Title:

Low daytime light and bright night-time light are associated with psychiatric disorders: an objective light study in >85,000 UK Biobank participants

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Abstract.

Circadian rhythm disturbance is a common feature of psychiatric disorders. Light is the primary input to the circadian clock, with daytime light exposure strengthening rhythms and nighttime light exposure weakening rhythms. However, the independent effects of day and night light exposure on psychiatric outcomes have not been well characterized. In this study, we performed the largest to-date cross-sectional analysis of objectively measured day and night light exposure and examined their relationship with psychiatric disorders. UK Biobank cohort participants aged 37-73 years were recruited into the UK Biobank general cohort population. In a subset of participants (n=86,772; 43% male), light and physical activity patterns were monitored for ~7 days. Using regression models adjusted for age, sex, ethnicity, photoperiod (day length), employment, and physical activity, we examined the independent associations of day and night-time light with psychiatric disorders and measures of symptom severity. We found that greater night light exposure was associated with greater odds of major depressive disorder (MDD), generalized anxiety disorder (GAD), bipolar disorder, post-traumatic stress disorder (PTSD), self-harm behavior and psychotic experiences. Conversely, greater daytime light exposure was associated with lower odds of MDD, PTSD, self-harm behavior and psychotic experiences. There was no significant association of day light exposure with GAD or bipolar disorder. Our findings demonstrate that low day light and bright night light exposure are associated with a wide range of psychiatric outcomes. Avoiding light at night and seeking light during the day may be a simple and effective, non-pharmacological means of broadly improving mental health.

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Introduction.

Virtually all psychiatric disorders have been associated with disrupted circadian rhythms and sleep[1]. In humans, nearly every cell in the body contains a circadian (~24-hour) clock. These clocks regulate basic cellular functions, including gene expression for >80% of the protein coding genome[2]. The network of circadian clocks throughout the body is organized by a central ('master') circadian clock in the suprachiasmatic nucleus (SCN) in the hypothalamus. Rhythms within the SCN are regulated by daily light exposure patterns, with direct retinal inputs communicating light/dark information to the central circadian clock. This biological system evolved under predictable conditions of bright light during the day and very dim light during the night to ensure stable, robust rhythms[3]. Alterations to this pattern in daily life could contribute to adverse psychiatric outcomes.

In this study, we used objective recordings of daily light exposure data to characterize the levels of light in the day and night in a sample of 86,772 UK Biobank participants. We used these data to test the two primary hypotheses: (i) greater light exposure in the day is associated with better psychiatric outcomes and that (ii) greater light exposure at night is associated with worse psychiatric outcomes. These hypotheses were motivated by the known effects of day and night light exposure on the human circadian system, and the well-established links between circadian disruption and psychiatric disorders. Since the circadian system is implicated in regulating virtually all areas of physiology and behavior, we investigated a constellation of psychiatric outcomes available in the UK Biobank Mental Health Questionnaire.

Results.

Of the 103,669 UK Biobank participants that completed the actigraphy assessment, we excluded those with poor quality or unreliable accelerometry, sleep, and light data (see Methods for details), leaving 86,772 participants. Of these, 86,631 had complete data for day and night light as well as the covariates in our fully adjusted model 3. Light in the day and night showed extreme positive skew (skewness > 1 for both). As such, the day and night light variables were divided into four equally sized quartiles ($n_{Q1\text{-}Q4}$ = 21,693) in ascending brightness and were entered together as independent categorical predictors in all models (referent = Quartile 1, lowest brightness). Characteristics of the sample are presented in Table 1 for the lowest (Q1 & Q2) and highest (Q3 & Q4) quartiles for both day and night light exposure.

The reliability of light measurements was assessed in a subset of the actigraphy sample (n = 2,988) that completed a series of four repeated actigraphy assessments. These assessments occurred on average 3.23 years (SD 0.65) after their initial assessment over the course of a year with three months between each measurement. A linear mixed-effects model with a crossed random effect structure including participant, assessment, and time of day was used to estimate the intra-class correlation (ICC) of light. Light measurements showed good reliability, ICC = 0.803.

339,092 UK Biobank participants were invited to complete the online Mental Health Questionnaire (MHQ) in 2016 and 157,366 completed the questionnaire. Measurement of psychiatric outcomes as part of the MHQ took place an average of 1.86 years (SD = 0.66) after the actigraphy assessment. The study sample comprised participants who completed both the MHQ and actigraphy assessment and sample sizes varied depending on the outcome

variable assessed, ranging from 26,956 to 61,442 for model 1 and 26,824 to 61,147 in model 3.

Figure 1 shows that in fully adjusted regression models (Model 3; adjusting for age, sex, ethnicity, photoperiod, physical activity and employment; see Table 2), when compared to participants in the lowest quartile of night light exposure (Q1), higher night light exposure was associated with higher odds of lifetime major depressive disorder (Likelihood Ratio Test (LRT) $p < 0.0001$; $OR_{Q4} = 1.30$, 95% CI = 1.23-1.38, $p < 0.0001$), self-harm (LRT $p < 0.0001$; $OR_{Q4} = 1.27$, 95% CI = 1.14-1.42, $p < 0.0001$), generalized anxiety disorder (LRT $p = 0.0001$; $OR_{Q4} = 1.23$, 95% CI = 1.11-1.36, $p = 0.0001$), PTSD (LRT $p < 0.0001$; $OR_{Q4} = 1.34$, 95% CI = 1.22-1.48, $p < 0.0001$), and lifetime psychotic experiences (LRT $p = 0.0009$; $OR_{Q4} = 1.21$, 95% CI = 1.09-1.34, $p = 0.0003$). There was no overall association of night light exposure with lifetime bipolar disorder (LRT $p = 0.18$), however, the brightest night light quartile was associated with increased odds of bipolar disorder ($OR_{Q4} = 1.20$, 95% CI = 1.02-1.42, $p = 0.03$). Figure 2 shows that greater night light exposure was associated with higher scores on the PHQ-9 (LRT $p < 0.0001$; Standardized $\beta_{Q4} = 0.13$, 95% CI = 0.11-0.15, $p < 0.0001$), GAD-7 (LRT $p < 0.0001$; $\beta_{Q4} = 0.07$, 95% CI = 0.05-0.09, $p < 0.0001$), PCL-6 (LRT $p < 0.0001$; $\beta_{Q4} = 0.11$, 95% CI = 0.08-0.14, $p < 0.0001$) and lower wellbeing scores (LRT $p < 0.0001$; $\beta_{Q4} = -0.11$, 95% CI = -0.13–0.08, $p < 0.0001$; see Supplementary Table 1). The results for Model 1 (unadjusted) and Model 2 (adjusted for age, sex, ethnicity and photoperiod) were similar in terms of direction, strength and significance to Model 3.

Figure 1 shows that in the fully adjusted regression models, higher day light exposure (see Table 3) was associated with lower odds of lifetime major depressive disorder (LRT $p < 0.0001$; $OR_{Q4} = 0.81$, 95% CI = 0.76-0.87, $p < 0.0001$), self-harm (LRT $p = 0.0001$; $OR_{Q4} = 0.76$, 95% CI = 0.67-0.87, $p = 0.0001$), PTSD (LRT $p = 0.01$; $OR_{Q4} = 0.82$, 95% CI = 0.73-0.92, $p = 0.001$) and psychotic experiences (LRT $p < 0.0001$; $OR_{Q4} = 0.69$, 95% CI = 0.61-0.79, $p < 0.0001$). There was no association of day light exposure with generalized anxiety disorder (LRT $p = 0.61$; $OR_{Q4} = 0.96$, 95% CI = 0.85-1.09, $p = 0.22$) or lifetime bipolar disorder (LRT $p = 0.22$; $OR_{Q4} = 0.86$, 95% CI = 0.70-1.05, $p = 0.13$). Figure 2 shows that greater day light exposure was associated with lower scores on the PHQ-9 (LRT $p < 0.0001$; $\beta_{Q4} = -0.09$, 95% CI = -0.12--0.07, $p < 0.0001$), GAD-7 (LRT $p < 0.0001$; $\beta_{Q4} = -0.05$, 95% CI = -0.08--0.03, $p = 0.0001$), PCL-6 (LRT $p = 0.002$; $\beta_{Q4} = -0.08$, 95% CI = -0.12–0.04, $p = 0.0001$) and higher wellbeing scores (LRT $p < 0.0001$; $\beta_{Q4} = 0.08$, 95% CI = 0.05-0.11, $p < 0.0001$; see Supplementary Table 2). The results for Model 1 (unadjusted) and Model 2 (adjusted for age, sex, ethnicity, and photoperiod) were similar in terms of direction and significance to Model 3. However, ORs tended to be smaller in Model 3 after the addition of physical activity and employment covariates.

Discussion.

We found that objective light exposure patterns were associated with the likelihood of psychiatric disorders and the severity of symptoms across a broad range of outcomes. Brighter light at night was associated with a greater likelihood of depression, self-harm behavior, PTSD, psychosis, generalized anxiety disorder, and mania/hypomania. Brighter light in the day was associated with lower odds of depression, self-harm behavior, PTSD, and psychosis. These associations were independent of demographic, physical activity, photoperiod, and employment covariates.

The most striking results were observed for the influence of light at night on depression. For individuals in the brightest night light quartile, we saw ~30% higher risk of Major Depressive Disorder. Similar results were observed for self-harm behavior, Generalized Anxiety Disorder, and mood measured with the PHQ-9. Depression has long been associated with the disruption of both the timing and amplitude of circadian rhythms. Patients with depression have been found to have weakened circadian rhythms (blunted amplitude)[4] an effect that is reversed in recovery[5,6]. Greater disruption of circadian timing has been associated with poorer mood outcomes[7,8]. The severity of mood symptoms and the duration of depressive episodes are greater in those who experience circadian rhythm disturbance[8,9] and the presence of circadian disturbance in depression is predictive of a greater risk for recurrence[10,11]. In postmortem brain tissue from patients with MDD, a profound disruption in rhythms was seen throughout the brain[12]. As light at night alters circadian timing and dampens circadian amplitude[13], our results are consistent with night light exposure as a cause of the disruption observed in people with depression. The human circadian system is highly sensitive to light at night[14], but this sensitivity is profoundly enhanced by the common antidepressant citalopram[15]. Thus, treatment of depression with these drugs could play a causal role in exacerbating circadian disruption. Patients with depression who tend to get more light at night responded more poorly to SSRIs, switching medications more often and having more suicidal ideation[16]. Together, these findings point to the avoidance of light at night as an important therapeutic target for recovery.

We found that brighter light in the day was associated with ~20% lower odds of Major Depressive Disorder, less self-harm behavior, and better mood on the PHQ-9. Daytime light therapy has long been shown to be efficacious in treating both seasonal and non-seasonal depression[17]. Light therapy has also been shown to significantly enhance treatment efficacy with a selective serotonin reuptake inhibitor[18]. Our findings suggest that the use of specialized light therapy boxes are not necessary for therapeutic effects of light. Our findings of objective measurements of daytime light exposure are consistent with our previous finding of an association of self-reported outdoor light exposure in >400,000 participants[19]. In that study, self-reported greater time spent outdoors during the day was associated with lower odds of lifetime major depressive disorder, less antidepressant usage, less frequent anhedonia, greater happiness, and lower neuroticism. Those findings were independent of demographic, lifestyle, and employment covariates and held in both cross-sectional and longitudinal analyses. Thus, both large-scale objective and subjective light exposure data demonstrate the beneficial effect of daytime light exposure on depression. Getting more light exposure in the day, and not necessarily in the morning, could be a simple means of improving depression trajectories.

At high levels of light exposure at night, we observed higher odds of bipolar disorder. Similar to depression, bipolar disorder has long been associated with circadian disruption (for a review, see[20]). In bipolar disorder, there is greater variability of circadian timing and a dampened amplitude of behavioral rhythms, both of which could be indicative of circadian disruption by light at night. Hypersensitivity of the circadian system to light at night has been proposed to be a trait marker of bipolar disorder[21,22] Drugs used to treat bipolar disorder have been shown to reduce the sensitivity of the circadian system to light at night[23,24] suggesting that a normalization of circadian light sensitivity may play a role in recovery by reducing the effects of light at night. Increased sensitivity to light may occur at the level of the retinal circadian photoreceptors (intrinsically photosensitive retinal ganglion cells; ipRGCs) that are highly sensitive to short-wavelength ("blue") light[25] as trait hypomania has been shown to be associated with increased ipRGC responsiveness to blue light[26]. Consistent with this, wearing

blue-blocking glasses at night was found to be effective in reducing mania in patients[27]. We did not see significant associations of bipolar disorder or hypomania/mania with brighter daytime light. This may reflect a ceiling effect of any light in the day on an already highly sensitive circadian system. For patients with episodes of mania, the avoidance of light at night specifically may be beneficial.

We found both an adverse association of nighttime light exposure and a beneficial association of daytime light exposure with PTSD. In previous studies, circadian dysrhythmia has been associated with symptom severity in PTSD[28] and lower urinary melatonin levels after a trauma exposure have been found to predict a higher risk for PTSD[29], a finding replicated in military personnel[30]. Though it is possible that low endogenous melatonin levels may produce this increased PTSD vulnerability, our results suggest bright night light exposure and/or high circadian light sensitivity may be antecedent factors leading to blunted and disrupted rhythms. This is supported by evidence that melatonin and phase advancing daytime light may be effective treatments for PTSD symptoms[31,32]. Furthermore, we have recently demonstrated that PTSD is genetically correlated with greater light sensitivity[33]. The avoidance of light at night and seeking bright daytime light after trauma may reduce the likelihood of developing PTSD and the severity of symptoms in those with the disorder.

Taken together, our findings of associations of brighter light in the day and less light at night as generally beneficial for psychiatric health point to the strengthening of circadian rhythms as an underlying factor supporting more robust mental health. Patterns of bright daytime light and low nighttime light can enhance the amplitude of the circadian clock strengthening the clock's control of circadian rhythms throughout the brain and body. High amplitude rhythms are also protective against perturbations from the disruptive effects of light at night. As modern humans spend ~90% of the day indoors[34], our light exposure patterns are typically less bright in the day and more bright at night than naturalistic patterns across our evolutionary history[35]. These patterns of low daytime light and bright light at night dampen the amplitude of circadian rhythms generated within the core circadian clock, leading to downstream disorganization of rhythms throughout the brain and body. Targeting circadian health is a highly promising means of promoting optimal general physiology, leading to more robust mental and general health.

Though light at night can induce poor mood in the long term via circadian disruption (like a perpetual jet lag), in the short term, light may be sought to acutely benefit mood. Light can enhance mood acutely. We have recently shown that light can acutely inhibit activity of the amygdala in humans[36] (a brain region involved in negative emotionality), with brighter light resulting in more suppression of amygdala activity. That study also showed that light dose-dependently enhanced the connectivity between the ventro-medial prefrontal cortex and amygdala, suggesting that light can enhance the control of negative emotionality. As poor mood is generally higher in the night/early morning hours[37], those experiencing such challenges may seek light at these times to enhance mood. Though this would enhance mood in the short term, it would lead to circadian disruption in the long term and potentially act to perpetuate mental illness. Such motivations toward light represent a potential challenge for promoting healthy light behaviors. However, these motivations to seek light may make the monitoring of self-exposure to light at night using wearables[38,39] a promising means of tracking mood in patients.

This study is the first to report an analysis of objectively measured light exposure data from the UK Biobank and is the largest examination of objective light exposure and mental health

to date. Across a broad range of psychiatric outcomes, our results demonstrate a powerful impact of healthy light exposure patterns. These results suggest that promoting brighter days and darker nights as a simple, freely available non-pharmacological intervention to enhance mental health.

Methods.

Participants.

The UK Biobank prospective general population cohort contains more than 502,000 UK residents (aged 37–73 years; ~54% women) recruited via National Health Service (NHS) patient registers from 2006 to 2010. The study population is described in detail elsewhere[40,41]. Participants provided detailed demographic, lifestyle, health, and employment information via assessment and touch-screen questionnaire. Accelerometry and light data were measured in a subset of more than 100,000 participants in 2013-2015 and approximately 160,000 participants completed an online Mental Health Questionnaire (MHQ) in 2016-2017. Our sample comprised participants whose activity and light data measurements passed rigorous quality control and had data on all covariates across regression models of increasing adjustment. Characteristics of participants with low (quartiles 1 & 2) and high (quartiles 3 & 4) day and night light exposure groups are presented in Table 1. Participants who accepted the invitation to join the UK Biobank cohort provided written, informed consent and the UK Biobank has generic ethical approval from the North West Multi-Center Research Ethics Committee (ref 11/NW/03820).

Measurement of predictors

In 2013, 240,000 UK Biobank participants were invited to wear an accelerometer for 7 days as part of a physical activity and light monitoring study. Of these participants, 103,669 (43%) accepted, and returned the accelerometer to UK Biobank after use. Participants who accepted the invitation received a wrist-worn AX3 triaxial accelerometer (Axivity, Newcastle upon Tyne, UK) with in-built light sensor (APDS9007 silicon photodiode sensor; spectral sensitivity λ = 470-650nm) in the post and were asked to wear the device on their dominant wrist continuously for 7 days, while continuing with their normal activities. At the end of the 7-day period, participants were instructed to return the accelerometer to UK Biobank using a prepaid envelope.

Output current of the light sensor was extracted from the Axivity CWA files, down-sampled from 100Hz to 1Hz and converted from the logarithmic scale to approximate lux according to the device manual (lux = 10^(device output current/341). Initial pre-processing of the light data involved averaging 1Hz light samples into 10-second epochs. Participants' light data were then cleaned based on accelerometer non-wear. Non-wear was defined by GGIR according to previously validated methodology[42,43]. Participants without valid days of sleep-wake data due to file corruption or consistent non-wear were also excluded. Of the 103,669 participants, 8,004 were excluded. The median (IQR) number of days of light data excluded in this process per participant was 0.06 (0.00-0.01) and the median (IQR) number of valid days per participant was 6.90 (5.95-6.99). Epochs were then smoothed with a median rolling window (10-minute window, 2-minute increments). Participants were then excluded if they had unusually dark (percentage of data below 1lux > 80%), consistently bright (percentage of data above 600lux >75%) or irregular light patterns (LRI > 100 or < 0) leaving 88,014 participants remaining.

Daily light profiles of participants were constructed by averaging epochs into forty-eight 30-min bins across the 24-hour period per study day and these bins were then averaged across the study days to generate an average 24-hour light exposure profile per-participant (i.e. a single 30-minute bin contained the average light exposure across the seven study days). Participants with < 2 study days' worth of light data per 30-minute bin were excluded, resulting in the loss of 18,301 bins of a possible 4,268,016 (0.43%) and 1,242 participants for a final sample of 86,772.

Light exposure predictors were defined by factor analysis of the forty-eight 30-minute light bins across the 24-hour period to identify superordinate patterns in light exposure behavior in the sample. Factor analysis supported the extraction of a two-factor structure (day, 7.30am-8.30pm; and night, 12.30am-6am; factor loadings ≥ 0.5, varimax rotation) based on the scree plot, the additional proportion of variance explained by each factor (>0.1) and the independence of resultant factors. A three-factor structure including an evening (7.30pm-12.00am) factor was also explored, however, day and evening light were strongly correlated (r = 0.76), indicating they were not independent and likely to misbehave in regression models, and evening light bins had considerable cross-loading onto the day factor. As such, the two-factor model was retained (cumulative proportion of variance explained = 0.56). Day and night light variables were calculated by averaging light values across the respective time bins.

Light exposure during the day had a small positive correlation with night light (r = 0.08, p < 0.0001). Internal consistency of both day (Cronbach's α = 0.98) and night (α = 0.93) light variables was very good. Test-retest reliability of day and night light measurements was assessed in a subset of the actigraphy sample (n = 2,988) that completed a series of four repeated actigraphy assessments. These repeated assessments occurred on average 3.23 years (SD = 0.65) after the main assessment and took place over the course of a year with three months between each measurement. A linear mixed-effects model with a crossed random effect structure including participant, assessment, and time of day was used to estimate the intra-class correlation (ICC). Light measurements showed good reliability, ICC = 0.803.

Measurement of outcomes

Definition of case-control psychiatric outcome variables from the UK Biobank MHQ followed guidelines established by Davis, Coleman [44]. Lifetime major depressive disorder cases were defined according to the CIDI-SF lifetime depression module based on the DSM definition of major depressive disorder[45]. Cases were those who reported that they had at least one core symptom of depression (persistent sadness or loss of interest), most or all of the day on most or all days for a two-week period, with at least five depressive symptoms that represent a change from usual occurring over the same time scale with some or a lot of impairment. Individuals who reported a depression diagnosis were also recorded as cases (UKB 20544 & 20002). Controls were those who did not meet the above criteria and did not report either of the canonical symptoms or a PHQ-9 score > 5. Lifetime generalized anxiety disorder cases according to the CIDI-SF lifetime GAD module based on the DSM-IV definition of GAD[45]. Cases were those who reported excessive worrying about a number of issues, occurring most days for six months and that were difficult to control, with three or more somatic symptoms and functional impairment. Lifetime bipolar disorder cases were defined according to DSM-IV guidelines[46,47]. Cases were those who reported that they were ever manic/hyper or irritable plus four other features of bipolar disorder for a duration of a

week or more with the symptoms causing significant problems or those who self-reported a diagnosis of bipolar or mania (20544 = 10). Self-harm cases and controls were defined by yes or no responses to the question "have you ever deliberately harmed yourself, whether or not you meant to end your life?". PTSD was defined using the PTSD-Checklist-6 using a clinical case-control threshold of 13[48]. Lifetime psychotic experiences cases were defined using participant responses to the MHQ which were adapted from the CIDI[49]. Cases were those who reported hearing an unreal voice, seeing an unreal vision, believing an unreal conspiracy, believing an unreal communication or sign or had a diagnosis of schizophrenia or psychotic illness (20544 = 2 or 3). Controls were those who did not meet the above criteria.

Continuous symptom severity scales for depression (PHQ-9; range = 0-27), anxiety (GAD-7, range = 0-21) and PTSD (PCL-6, range = 6-29) were calculated by summing across the individual items in the MHQ to generate a total score[48,50]. A total well-being score was calculated by summing across three items indexing general happiness (20458), happiness with health (20459) and life meaningfulness (20460; range 3-17).

Statistical analysis

Associations between day and night light exposure and each of the psychiatric outcome variables were examined in three separate regression models with increasing adjustment for potential confounders. Each model included both day and night light categorical predictors to examine their independent effects.

Due to the large positive skew in both day and night light variables (skewness > 1 for both) and zero-inflation of the night light variable, both variables were converted into categorical predictors by dividing them into four equal-sized quartiles ($n_{Q1\text{-}Q4}$ = 21,693) in ascending brightness. Four bins were chosen to maximize the per-bin sample size while allowing for the observation of non-linear effects.

The association between day and night light and case/control outcomes of lifetime major depressive disorder, self-harm, GAD, PTSD, bipolar disorder, and psychotic experiences were examined with multiple logistic regression. Odds ratios (OR) and their 95% confidence intervals are reported. Linear regression was used for all continuous symptom severity scales and standardized beta values are reported. For all models, a likelihood-ratio test was used as an omnibus test of significance for the day and night light factors by comparing a model with the given light variable included against a model without it. These associations were tested hierarchically in three models with increasing adjustment for potential confounders. Model 1 examined the unadjusted association between day and night light and psychiatric outcomes. Model 2 adjusted for age at the time of actigraphy, sex, ethnicity (white vs. non-white), photoperiod as a measure of seasonality defined as the duration between sunrise and sunset at the beginning of the actigraphy assessment. Finally, model 3 additionally adjusted for employment (employed vs. unemployed) and physical activity defined as overall acceleration average in milligravity units (UKB field 90012). Data preprocessing for the physical activity measure was done by the UK Biobank accelerometer expert working group[42]. Coefficient plots of the three models were constructed with inside and outside error bars reflecting one standard error of the mean and the 95% confidence interval, respectively.

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The funder of the study played no role in study design, data collection, data analysis, data interpretation or writing of the report. The corresponding authors have full access to the study data and final responsibility for the decision to submit for publication.

Conflicts of interest

AJKP and SWC have received research funding from Delos and Versalux, and they are co-founders and co-directors of Circadian Health Innovations PTY LTD. SWC has also received research funding from Beacon Lighting and has consulted for Dyson. ACB: none; DPW: none; MKR: none; RS: none; JML: none; CV: none; PO: none.

Data availability statement

This work utilized the UK Biobank resource (application 26209; Martin Rutter).

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Figures

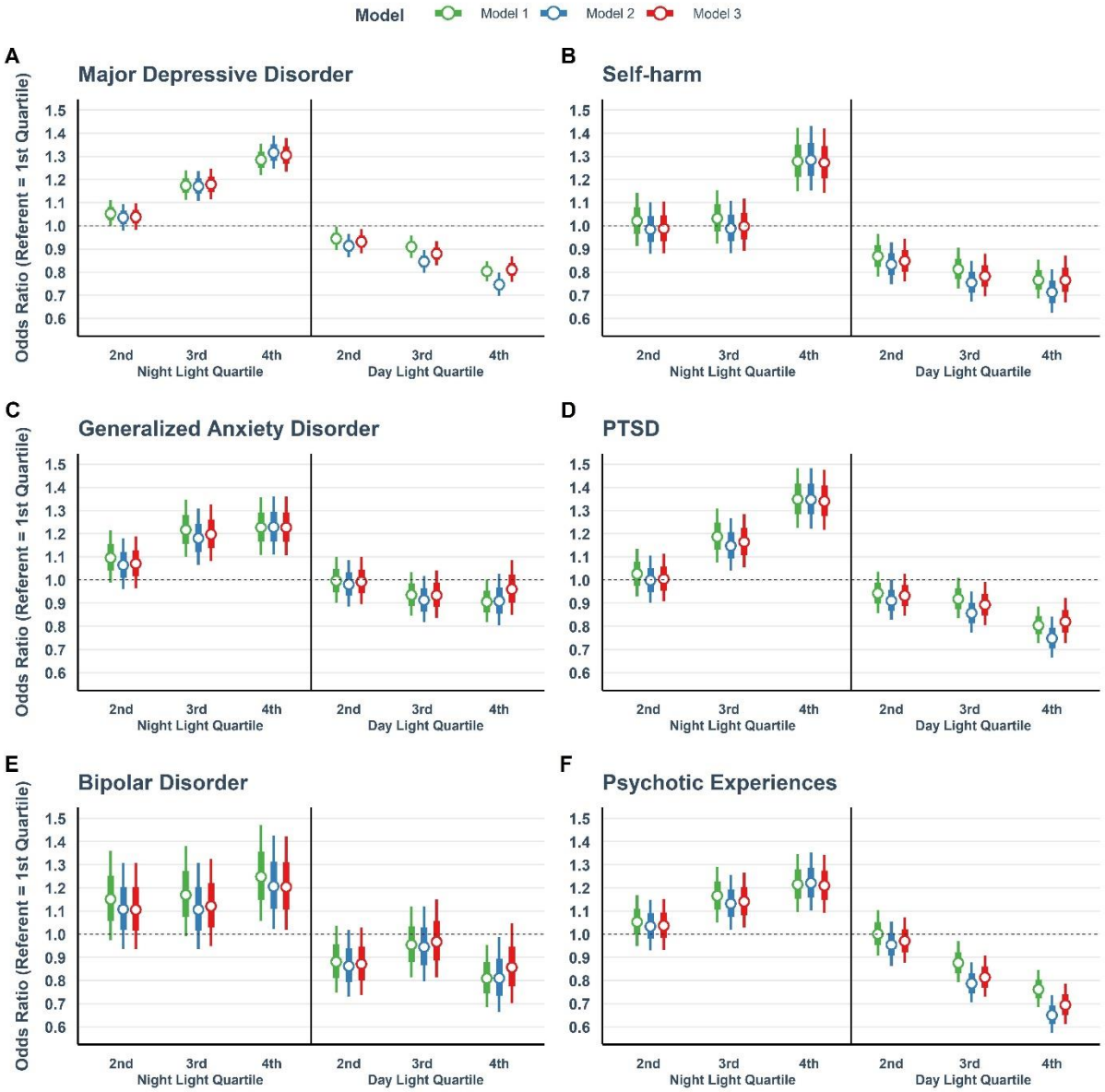

Figure 1. Coefficients plot for day and night-time light associations with (A) major depressive disorder, (B) self-harm behavior, (C) generalized anxiety disorder, (D) PTSD, (E) bipolar disorder and (F) psychotic experiences. Coefficients represent the odds ratios ± the SEM (inner error bar) and 95% CI (outer error bar) for each quartile of day and night light exposure relative to the low light (Q1) referent. Three models are presented with increasing adjustment for confounders: Model 1 (green) is unadjusted, Model 2 (blue) adjusts for age, sex, ethnicity and photoperiod and Model 3 (red) additionally adjusts for employment and physical activity.

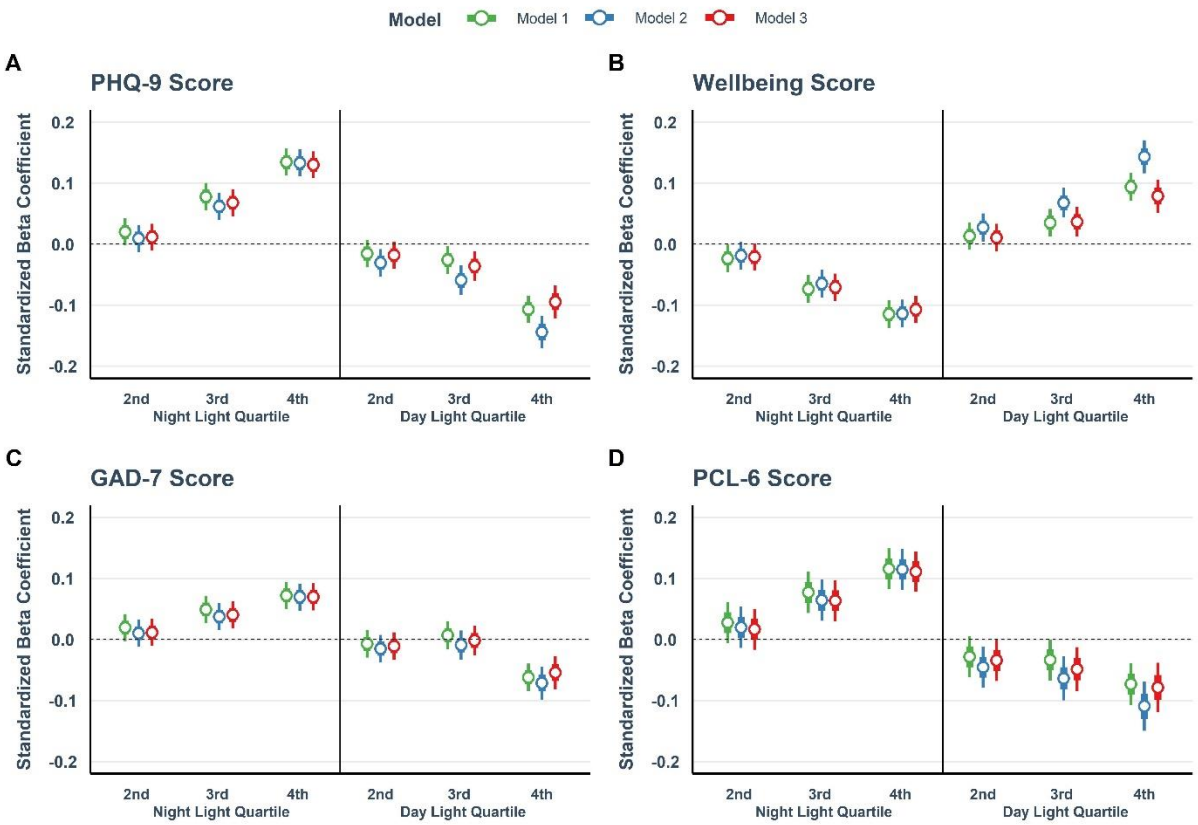

Figure 2. Coefficients plot for day and night-time light associations with (A) PHQ-9 score, (B) wellbeing score, (C) GAD-7 score and (D) PCL-6 score. Coefficients represent the standardized betas ± the SEM (inner error bar) and 95% CI (outer error bar) for each quartile of day and night light exposure relative to the low light (Q1) referent. Three models are presented with increasing adjustment for confounders: Model 1 (green) is unadjusted, Model 2 (blue) adjusts for age, sex, ethnicity and photoperiod and Model 3 (red) additionally adjusts for employment and physical activity.

Table 1. Demographic characteristics of participants by low and high day and night light exposure

	Day light			Night light		
	Low Q1 & Q2 N=43386	**High Q3 & Q4 N=43386**	***p* value**	**Low Q1 & Q2 N=43387**	**High Q3 & Q4 N=43385**	***p* value**
Age						
Mean (SD)	62.0 (7.94)	62.7 (7.71)	<0.001	62.6 (7.86)	62.1 (7.79)	<0.001
Median [Min, Max]	62.9 [43.6, 78.9]	64.0 [43.5, 78.8]		63.8 [43.5, 78.8]	63.2 [43.5, 78.9]	
Sex						
Female	25159 (58.0%)	24321 (56.1%)	<0.001	25352 (58.4%)	24128 (55.6%)	<0.001
Male	18227 (42.0%)	19065 (43.9%)		18035 (41.6%)	19257 (44.4%)	
BMI						
Mean (SD)	26.7 (4.57)	26.7 (4.47)	0.212	26.3 (4.31)	27.1 (4.68)	<0.001
Median [Min, Max]	26.0 [12.1, 67.3]	26.1 [14.1, 65.2]		25.7 [14.7, 58.4]	26.4 [12.1, 67.3]	
Missing	102 (0.2%)	83 (0.2%)		83 (0.2%)	102 (0.2%)	
White ethnicity	41679 (96.1%)	42226 (97.3%)	<0.001	42233 (97.3%)	41672 (96.1%)	<0.001
Missing	150 (0.3%)	141 (0.3%)		136 (0.3%)	155 (0.4%)	
Employment						
No	15912 (36.7%)	17412 (40.1%)	<0.001	17353 (40.0%)	15971 (36.8%)	<0.001
Yes	27474 (63.3%)	25974 (59.9%)		26034 (60.0%)	27414 (63.2%)	
Shiftwork						
No	39780 (91.7%)	40152 (92.5%)	<0.001	40545 (93.4%)	39387 (90.8%)	<0.001
Yes	3606 (8.3%)	3234 (7.5%)		2842 (6.6%)	3998 (9.2%)	
Townsend						
Mean (SD)	-1.60 (2.89)	-1.94 (2.68)	<0.001	-1.93 (2.69)	-1.61 (2.87)	<0.001
Median [Min, Max]	-2.34 [-6.26, 10.5]	-2.60 [-6.26, 9.89]		-2.60 [-6.26, 10.5]	-2.35 [-6.26, 9.99]	
Physical activity						
Mean (SD)	27.3 (7.89)	29.0 (8.16)	<0.001	28.1 (7.97)	28.3 (8.17)	<0.001
Median [Min, Max]	26.4 [5.12, 69.3]	28.1 [4.83, 69.4]		27.1 [4.83, 69.2]	27.3 [5.12, 69.4]	
Missing	39 (0.1%)	94 (0.2%)		60 (0.1%)	73 (0.2%)	
Photoperiod						
Mean (SD)	10.9 (2.87)	14.1 (2.58)	<0.001	12.4 (3.06)	12.6 (3.28)	<0.001
Median [Min, Max]	10.2 [7.47, 17.0]	14.8 [7.47, 17.0]		12.4 [7.47, 17.0]	12.8 [7.47, 17.0]	

Table 2. Associations between night light exposure and psychiatric outcomes

	Model 1 OR (95% CI)				Model 2 aOR (95% CI)*				Model 3 aOR (95% CI)†			
Night light	**2nd Quartile**	**3rd Quartile**	**4th Quartile**	**LRT *p*‡**	**2nd Quartile**	**3rd Quartile**	**4th Quartile**	**LRT *p*‡**	**2nd Quartile**	**3rd Quartile**	**4th Quartile**	**LRT *p*‡**
Major depressive disorder	1.05 (1.00 – 1.11)	**1.17 (1.11 – 1.24)**	**1.28 (1.22 – 1.36)**	**<0.0001**	1.04 (0.98 – 1.09)	**1.17 (1.11 – 1.24)**	**1.32 (1.25 – 1.39)**	**<0.0001**	1.04 (0.98 – 1.10)	**1.18 (1.12 – 1.25)**	**1.30 (1.23 – 1.38)**	**<0.0001**
Self-harm	1.02 (0.91 – 1.14)	1.03 (0.92 – 1.15)	**1.28 (1.15 – 1.42)**	**<0.0001**	0.99 (0.88 – 1.10)	0.99 (0.88 – 1.11)	**1.28 (1.15 – 1.43)**	**<0.0001**	0.99 (0.88 – 1.11)	1.00 (0.89 – 1.12)	**1.27 (1.14 – 1.42)**	**<0.0001**
Generalized anxiety disorder	1.10 (0.99 – 1.21)	**1.22 (1.10 – 1.35)**	**1.23 (1.11 – 1.36)**	**<0.0001**	1.06 (0.96 – 1.18)	**1.18 (1.07 – 1.31)**	**1.23 (1.11 – 1.36)**	**0.0002**	1.07 (0.97 – 1.19)	**1.20 (1.08 – 1.33)**	**1.23 (1.11 – 1.36)**	**0.0001**
PTSD	1.03 (0.93 – 1.13)	**1.19 (1.08 – 1.31)**	**1.35 (1.23 – 1.48)**	**<0.0001**	1.00 (0.90 – 1.11)	**1.15 (1.04 – 1.27)**	**1.35 (1.22 – 1.48)**	**<0.0001**	1.00 (0.91 – 1.11)	**1.16 (1.05 – 1.29)**	**1.34 (1.22 – 1.48)**	**<0.0001**
Bipolar Disorder	1.15 (0.98 – 1.36)	1.17 (0.99 – 1.38)	**1.25 (1.06 – 1.47)**	0.06	1.11 (0.94 – 1.31)	1.11 (0.94 – 1.31)	**1.21 (1.02 – 1.43)**	0.18	1.11 (0.94 – 1.31)	1.12 (0.95 – 1.32)	**1.20 (1.02 – 1.42)**	0.18
Psychotic Experiences	1.05 (0.95 – 1.17)	**1.17 (1.05 – 1.29)**	**1.21 (1.10 – 1.35)**	**0.0005**	1.03 (0.93 – 1.15)	**1.13 (1.02 – 1.26)**	**1.22 (1.10 – 1.35)**	**0.0004**	1.04 (0.93 – 1.15)	**1.14 (1.03 – 1.27)**	**1.21 (1.09 – 1.34)**	**0.0009**

Note: logistic regression was used for all outcomes and odds ratios (ORs) are presented with their 95% confidence intervals for each ascending night light quartile relative to the low light (Q1) referent. Model 1 is unadjusted. *Model 2 adjusted for age, sex, ethnicity, and photoperiod as a measure of seasonality. †Model 3 is additionally adjusted for employment and physical activity. ‡Likelihood ratio tests (LRT) were done as an omnibus test of significance for the night light factor. Bolded coefficients indicate significance at the .05 level.

Table 3. Associations between day light exposure and psychiatric outcomes

	Model 1 OR (95% CI)				Model 2 aOR (95% CI)*				Model 3 aOR (95% CI)†			
Day light	**2nd Quartile**	**3rd Quartile**	**4th Quartile**	**LRT *p*‡**	**2nd Quartile**	**3rd Quartile**	**4th Quartile**	**LRT *p*‡**	**2nd Quartile**	**3rd Quartile**	**4th Quartile**	**LRT *p*‡**
Major depressive disorder	**0.94 (0.90 – 1.00)**	**0.91 (0.86 – 0.96)**	**0.80 (0.76 – 0.85)**	**<0.0001**	**0.91 (0.86 – 0.97)**	**0.85 (0.80 – 0.90)**	**0.75 (0.70 – 0.80)**	**<0.0001**	**0.93 (0.88 – 0.99)**	**0.88 (0.83 – 0.93)**	**0.81 (0.76 – 0.87)**	**<0.0001**
Self-harm	**0.87 (0.78 – 0.97)**	**0.81 (0.73 – 0.90)**	**0.77 (0.69 – 0.85)**	**<0.0001**	**0.83 (0.75 – 0.93)**	**0.76 (0.67 – 0.85)**	**0.71 (0.63 – 0.81)**	**<0.0001**	**0.85 (0.76 – 0.94)**	**0.78 (0.70 – 0.88)**	**0.76 (0.67 – 0.87)**	**0.0001**
Generalized anxiety disorder	1.00 (0.90 – 1.10)	0.94 (0.85 – 1.03)	0.91 (0.82 – 1.00)	0.14	0.98 (0.89 – 1.09)	0.91 (0.82 – 1.02)	0.91 (0.81 – 1.03)	0.28	0.99 (0.90 – 1.10)	0.93 (0.84 – 1.04)	0.96 (0.85 – 1.09)	0.61
PTSD	0.94 (0.86 – 1.04)	0.92 (0.83 – 1.01)	**0.80 (0.73 – 0.89)**	**0.0001**	0.91 (0.83 – 1.00)	**0.86 (0.77 – 0.95)**	**0.75 (0.67 – 0.84)**	**<0.0001**	0.93 (0.85 – 1.03)	**0.89 (0.81 – 0.99)**	**0.82 (0.73 – 0.92)**	**0.01**
Bipolar disorder	0.88 (0.75 – 1.04)	0.95 (0.81 – 1.12)	**0.81 (0.69 – 0.95)**	0.06	0.86 (0.73 – 1.02)	0.94 (0.80 – 1.12)	**0.81 (0.67 – 0.99)**	0.10	0.87 (0.74 – 1.03)	0.97 (0.81 – 1.15)	0.86 (0.70 – 1.05)	0.22
Psychotic Experiences	1.00 (0.91 – 1.10)	**0.88 (0.79 – 0.97)**	**0.76 (0.69 – 0.85)**	**<0.0001**	0.95 (0.86 – 1.06)	**0.79 (0.71 – 0.88)**	**0.65 (0.57 – 0.74)**	**<0.0001**	0.97 (0.88 – 1.07)	**0.81 (0.73 – 0.91)**	**0.69 (0.61 – 0.79)**	**<0.0001**

Note: logistic regression was used for all outcomes and odds ratios (ORs) are presented with their 95% confidence intervals for each ascending day light quartile relative to the low light (Q1) referent. Model 1 is unadjusted. *Model 2 adjusted for age, sex, ethnicity, and photoperiod as a measure of seasonality. †Model 3 is additionally adjusted for employment and physical activity. ‡Likelihood ratio tests (LRT) were done as an omnibus test of significance for the day light factor. Bolded coefficients indicate significance at the .05 level.