et al., 2011), and Garcia-Saenz et al. (2018) reported no association between the subjective perception of indoor LAN and outdoor satellite measures of LAN. To overcome an important limitation of satellite data, that of the spatial resolution of ecological-level ALAN assessment, we estimated ALAN at the level of individual residences using a database of public lighting in Ireland. The use of MSI as a measure of light exposure is superior to the collection of light measurements in luminance by taking into account the amount of blue wavelength light most likely to exert biological effects and making an attempt to estimate the incidence of light in the vertical plane in comparison to a horizontal illuminance estimate provided by satellite imagery data, as evidence suggests that upward light remains weakly correlated to the light that may enter the house windows (Garcia-Saenz et al., 2018). As such, we believe that the approach taken in the current study is superior to approaches based on satellite data. However, future work should compare how exterior levels of ALAN corresponds to ALAN within the bedroom as directly experienced by participants during the sleep period.

An important feature of the current results is the apparent mismatch between the levels of ALAN estimated at the level of the individual residence and the subjective perception of either the presence of ALAN in the bedroom during sleep or the perceived disruptive effect of ALAN on sleep. Although our study cannot determine exactly why poor sleepers identify perceiving external light while residing in areas with equally comparable levels of outdoor ALAN to those that do not perceive it, a possible interpretation of these findings is that poor sleepers and/or those with higher levels of psychological distress are hyper-aware of the quality of their sleep and display sleep-related attentional bias to facets of their sleeping environment (Espie et al., 2006). Evidence of sleep related attentional bias (SAB) has come from subclinical populations of poor sleepers and insomniacs using cognitive paradigms (Harris et al., 2015). Tang, Schmidt and Taylor (2006) found that clock monitoring resulted in higher self-reported levels of worry and disturbed sleep along with delayed onset of sleep latency. Woods et al. (2009) used a modified version of the Posner paradigm whereby alarm clock displaying sleep times were presented and reported that participants with insomnia disorder were quicker in identifying valid trials compared with invalid trials, suggesting that the salience of the alarm clock cue resulted in participants with insomnia directing their attention to the sleep-salient stimulus (alarm clock). Therefore participants who have existing poor sleep quality display SAB towards ALAN entering the bedroom and as such are more likely to report the presence of bedroom ALAN and its disruptive impacts on sleep. Given the high level of association between subjective sleep quality and psychological distress, SAB may also mediate the associations of ALAN perception and greater GHQ scores reported here.

Another possible suggestion is that poor sleepers have a higher sensitivity towards light and as a result are more vulnerable to disruption to sleep. Philips, et al. (2019) found that while humans are sensitive to evening light there is significant inter-individual differences in sensitivity to light with some having greater than 50% reduction in melatonin suppression when exposed to light levels as low as 10 lux. However, the relative lack of associations between MSFsc and SJL and ALAN perceptions may argue against a biological effect of ALAN in impacting on the circadian system, and alternatively may favour an attentional or another psychological explanation. Another finding that may support the subjectivity of perception of bedroom ALAN is our finding that perception of light coming into the bedroom from indoor sources like bathrooms and landings was not associated with differences in GHQ scores and showed smaller associations with CFQ and PSQI scores than external ALAN did. This differential may be explained by locus of control; external sources of ALAN (e.g. streetlights, skyglow) cannot be “switched off” by participants, whilst sources such as bathroom lights could be if deemed to be of nuisance value. Such an explanation would be consistent with the relationship between ALAN perception and environmental noise perception which could arise out of the common psychological mechanism of greater ASBs in poor sleepers who are more likely to report intrusion of a number of stimuli in their sleeping environment. The current result therefore may generate testable hypotheses linking ASB and perceptions of bedroom ALAN, and future work may examine such.

It has been proposed that the link between ALAN (at the neighbourhood level) and depression symptoms is mediated through socioeconomic status (SES); that poorer SES is associated with both more mental distress and with residence in higher density urban areas with high levels of ALAN (Helbich et al., 2020). In the current study as ALAN was assessed at the level of the individual residence, rather than at the level of the neighbourhood as for studies using satellite measures of ALAN, it is not clear whether neighbourhood indicators of SES would be appropriate to apply to the current data. Further, as we show no association between ALAN (as measured by residence level MSI) and psychological distress, there is no effect to examine whether SES mediates it. Rather, we have demonstrated a link between psychological distress and perceptions of ALAN, for which we do not have an a-priori reason to suspect would be mediated by SES. However, future work might explore this question using residence or individual level measures of SES.

Our findings indicate that 80% of participants indicated using light emitting technology before bed, whilst 46% of respondents perceived a negative effect of device usage on their sleep. Those that reported negative impacts of device use on sleep had higher scores on the PSQI, GHQ and CFQ than those who did not, a finding that may be consistent with previous reports that light emitting technology usage is associated with greater onset to sleep latency, poor sleep quality and quantity, and excessive daytime sleepiness (Gringras et al., 2015; Carter et al., 2016). Further, Christensen et al. (2016) report that smartphone screen time measured objectively was associated with poorer sleep quality, decreased sleep efficiency and longer sleep onset latency. An important caveat is that self-report of technology before sleep may not reflect actual device use; for example, Reddy Katapally and Chu (2019) found that individuals consistently underreport their screen time when compared with objective measures. With regards to the influence of external ALAN, those participants with poorer psychological and sleep health may display more negative attributions towards device usage, and as such the reported association between perceived sleep impacts of device usage and both

psychological and sleep health may not be in the direction of device use to psychological distress/poor sleep, but vice versa.

If there is an impact of ALAN on sleep and psychological health, the mechanism underlying such associations remains underexplored. Circadian rhythm dysfunction may be associated with poor psychological health as indicated by experimental studies of animal models (e.g. circadian clock gene knockouts) and some human studies (McClung et al., 2013). Night-time ALAN may supress the secretion of the pineal hormone melatonin, and multiple lines of evidence indicate that exposure to light at the biological night, even at low levels, can supress melatonin production resulting in delayed sleep onset, impaired sleep maintenance and poor quality of sleep (Scheer and Czeisler, 2005; Vartanian et al., 2015). In animal studies, ALAN which induces circadian disruption leads to changes in brain regions which contribute to depression and mood disruption (Fernandez et al., 2018; Germain and Kupfer, 2008). Therefore it is biologically plausible that night-time ALAN exposure in humans could cause increased risk of psychological distress and/or poorer sleep; however, the current findings do not support that hypothesis, but rather highlight the importance of considering psychological factors that may influence perception of ALAN and its impacts.

There are a number of limitations to this study which impact on the generalisability of the findings. Firstly, this is a cross-sectional study that did not seek to assess causality in the explored relationships. Secondly, perceptions of ALAN in the sleeping environment were determined through self-reported measures and we did not measure ALAN in the bedroom environment in terms of illuminance levels, spectral composition and timing. As noted earlier it is not clear how ALAN assessed at the level of the residence corresponds to levels within the bedroom, and a number of studies have found no association between outdoor ALAN and levels of sleeping environment LAN (Huss et al., 2019; Rea et al., 2011). Further, the questionnaires employed only asked about ALAN in the bedroom, and did not assess ALAN outside of the bedroom in the hours before bedtime which could impact on sleep. The method used to calculate ALAN at the level of the residence was based on the use public lighting databases, and we believe this approach has significant advantages over the use of satellite-based data in terms of spatial resolution, though it may also under-estimate ALAN exposure due to other lighting sources, such private and commercial lighting, which were not included in the MSI calculations. The calculation of MSI is based upon the assumption that public lighting databases are accurate and complete and appropriate to the date of the survey, that public lighting is the sole contributor to the light level at the residence and that the calculated light level is appropriate for the nominal location, i.e. that an unobstructed view of the light source is present and that there is no loss of light output due to the aging of the lamp or cleanliness of the optics (the maintenance factor). The expected light output assumes a uniform emitter while, realistically, lantern photometry shows that light output varies with both azimuth and elevation angles. Further, we used the method of Aubé et al. (2013) to calculate the MSI, which is based on a different melatonin suppression action spectrum to that used recently by other authors for quantifying the impact of light on circadian timing and other non-visual functions (melanopic equivalent daylight illuminance; Brown et al., 2022). As such, potential discrepancy between the current results and those that may arise from analysis based on different approaches to calculating the biologically-active melanopic component of the public lighting sources is acknowledged.

5. Conclusions

Our study indicates that perception of ALAN in the bedroom and its impact on sleep is associated with more psychological distress, more daily cognitive difficulties and poorer subjective sleep quality, although it is not clear how these associations are linked (e.g. poorer sleep precipitating more distress and more cognitive failures). Further, the perception of bedroom ALAN and its impacts do not appear to be strongly correlated with objectively assessed ALAN at the level of the individual residence based on public street lighting, indicating that psychological factors that amplify the perceived nuisance value of ALAN may be important in mediating its impacts on psychological and sleep health. We believe that this work represents a first approach to estimate quantitatively the impact of external public lighting conditions on sleep inside the home. A recent Citizen Science study on public perception of ALAN in Ireland indicated that urban dwellers rated public lighting as the most important source of ALAN, although rural dwellers reported the main source being other residences in the locale (Coogan et al., 2020). As such, future work is warranted for the granular examination of ALAN at the level of the residence and the individual in order to better inform public lighting and health policy.

Declarations

Author contribution statement

Michael Cleary-Gaffney: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Brian Espey: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Andrew N. Coogan: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

Supplementary content related to this article has been published online at https://doi.org/10.1016/j.heliyon.2022.e11284.

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