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Mechanisms underlying the associations between different types of nature exposure and sleep duration: An 18-country analysis

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ABSTRACT

Whilst green space has been linked to healthier sleep outcomes, the roles of specific types of nature exposure, potential underlying mechanisms, and between-country variations in nature-sleep associations have received little attention. Drawing on cross-sectional survey data from an 18-country sample of adults (N = 16,077) the current study examined: 1) the relative associations between six different types of nature exposure (streetscape greenery, blue view from home, green space within 1 km, coast within 1 km, green space visits, blue space visits) and insufficient sleep (<6 h vs. 7–10 h per day); 2) whether these relationships were mediated by better mental wellbeing and/or physical activity; and 3) the consistency of these pathways among the different countries. After controlling for covariates, neighbourhood nature measures (green space, coast within 1 km) were not significantly associated with insufficient sleep; but nature visible from home (streetscape greenery, blue views) and recreational visits to green and blue spaces were each associated with less insufficient sleep. Significant nature-sleep associations were mediated, to varying degrees, by better mental wellbeing, but not self-reported physical activity. Country-level heterogeneity in the strength of nature-sleep associations was observed. Increasing nature visible from the home may represent a promising strategy for promoting healthier sleep duration at the population level, whilst nature-based interventions encouraging individuals to spend time in local green/blue spaces may be an appropriate target to assist individuals affected by insufficient sleep.

1. Introduction

Insufficient sleep - typically defined as less than 6 h per day - is a major determinant of morbidity and mortality worldwide (Chattu et al., 2019). Systematic reviews have linked insufficient sleep to a range of adverse health and wellbeing outcomes, including increased risks of mortality (Gallicchio and Kalesan, 2009; Cappuccio et al., 2011; Shen et al., 2016), non-communicable diseases (Guo et al., 2013; Cappuccio et al., 2011; Leng et al., 2015; Shan et al., 2015), obesity (Wu et al., 2014), cognitive impairments (Lo et al., 2016), and mental health issues

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(Baglioni et al., 2016). With non-trivial proportions of the population from industrialised countries reporting less than 6 h sleep per day (e.g. 18% and 16% of adults in the USA and UK, respectively; National Sleep Foundation, 2013), insufficient sleep constitutes a significant public health (Chattu et al., 2019).

Whilst the individual-level risk factors of insufficient sleep are well-established (e.g Stranges et al., 2008), there is increasing recognition of the environmental factors linked to human behaviour (Pearce et al., 2012; Martin et al., 2020a), including neighbourhood deprivation (Hale et al., 2010; Hale et al., 2010), urban/rural status (Ursin et al., 2005) and, crucially for the current study, neighbourhood green space. Shin et al. (2020) systematic review demonstrated that 6/7 cross-sectional studies reported that the availability of green space was associated with favourable sleep outcomes, including a lower risk of insufficient sleep. Intervention and longitudinal studies have observed similar benefits of green space, suggesting that these effects may be causal (Lee and Kim, 2008; Rappe and Kivelä, 2005; Astell-Burt and Feng, 2020; Mayne et al., 2021).

Whilst promising, the role of specific types of nature exposure, as well as potential underlying pathways and between-country differences in the nature-sleep relationship remain underexplored. Thus, the overarching aim of the current paper was to investigate these issues, using data from a large-scale multi-country cross-sectional survey.

2. Literature review

2.1. Distinguishing between different types of nature exposure

Nature-sleep research has predominantly used objective indices of green space within a defined geographical boundary, typically operationalised as the proportion of green space available within the *wider neighbourhood* (Triguero-Mas et al., 2017; Grigsby-Toussaint et al., 2015; Astell-Burt et al., 2013), or as subjective self-reports of natural features around an individual's *immediate residential location* (e.g. green views from home; Bodin et al., 2015). Both operationalisations have been associated with sleep outcomes, including higher nature exposure being linked to lower rates of insufficient sleep (Shin et al., 2020).

Yet, with studies focusing exclusively on a singular metric, the relative associations between different types of nature exposure and insufficient sleep remain unclear (i.e. the adjusted associations after controlling for potential shared variance between various types of nature contact). Evidence that perceptions of natural features do not always correspond to objective measures (Barlow et al., 2021), combined with research indicating that nature directly around the home exhibits stronger associations to broader health and wellbeing outcomes than objective neighbourhood measurements (Martin et al., 2019), highlights the importance of distinguishing between these two aspects of nature exposure.

Moreover, both neighbourhood and residential green space measures represent largely incidental forms of nature exposure (i.e. experiencing nature as a by-product of another activity, Keniger et al., 2013). There is increasing awareness that, compared to incidental contact, time spent voluntarily engaging with nature (e.g. making intentional nature visits) may be a stronger determinant of broader health and wellbeing outcomes (Shanahan et al., 2016; White et al., 2017; Martin et al., 2020b; White et al., 2020; 2021), as well as a range of health behaviours (e.g. smoking/excess drinking, Martin et al., 2020; Wiley et al., 2022). Intervention studies demonstrate that nature-based activities (e.g. forest walking, Morita et al., 2011; garden visits, Rappe and Kivelä, 2005) significantly improve sleep outcomes.

Whilst promising, such studies typically use relatively small, non-representative samples that are unable to adequately control for socio-demographic covariates that have previously been shown to be important for sleep outcomes (e.g. area-level deprivation, Hale et al., 2010; socio-economic status, Gellis et al., 2005). It is therefore unclear how generalisable these associations are beyond the specific samples used, after adjusting for potential socio-demographic confounders.

Further, heterogeneity in the operationalisation of nature exposures and sleep outcomes between studies limits the scope for cross-study comparisons (Feng et al., 2020). Thus, the relative associations between different types of nature exposure and insufficient sleep are yet to be established. This is important to address for two reasons. First, this type of comparison enables policy makers and practitioners to determine the focus of public health strategies and environmental interventions. Second, with evidence of additive effects of multiple types of nature exposure on broader health and wellbeing outcomes (Shanahan et al., 2016; White et al., 2017, 2021; Martin et al., 2020b), it is conceivable that multiple types of nature exposure may be simultaneously associated with insufficient sleep.

2.2. Environment type: green space & blue space

To date, the nature-sleep literature has focused almost exclusively on green spaces (e.g. Astell-Burt and Feng, 2020) or natural spaces in general (e.g. Triguero-Mas et al., 2017). There are several reasons, however, to assume that exposure to blue spaces (e.g. rivers, lakes, coastlines) may also be relevant to rates of insuffient sleep.

Firstly, there is growing evidence of the potential benefits of blue spaces for adult health and wellbeing (Hermanski et al., 2022; Völker and Kistemann, 2011, 2015; White et al., 2020), even after accounting for residential green space (White et al., 2021). Given the strong relationship between broader health/wellbeing outcomes and health behaviours (WHO, 2016), it seems plausible to hypothesise that greater exposure to blue spaces may independently predict lower rates of insuffient sleep. Secondly, blue spaces have unique sensory qualities (Völker and Kistemann, 2015; Ruiz-Gil et al., 2020) that could potentially aid better sleep. For instance, listening to ocean soundscapes that emulate white noise (Riedy et al., 2021; Harris, 2022) has been shown to improve a range of sleep outcomes, including sleep duration, within healthcare settings (Williamson, 1992). Equally, the sound of slow running fresh water sources (e.g. streams, rivers) may be useful for masking urban traffic noise (You, Lee, &. Jeon, 2010), which is itself associated with sleep disturbances (Halonen et al., 2012). Thirdly, recent research has linked the presence of residential blue spaces to better quality of sleep (Li et al., 2024). Whilst these findings situate blue space exposure as a potentially important predictor of insufficient sleep in its own right, it remains to be established whether these links are demonstrable at the population level, after accounting for relevant socio-demographic covariates and green space exposures.

To address these gaps in the literature, the first aim of the current study was to examine the relative associations between six distinct types of nature exposure and insufficient sleep, whilst adjusting for a wide range of individual and area-level covariates. Specifically, we distinguished between two broad environment types (green space, blue space) across three different categories of nature exposure (perceived nature visible from home [streetscape greenery, blue view]; objective nature within the wider neighbourhood: [green space within 1 km, coast within 1 km]; and self-reported recreational nature visits [green space visits, blue space visits]).

2.3. Potential mechanisms underlying nature-sleep associations

Identifying the lack of research concerning nature-sleep mediators, Astell-Burt and Feng (2020) propose three potential pathways underpinning the association between nature exposure and lower rates of insufficient sleep. Briefly, nature exposure may prevent insufficient sleep by: 1) mitigating urban noise, air pollution and heat island effects (Annerstedt et al., 2013; Abhijith et al., 2017); 2) promoting psychologically restorative experiences that benefit mental wellbeing (Hartig et al., 2014); and, 3) providing settings that facilitate increased physical activity (Kredlow et al., 2015). Examination of mitigation pathways is beyond the scope of the current study, therefore our focus here is on exploring the potential for better mental wellbeing and greater physical activity to mediate nature-sleep associations.

There is a substantial body of empirical work indicating reduced stress levels and improved affect amongst individuals exposed to relatively natural (*vs.* more urban) environments (Gidlow et al., 2016; Bowler et al., 2010; Yao et al., 2021; McMahan and Estes, 2015; Browning et al., 2020). Epidemiological studies have linked both neighbourhood green space (Cohen-Cline et al., 2015; Zhang et al., 2021; Reyes-Riveros et al., 2021; Feng et al., 2022) and coastal proximity (Hermanski et al., 2022; McDougall et al., 2021; White et al., 2021) to a lower incidence of mental health issues, as well as better subjective wellbeing. Similarly, natural features immediately visible from home (Guzman et al., 2021; Honold et al., 2016), as well as recreational visits to green and blue spaces (White et al., 2021), have been positively associated with a variety of wellbeing outcomes. Given evidence from prospective studies identifying affective disorders as a risk factor for sleep disturbances in later life (Smagula et al., 2016; although see Kalmbach et al., 2014 for a discussion of potential bi-directionality), better mental wellbeing has the potential to mediate the associations between each type of nature exposure and insufficient sleep.

Meta-analyses indicate that greater physical activity can support healthier sleep duration (Atoui et al., 2021; Kredlow et al., 2015). Despite being intuitively appealing, evidence that more incidental forms of nature exposure (e.g. neighbourhood green space, coastal proximity) are related to greater physical activity is mixed (Remme et al., 2021). Whilst some studies have observed significant positive relationships (Giles-Corti, et al., 2005; Coombes et al., 2010), associations are often weak and have been contradicted by numerous studies reporting no significant effects (Feng et al., 2022; Klompmaker et al., 2018; Maas et al., 2008; Mytton et al., 2012).

Unequivocal findings may be an artefact of differences in the measurements of both nature exposure and physical activity, as well as genuine heterogeneity driven by contrasting climatic, ecological, cultural and socioeconomic contexts. Conversely, there is good evidence that recreational nature visits are a predictor of greater engagement in physical activity, even after controlling for other types of nature exposure (Flowers et al., 2016; Poulsen et al., 2022), as well as support for the contention that physical activity within natural environments supports better sleep (Ratcliffe, 2015).

Some researchers conceptualise nature visits as partially mediating the associations between neighbourhood nature and physical activity (i.e. living in greener neighbourhood encourages more nature visits, thereby increasing physical activity, Hartig et al., 2014; Markevych et al., 2017). However, people travel considerable distances to visit their favourite places (Amegbor et al., 2021; Schindler et al., 2022; Astell-Burt and Feng, 2021), with a substantial proportion of nature visits taking place outside of an individual's immediate neighbourhood (Wyles et al., 2019). Moreover, contrary to common assumptions about greener areas facilitating more time in nature, there is evidence that people living in the *least* green areas spend significantly more time in nature than those living in greener areas (White et al., 2020). This suggests that recreational nature visits are not solely determined by the availability of neighbourhood nature.

On this basis, we would not expect the association between neighbourhood nature and insufficient sleep to be mediated by more frequent nature visits and higher physical activity in a serial manner. Rather, prior research findings suggest that recreational nature visits may independently predict higher physical activity levels, which could in turn be associated with lower rates of insufficient sleep. Accordingly, the second aim of the current study was to explore the roles of mental wellbeing and physical activity as potential mechanisms underlying nature-sleep associations.

2.4. Potential country/region variations in nature-sleep associations

According to an international sleep poll, the rates of insufficient sleep varies considerably between countries, with two-thirds (66%) of Japanese respondents reporting less than 6 h of sleep per day compared to around 16% of respondents from the UK (National Sleep Foundation, 2013). Equally, whilst individuals from different cultures tend to prefer more natural as opposed to highly-built environments (Ulrich, 1993), cultural factors have been shown to affect people's aesthetic perceptions and preferences (Kaplan and Herbert, 1987; Kaplan and Talbot, 1988; Todorova et al., 2004; Van den Berg et al., 1998; White et al., 2014), as well as their recreational use of natural spaces (Loukaitou-Sideris, 1995). Therefore, country-specific differences in sleeping habits and environmental preferences have the potential to influence the strength of nature-sleep associations. Indeed, Feng et al. (2020) findings that the strength of the relationship between greenspace and insufficient sleep among 10 year old participants varied substantially between German and Australian samples, indicate potential between country differences in nature-sleep associations.

With no prior work regarding cross-cultural differences in nature contact and insufficient sleep in adult samples, we made no specific hypotheses regarding the consistency of these associations across countries/regions. Nonetheless, due to the international nature of the sample, the final aim of the current study was to assess the consistency of associations between different types of nature exposure, proposed mediators, and the rates of insufficient sleep across 18 countries/regions.

2.5. The current study

The current study extended prior research by investigating the associations between six types of nature exposure (perceived nature visible from home: streetscape greenery, blue view; objective nature within the wider neighbourhood: green space 1 km, coast within 1 km; recreational nature visits: green space visits, blue space visits), mental wellbeing, physical activity, and insufficient sleep, using representative cross-sectional samples from 18 countries/regions. The aims of the study were threefold: 1) to investigate the relative associations between six types of nature exposure and the rates of insufficient sleep, whilst controlling for a range of socio-demographic covariates; 2) to explore whether these relationships were mediated by higher mental wellbeing and/or greater levels of physical activity; and 3) to examine the consistency of these associations between different countries/regions.

Fig. 1 presents a schematic model depicting the hypothesised associations between variables of interest. Based on prior theory and research, our overarching hypotheses were as follows: 1) that each type of nature exposure would be associated with lower rates of insufficient sleep (H1); 2) positive associations would be observed between each nature exposure type and mental wellbeing (H2); 3) the frequency of nature visits would be associated with greater engagement in physical activity (H3); and, 4) greater mental wellbeing (H4) and physical activity (H5) would predict lower rates of insufficient sleep.

3. Method

3.1. Participants and procedure

Data were extracted from the BlueHealth International Survey ([BIS]; Grellier et al., 2017), a cross-sectional survey of 18,838 adults (9645 females) from 18 countries/regions (Bulgaria, California [USA], Canada, Czech Republic, Estonia, Finland, France, Germany, Greece, Hong Kong [China], Ireland, Italy, the Netherlands, Portugal, Queensland [Australia], Spain, Sweden, and the United Kingdom). Representative samples, typically stratified on age, sex, and region of residence, were obtained for each country/region by the international polling company YouGov using online survey panels, in four seasonal waves between June 2017 and April 2018. Full details are available in the technical report (Elliott and White, 2020).

The current study used a sub-sample of the BIS dataset ($N = 16{,}077$) for cases where there were no missing data for any of the variables

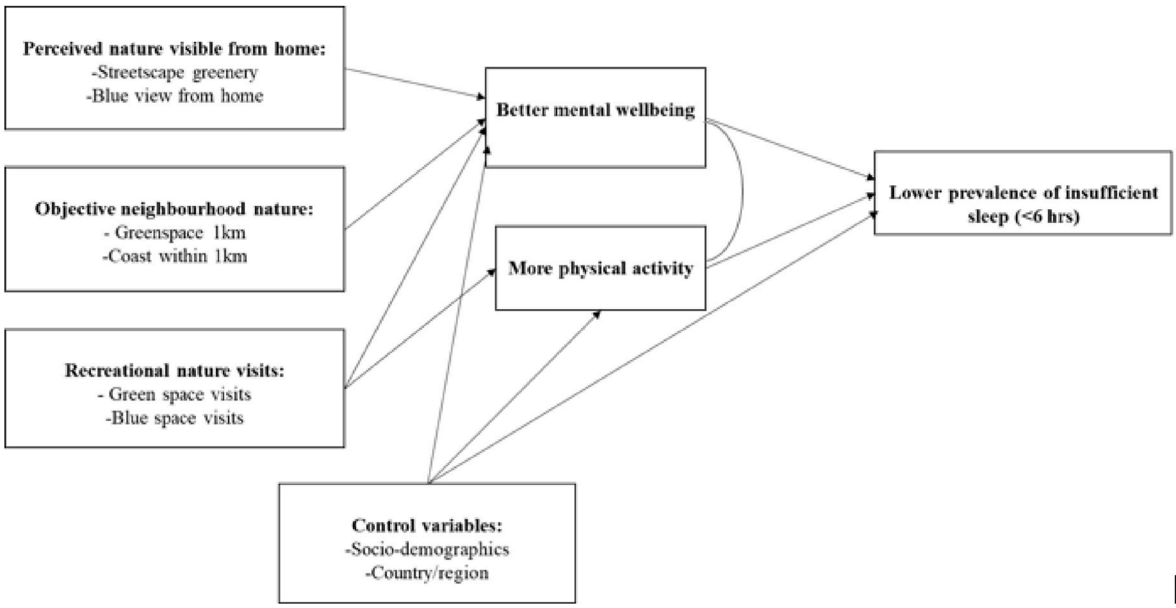

Fig. 1. Schematic representation of conceptual model of the relationships between nature exposures, proposed mediators and insufficient sleep.

included within the analyses. There was little variation in the proportion of respondents within each socio-demographic group as a function of the reduced sample, indicating no systematic biases in the exclusion of cases.

3.2. Measures

3.2.1. Outcome variable - insufficient sleep

Sleep duration was assessed using a single item question adapted from Astell-Burt et al. (2013): '*About how many hours in each 24 h day do you usually spend sleeping, including at night and naps*?' Response options were: 1) Less than 6 h; 2) 7 h; 3) 8 h; 4) 9 h; 5) 10 h; and 6) Over 10 h. Consistent with prior research in the field (Astell-Burt and Feng, 2020) insufficient sleep was operationalised as less than 6 h (*vs.* 7–10 h) sleep. With longer sleep durations linked to poor health (Jike et al., 2018; Stamatakis and Punjabi, 2007), respondents who reported sleeping over 10 h ($N = 214$), as well as two missing cases (from Hong Kong, where skipping questions was permitted) were excluded from the analyses.

3.2.2. Predictor variables - nature exposure

Following previous research (Weinstein et al., 2015; Martin et al., 2020a,b) a range of nature exposure metrics were operationalised.

Streetscape greenery: perceived streetscape greenery was assessed using a single-item question adapted from de Vries et al. (2013), in which respondents were required to rate how green the street on which they lived was, on a 5 point scale, ranging from not very green (1) to very green (5). It was unclear whether respondents who selected 'Non-applicable, I do not live on a street' ($N = 262$) had no streetscape greenery at all, or simply lived in a rural location which they did not consider a street, therefore these individuals were excluded from the analyses.

Blue view: respondents indicated whether they had a view of blue space from home (no = reference, yes; Garrett et al., 2019). Respondents with missing data ($N = 2$) were excluded from the analyses.

Two objective measures of nature exposure within 1 km of respondent's home geolocation (representing a 10–15 min walk; Smith et al., 2010) were derived from existing datasets. As these data were only available for respondents who provided a valid geolocation, including these variables excluded 1804 cases. Home geolocations were entered by the respondents using a Google Maps API and exact coordinates were rounded to three decimal degrees on the latitude and longitude scale, to preserve anonymity. This resulted in on average 55m error in the precise geolocation, with greater error at more extreme latitudes.

Neighbourhood green space: the proportion (%) of neighbourhood green space within a 1 km radial buffer of each respondent's geolocation was assigned using the 2010 Global Land Cover dataset (GlobeLand30). Developed by the National Geomatics Center of China, with 30m spatial resolution, the dataset provides a globally-consistent classification of remotely-sensed land cover data. Land classified as forests, grassland, shrubland, and cultivated land was collapsed into a single continuous 'green space' measure.

Distance from the coast: Distance from the home coordinate to the nearest coastline, using a Euclidean (crow-flies) distance metric, was defined by the highest resolution version of the Global Self-consistent Hierarchical High-resolution Geography shoreline database from the US National Oceanic and Atmospheric Administration (NOAA) (Wessel and Smith, 1996). This measure did not include other waterbodies (e.g. rivers or lakes). With large skews in the distribution, consistent with prior work (White et al., 2021) distance to coast was dichotomised according to whether respondents had a coastline within 1 km of their home coordinates (no = reference, yes).

3.2.2.1. Recreational nature visits.

Consistent with the People and Nature Survey (Natural England, 2018) respondents were required to indicate how often they had visited various types of green spaces (e.g. local parks, woodlands) and blue spaces (e.g. lakes, beaches), in the last four weeks. Response options were: 1) Not at all; 2) Once or twice; 3) Once a week; 4) Several times a week. Consistent with prior work using the same dataset (White et al., 2021), a numerical equivalent of these response options was estimated to be zero, one, four and eight visits in the last four weeks, respectively. Our decision regarding the latter, was informed by an unpublished analysis of ten waves of nationally representative survey data (Natural England, 2018) wherein respondents who considered themselves to visit natural environments 'several times a week' over the course of a year (N = 22,559), reported an average of two visits when asked to provide a count of their nature visits within the last seven days (Supplementary Materials 1). Given evidence that self-report recall accuracy diminishes over time (Short et al., 2009), we suspect that many people overestimate their visit frequency over longer recall periods, therefore we opted to be cautious and coded 'several times a week' as eight visits in the last four weeks. The frequencies of visits to green and blue spaces over the last four weeks were derived by summing the frequency estimates of corresponding environment types. With a small proportion of individuals ($\leq$1.5%) reporting very high visit frequencies introducing considerable skew, the total number of visits were capped to 56, consistent with somebody, for example, visiting natural spaces twice a day over a four week period. For temporal consistency with other variables of interest (i.e. mental wellbeing), visit totals were subsequently divided by two, thereby representing the number of visits to green and blue spaces over the last two weeks. A robustness check operationalising green/blue spaces visits as categorical variables (Supplementary Materials 2) showed that the direction of associations between nature visits and variables of interest (mental wellbeing, physical activity, insufficient sleep) were consistent with the main models, indicating our estimations of visit frequency did not affect the overall pattern of findings.

3.2.3. Proposed mediators

3.2.3.1. Mental wellbeing. With favourable psychometric properties (Topp et al., 2015; $\alpha = 0.92$ in the current study), the WHO-5 was used as a concise global measure of subjective wellbeing. The scale consists of five positively phrased items: 1) “I have felt cheerful and in good spirits”; 2) “I have felt calm and relaxed”; 3) “I have felt active and vigorous”; 4) “I woke up feeling fresh and rested”; and 5) “My daily life has been filled with things that interest me”. Respondents were required to indicate the extent to which each applied to them during the last two weeks on scales ranging from “At no time” (0) to “All of the time” (5). Respondents with missing data for any of the five items ($N = 22$) were excluded from the analyses. Item scores are summed and multiplied by four, to give a total score out ranging from 0 to 100, with higher scores reflecting better wellbeing.

Despite exhibiting a significant but weak correlation with sleep insufficiency ($r = 0.17$, $p = <.001$), given that the wording of item four pertains to how respondents felt upon waking, it has the potential to inflate the associations between composite scores and our outcome variable. To assess this possibility, we conducted a sensitivity analysis comparing models including *vs.* excluding this item (Supplementary Materials 3). With little difference in the strength of the associations between sleep insufficiency and mental wellbeing across models, those based on the full measure are reported here in order to maintain scale integrity.

3.2.3.2. Physical activity. A validated single-item instrument developed by Milton et al. (2010) provided a measure of physical activity. Respondents were provided with the following information: ‘*Think now about any physical activity you might engage in. This may include sport, exercise, and brisk walking or cycling for recreation or to get to and from places, but should not include housework or physical activity that may be part of your job*’ and required to indicate, within the last seven days, how many days they engaged in a total of 30 min or more of physical activity that was enough to raise their breathing rate (0–7). To ensure that this item was temporally consistent with other variables, scores on the item were multiplied by two, to provide an estimation of physical activity within the last two weeks.

3.2.4. Control variables

Given that the outcome and predictor variables have been previously associated with a range of socio-demographic covariates (e.g. socio-economic status, Gellis et al., 2005) several control variables were included within the multivariate analyses. Demographic controls included: gender (female, male = reference); age (18–29 = reference, 30–39, 40–49, 50–59, 60+); long-term limiting illness or disability (no = reference, yes); completed higher education (yes, no = reference); working status (unemployed = reference, employed, in education, retired, other); marital status (married/cohabiting, single/widowed/divorced = reference, undisclosed); whether the respondent identified as belonging to a minority ethnic group in their country of residence (no = reference, yes, undisclosed); taking pain medication (no = reference, yes); coping on present income (no = reference, yes); children in household (no = reference, yes); dog ownership (no = reference, yes); and population density (km^2, Gridded Population of the World[1]). Country/region of residence (Queensland [Australia] = reference, Bulgaria, California [US], Canada, Czech Republic, Estonia, Finland, France, Germany, Greece, Hong Kong [China], Ireland, Italy, Netherlands, Portugal, Spain, Sweden, United Kingdom) was also included in the full-sample models as a random intercept term.

3.3. Analytical approach

Analyses were conducted using STATA 16 (StataCorp, College Station, TX). Bivariate correlations were used to determine the direction of associations between our key variables. Whole sample and country-specific mediation effects were formally tested using Generalised Structural Equation Modelling (GSEM) approach, which is capable of handling discrete and continuous endogenous variables (i.e. those that are hypothesised to be influenced by their relationships to other variables), as well as testing mediation effects in clustered data (i.e. by country; Krull and MacKinnon, 2001). Specifically, GSEM was used to test the systematic model depicted in Fig. 1 whilst controlling for covariates.

The observed nature exposure variables (streetscape greenery, blue view, green space 1 km, coast within 1 km, green space visits and blue space visits), observed mediator variables (mental wellbeing, physical activity), plus control variables, were included in the model to predict the observed variable insufficient sleep (<6 h). With evidence that logistic regressions for common binary outcomes (>10%) can overinflate relative risk, (McNutt et al., 2003; Chen et al., 2018), these paths were estimated using Poisson regressions with robust standard errors. Finally, using ordinary least squares linear regressions, the six nature exposure indicators plus control variables were regressed onto mental wellbeing; and recreational nature visit variables and covariates were regressed onto physical activity. As conceptually related processes, the residual terms of each mediator variable (mental wellbeing and physical activity) were allowed to co-vary.

For our whole sample analyses, we used a two-level model, with country/region of residence included as a random intercept term within each regression equation, to account for national-level respondent clustering. We report the unstandardised regression coefficients (*b*), robust standard errors (SE) and bootstrapped 95% confidence internals (95% CIs; 1000 resamples). For all models, goodness of fit indices included: the comparative fit index (CFI) > 0.95; Tucker-Lewis Index (TLI) > 0.95; standardized root-mean-square residual (SRMSR) < 0.08; and the root-mean-square error of approximation (RMSEA) < 0.06 (Schreiber, 2008). Chi-square goodness of fit values ($\chi 2$) were not used to assess fit, because this index is less informative with larger samples (Schermelleh-Engel et al., 2003).

Decomposition of total, direct, and indirect effects were calculated using the product-of-coefficients approach (VanderWeele and Vansteelandt, 2014; Hou, 2014). Specific indirect effects were examined in both the presence/absence of non-significant total effects, as suppression effects have the potential to obscure the impact of individual mediators (MacKinnon et al., 2000).

[1] Population density data was obtained from the Gridded Population of the World, Version 4 (GPWv4) and was assigned respondents using home latitude and longitude.e The measure represents the number of people per square kilometre based on counts Units are the number of people per square kilometre based on counts consistent with national censuses and population registers with respect to relative spatial distribution, but adjusted to match the 2015 Revision of the United Nation’s World Population Prospects (UN WPP) country totals.

4. Results

4.1. Preliminary analysis

Descriptive statistics and bivariate analyses are presented in Table 1. Consistent with previous studies (National Sleep Foundation, 2013), approximately one fifth of respondents (19%) reported insufficient sleep (<6 h). Bivariate associations were consistent with the hypothesis that each type of nature exposure would be positively related to mental wellbeing; and visits to green and blue spaces exhibited the strongest positive associations to physical activity.

Associations with insufficient sleep were more nuanced at the bivariate level: 1) more streetscape greenery and more frequent green space visits were negatively associated with insufficient sleep, as predicted; 2) for blue views from home and coast within 1 km, hypothesised negative associations were weak and non-significant; and 3) contrary to expectations, more frequent blue space visits were positively related to insufficient sleep.

4.2. Main analysis

4.2.1. Whole sample models

The whole sample model exhibited an excellent fit to the data (CFI = 0.99, SRMR = 0.003, RMSEA = 0.03). Fig. 2 depicts all paths between variables of interest. Table 2 presents a decomposition of the total, direct, and indirect effects of nature exposure indicators on insufficient sleep, as well as the indirect effects through mental wellbeing and physical activity (full model details, including covariates are reported in Supplementary Materials 4).

Perceived nature visible from home: Both streetscape greenery (b = 1.2792; *95% CIs* = 1.0348, 1.5236, $p < 0.001$) and blue view from home (b = 0.9338; *95% CIs* = 0.2172, 1.6504, $p = 0.011$) were associated with higher mental wellbeing, which in turn predicted lower rates of insufficient sleep (b = −0.0106; *95% CIs* = −0.0088, −0.1168, $p < 0.001$). Significant direct (b = −0.0337; *95% CIs* = −0.0047, −0.3742, p = 0.023) and indirect (b = −0.0135; *95% CIs* = −0.0169, −0.0101, $p <$ 0.001) paths between streetscape greenery and insufficient sleep indicate that mental wellbeing partially mediated this association, accounting for 29% of the total effect (b = −0.0472; *95% CIs* = −0.0763, −0.0182, $p < 0.001$). In contrast, having a blue view from home exhibited non-significant direct (b = 0.0355; *95% CIs* = −0.0507, 0.1217, p = 0.420) and significant indirect effects through mental wellbeing on insufficient sleep (b = −0.0099; *95% CIs* = −0.0176, −0.0021, $p = 0.013$), suggesting that having a blue view from home was linked to lower rates of insufficient sleep via higher mental wellbeing.

Objective nature within the wider neighbourhood: neighbourhood green space (b = −0.0079; *95% CIs* = −0.0162, 0.0004, $p = 0.062$) and living less than 1 km from the coast (b = −0.0827; *95% CIs* = −1.0773, 0.9120, p = 0.871) had unexpected non-significant associations with mental wellbeing, as well as non-significant direct effects on insufficient sleep (b = −0.0002; *95% CIs* = −0.0012, 0.0008, $p = 0.654$; and b = −0.0513; *95% CIs* = −0.1731, 0.0705, $p = 0.409$, respectively).

Recreational nature visits: more visits to green space and blue space were associated with higher mental wellbeing (b = 0.5680; *95% CIs* = 0.5068, 0.6292, $p < 0.001$; *and* b = 0.3358; *95% CIs* = 0.2790, 0.3926, p < 0.001, respectively), as well as higher levels of physical activity (b = 0.1526; *95% CIs* = 0.1400, 0.1652, $p < 0.001$; and b = 0.0470; *95% CIs* = 0.0357, 0.0583, p < 0.001, respectively). Mental wellbeing scores were, in turn, associated with lower rates of insufficient sleep (b = −0.0106; *95% CIs* = −0.0088, −0.1168, $p < 0.001$), whereas physical activity did not significantly predict sleep duration (b = −0.0014; *95% CIs* = −0.0010, 0.0072, $p = 0.754$). Examination of the specific indirect effects indicated that the negative associations between the two visit indicators and insufficient sleep were mediated by better mental wellbeing (green space visits: b = −0.0060; *95% CIs* = −0.0072,-0.0048, $p <$ 0.001; and blue space visits: b = −0.0016; *95% CIs* = −0.0044, −0.0027, $p < 0.001$).

4.2.2. Country/region specific models

To assess the consistency of these associations across countries/regions, a series of country-specific SEM models were specified. A summary of the direction of the associations between key variables across the 18 country/regional sub-samples are presented in Table 3 (Full models are presented in Supplementary Materials 5). Consistent with our main models, more streetscape greenery, green space visits and blue space visits typically had positive direct effects on mental wellbeing, but the strength of these associations varied between countries/regions.

Notably, for streetscape greenery significant positive direct effects on mental wellbeing were observed in 12/18 countries (California, Canada, Czechia, Estonia, Finland, France, Ireland, Italy, Netherlands, Portugal, Spain, UK); with positive associations failing to reach the threshold of statistical significance in the remaining countries/regions (except Hong Kong were a non-significant negative association was observed). For green space visits, significant positive direct effects were observed for each country/region aside from Canada.

More blue space visits were associated with positive direct paths to

Table 1
Bivariate correlations between types of nature exposure, proposed mediators and insufficient sleep.

	1	2	3	4	5	6	7	8	9
1. Streetscape greenery	*3.37 (1.26)*								
2. Blue view (yes)	0.11 (<0.001)	*4545 (25.89%)*							
3. Green space 1 km (%)	0.16 (<0.001)	0.08 (<0.001)	*44.97 (38.19)*						
4. Coast within 1 km (yes)	−0.02 (0.010)	0.11 (<0.001)	−0.19 (<0.001)	*1831 (10.91%)*					
5. Green space visits	0.16 (<0.001)	0.21 (<0.001)	0.13 (<0.001)	−0.01 (0.062)	*6.08 (6.39)*				
6. Blue space visits	0.08 (<0.001)	0.30 (<0.001)	0.04 (<0.001)	0.14 (<0.001)	0.61 (<0.001)	*5.44 (7.01)*			
7. Mental wellbeing	0.13 (<0.001)	0.10 (<0.001)	0.04 (<0.001)	0.02 (0.050)	0.26 (<0.001)	0.23 (<0.001)	*60.00 (21.88)*		
8. Physical activity	0.10 (<0.001)	0.06 (<0.001)	0.02 (0.017)	−0.01 (0.528)	0.25 (<0.001)	0.18 (<0.001)	0.23 (<0.001)	*4.88 (4.44)*	
9. Insufficient sleep	−0.04 (<0.001)	−0.00 (0.940)	−0.00 (0.666)	−0.01 (0.337)	−0.03 (<0.001)	0.02 (0.002)	−0.15 (<0.001)	−0.04 (<0.001)	*3342 (19.25%)*

Note.; Figures below the diagonal derived from Pearson coefficients for continuous data and point bi-serial correlations for binary variables. Where both variables were binary, Pearson coefficients were used to estimate relationships for conciseness. Figures in bold along the diagonal express the Mean (Standard Deviation) of continuous variables and Numbers (%) for binary variables, all over figures reflect Coefficient (p-value).

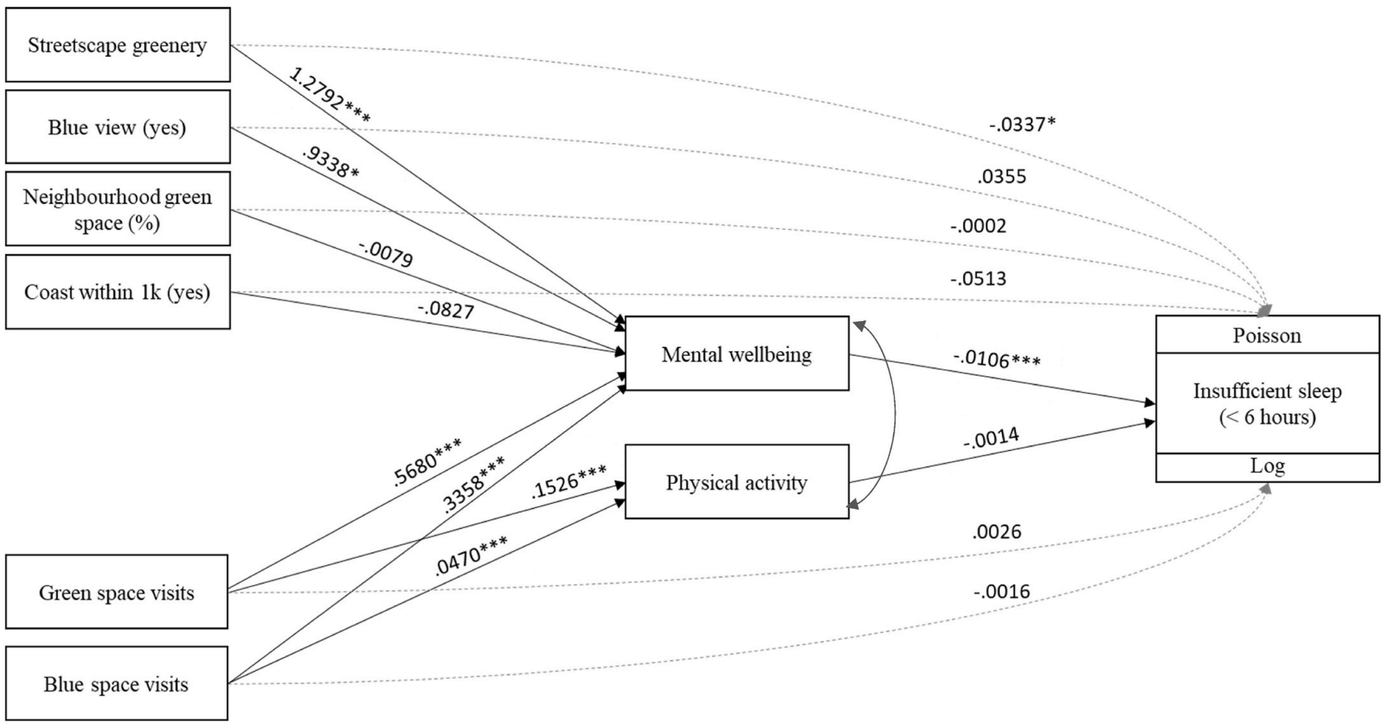

Fig. 2. *Path diagram with unstandardised coefficients between variables of interest, controlling for covariates (fixed-effects) with country/region included as a random effect. Note.* *p < 0.05, ***p < 0.001.

Table 2
Summary of total, direct and indirect pathways between nature contact variables and insufficient sleep (<6 h).

Outcome	Predictor	Pathway	*b*	*95% CIs*	*p*
Mental wellbeing	Streetscape greenery	Direct	1.2792	(1.0348, 1.5236)	<0.001
	Blue view from home (yes)	Direct	0.9338	(0.2172, 1.6504)	0.011
	Neighbourhood green space (%)	Direct	−0.0079	(-0.0162, 0.0004)	0.062
	Coast within 1 km (yes)	Direct	−0.0827	(-1.0773, 0.9120)	0.871
	Green space visits	Direct	0.5680	(0.5068, 0.6292)	<0.001
	Blue space visits	Direct	0.3358	(0.2790, 0.3926)	<0.001
Physical activity	Green space visits	Direct	0.1526	(0.1400, 0.1652)	<0.001
	Blue space visits	Direct	0.0470	(0.0357, 0.0583)	<0.001
Insufficient sleep (<6 h)	Mental wellbeing	Direct	−0.0106	(-0.0123, −0.0088)	<0.001
	Physical activity	Direct	−0.0014	(-0.0010, 0.0072)	0.754
	Streetscape greenery	Direct	−0.0337	(-0.0047, −0.3742)	0.023
		Indirect via mental wellbeing	−0.0135	(−0.0169, −0.0101)	<0.001
		Total	−0.0472	(−0.0763, −0.0182)	<0.001
	Blue view from home (yes)	Direct	0.0355	(−0.0507, 0.1217)	0.420
		Indirect via mental wellbeing	−0.0099	(−0.0176, −0.0021)	0.013
		Total	0.0256	(−0.0609, 0.1122)	0.562
	Neighbourhood green space (%)	Direct	−0.0002	(-0.0012, 0.0008)	0.654
		Indirect via mental wellbeing	0.0001	(-0.5211, 0.0002)	0.065
		Total	−0.0001	(-0.0011, 0.0008)	0.779
	Coast within 1 km (yes)	Direct	−0.0513	(-0.1731, 0.0705)	0.409
		Indirect via mental wellbeing	0.0009	(-0.0096, 0.0114)	0.871
		Total	−0.0505	(-0.1727, 0.0718)	0.419
	Green space visits	Direct	0.0026	(-0.0050, 0.0101)	0.508
		Indirect via mental wellbeing	−0.0060	(-0.0072, −0.0048)	<0.001
		Indirect via physical activity	−0.0002	(-0.0015, 0.0011)	0.754
		Total	−0.0036	(-0.0111, 0.0038)	0.336
	Blue space visits	Indirect via mental wellbeing	−0.0016	(-0.0044, −0.0027)	<0.001
		Indirect via physical activity	−0.0001	(-0.00047,0.0003)	0.754
		Total	−0.0052	(-0.0122, 0.0018)	0.144

Note. Estimates are based on fully-adjusted SEM controlling for covariates and including country/region as a random intercept (see Section 2.3), *b* = unstandardised coefficients.

mental wellbeing in 11/18 countries/regions (Queensland [Australia], Estonia, Finland, France, Germany, Greece, Italy, Portugal, Spain, Sweden, UK). Similarly, direct positive paths were present between green/blue space visits and physical activity in the vast majority of countries, but these relationships did not always meet the threshold for statistical significance given reduced samples (i.e. green space visits non-significant in Queensland [Australi]a, blue space visits non-significant in Bulgaria, Canada, California, Czechia, Hong Kong,

Table 3
Country/region specific models: summary of total, direct and indirect pathways between nature contact variables and insufficient sleep, after accounting for socio-demographic covariates.

Outcome	Predictor	Pathway	Australia	Bulgaria	California	Canada	Czechia	Estonia	Finland	France	Germany	Greece	Hong Kong	Ireland	Italy	Netherlands	Portugal	Spain	Sweden	UK
Mental wellbeing	Streetscape greenery	Direct	+	+	+	+	+	+	+	+	+	+	–	+	+	+	+	+	+	+
	Blue view	Direct	++	–	+	+	+	+	–	–	+	+	+	+	+	–	+	–	+	+
	Neigh. green space	Direct	–	–	+	–	-	-	–	+	–	–	–	–	+	+	+	–	+	–
	Coast within 1 km	Direct	+	–	+	–		-	+	+	–	–	–	+	+	+	+	+	+	+
	Green space visits	Direct	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	Blue space visits	Direct		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Physical activity	Green space visits	Direct	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	Blue space visits	Direct	+	+	+	–	–	+	+	+	+	+	+	+	+	–	+	+	+	+
Insufficient sleep	Mental wellbeing	Direct	-	-	-	–	+	–	–	–	–	–	–	–	–	–	–	–	–	–
	Physical activity	Direct	–	+	+	+	+	+	+	–	+	+	–	–	–	–	+	+	+	+
	Streetscape greenery	Direct	+	-	–	–	–	–	+	–	–	–	–	+	–	–	–	–	–	–
		Indirect via mental wellbeing	–	-	-	–	+	-	–	–	–	–	+	–	–	–	–	–	–	–
		Total	+	-	-	–	–	–	–	–	–	–	–	+	–	–	–	–	–	–
	Blue view	Direct	–	-	-	+	+	+	–	+	–	+	+	–	+	–	–	–	–	+
		Indirect via mental wellbeing	–	+	-	–	+	–	–	+	–	–	–	–	–	+	–	+	–	–
		Total	–	-	-	+	+	+	–	+	+	+	+	–	+	–	–	–	–	+
	Neigh. green space	Direct	–	+	-	–	–	–	–	–	+	–	++	–	–	+	–	–	–	+
		Indirect via mental wellbeing	–	+	-	+	–	+	+	–	–	+	+	–	–	–	–	+	–	+
		Total	–	+	-	–	–	–	–	–	+	+		–	–	+	–	–	–	+
	Coast within 1 km	Direct	+	+	-	–		+	–	+	+	–	–	–	+	–	–	+	+	–
		Indirect via mental wellbeing	+	+	-	+		+	–	–	+	+	+	–	–	–	–	–	–	–
		Total	+	+	-	–		+	–	+	+	–	–	–	+	–	–	+	+	–
	Green space visits	Direct	+	+	+	–	–	+	–	+	+	+	–	+	+	–	+	+	–	–
		Indirect via mental wellbeing	-	-	-	–	+	-	–	–	–	–	–	–	–	–	–	–	–	–
		Indirect via physical activity	–	+	+	+	–	+	+	–	+	–	–	–	–	–	+	+	+	–
		Total	+	+	+	–	–	+	–	+	–	+	–	–	–	–	+	+	–	–
	Blue space visits	Direct	–	+	–	+	+	–	+	–	–	–	–	+	+	–	–	+	+	+
		Indirect via mental wellbeing	-	–	–	–	+	–	–	–	-	–	–	–	–	–	–	–	–	–
		Indirect via physical activity	–	+	+	–	–	+	+	–	+	–	–	–	–	+	+	+	+	–
		Total	–	+	–	+	+	–	–	–	–	–	–	+	+	–	–	–	–	+

Note. + significant positive association, - significant negative association; grey represents the direction of non-significant associations.

Ireland and Netherlands).

Whilst higher mental wellbeing had significant negative direct effects on insufficient sleep in fifteen countries/regions, there was considerable country/region level heterogeneity in the indirect effects on insufficient sleep via mental wellbeing. Notably, significant negative indirect effects of streetscape greenery on insufficient sleep via mental wellbeing were only observed in six countries/regions (California, Canada, Estonia, Finland, Italy and Spain). Equally, the indirect effects of green space visits on insufficient sleep through mental wellbeing only reached statistical significance in eleven countries (Queensland [Australia],

Bulgaria, California, Estonia, Finland, Germany, Greece, Ireland, Italy, Spain and Sweden), whereas significant negative indirect effects of blue space visits via mental wellbeing were observed in just six countries (Queensland [Australia], Finland, Germany, Italy, Spain and.

Sweden). Overall, the results indicate that whilst positive associations between a) streetscape greenery, b) green space visits and c) blue space visits, and mental wellbeing are largely consistent across countries/regions, the extent to which this, in turn, predicted lower rates of insufficient sleep varied in terms of the strength of the relationship.

5. Discussion

Despite accumulating evidence that green space may support healthier sleep outcomes (Shin et al., 2020; Astell-Burt and Feng, 2020), the roles of specific types of nature exposure, potential underlying mechanisms and between country differences in nature-sleep associations have received little empirical attention. The current study investigated the associations between six types of nature exposure, two proposed mediators (mental wellbeing, physical activity) with insufficient sleep duration (<6 h per day), using representative cross-sectional samples from 18 countries/regions. The aims of the study were to investigate: 1) the relative associations between different types of nature exposure and the ratesof insufficient sleep; 2) whether these relationships were mediated by better mental wellbeing and/or physical activity; and, 3) the consistency of these pathways between different countries/regions.

5.1. Interpretation of main findings

In keeping with Bodin et al.'s. (2015) observation that individuals who have green views from home have healthier sleep patterns, streetscape greenery in the current study was inversely associated with insufficient sleep. We extended previous nature-sleep research, by demonstrating that having views of bluespace from home is also associated with a lower rate of insufficient sleep. In line with the broader health and wellbeing benefits of blue spaces (Hermanski et al., 2022; Völker and Kistemann, 2011, 2015), our findings suggest that having equitable access to public blue spaces may be a promising place-based intervention for supporting healthier sleep duration. Future research might usefully examine which types of visible blue spaces are most effective (e.g. oceans, lakes, ponds, water features) are most effective.

Supporting predictions that mental wellbeing may be one mechanism that underlies the relationships between nature exposure and insufficient sleep, path analyses indicated that both having more streetscape greenery and blue views from home were associated with lower rates of insufficient sleep via better mental wellbeing. Consistent with prior work demonstrating the affective benefits of natural features directly around the home (Guzman et al., 2021; Honold et al., 2016), the association between blue view from home and insufficient sleep was fully mediated by mental wellbeing. Partial mediation of the relationship between streetscape greenery and insufficient sleep via mental wellbeing suggests additional mechanisms may underpin this association.

Contrary to our hypotheses, neither measure of nature exposure within the wider neighbourhood (i.e. neighbourhood green space, coast within 1 km) significantly predicted mental wellbeing or insufficient sleep. This is inconsistent with the large body of research linking neighbourhood nature to wellbeing (Gascon et al., 2015; Collins et al., 2020) and healthier sleep outcomes (Shin et al., 2020). However, similar non-significant associations have been observed elsewhere (Chum et al., 2015; Martin et al., 2020a; Feng et al., 2020), with divergent findings between studies pertaining to green space and sleep being attributed to heterogeneity in the operationalisation of variables (Shin et al., 2020; Triguero-Mas et al., 2017).

Moreover, studies examining the relative associations between different types of nature contact and wellbeing have noted non-significant green space associations after controlling for other types of nature contact, indicating potential shared variance between nature exposure measures (Martin et al., 2020a; White et al., 2017). The non-significant bivariate correlations between measures of neighbourhood nature and insufficient sleep (Table 1) observed within the current study, however, suggest that this was not the case here. It is therefore possible, that the presence of natural characteristics within the wider neighbourhood were simply not an important determinant of healthy sleep duration within the current sample, whereas nature directly around and/or visible from home was a key factor.

Whilst speculative, visible green and blue spaces from home could operate as a micro-restorative settings, with immediate visual access providing more regular restorative opportunities (Hartig et al., 2014; Kaplan, 1995) than natural features within the wider neighbourhood. Certainly, the broader health and wellbeing benefits of having natural views from home have been noted elsewhere (Cox et al., 2017; Ward--Thompson et al., 2016; Kaplan, 2001; De Vries et al., 2013; Sop Shin, 2007; Dempsey et al., 2018; Nutsford et al., 2016). Alternatively, given that individuals' perceptions of natural features do not always correspond to objective measures (Barlow et al., 2021), our findings may simply reflect that self-reported perceptions of nature around the home better predict insufficient sleep than our objective neighbourhood measures. It is also possible that self-reported perceptions may tap into the perceived quality of natural features, rather than quantity per se (Astell-Burt and Feng, 2022). Further research comparing subjective and objective nature measures across different spatial scales, factoring in the quality of natural spaces, would be a useful next step.

Building upon interventions studies showing that nature-based activities improve a range of sleep outcomes (Morita et al., 2011; Rappe and Kivelä, 2005), we demonstrate for the first time, using population-level data, that more frequent visits to both green *and* blue spaces are independently associated with lower rates of insufficient sleep. Our findings highlight that the benefits associated with recreational nature visits may extend beyond health and wellbeing outcomes (White et al., 2017; Cox et al., 2018) to healthier sleep duration. Regarding the mechanisms underlying these associations, consistent with prior research (e.g. White et al., 2021; Poulsen et al., 2022), visits to green and blue spaces predicted both better mental wellbeing and greater engagement in physical activity. However, only the indirect paths via mental wellbeing were, in turn, associated with lower rates of insufficient sleep. In line with prospective studies identifying affective disorders as a risk factor for sleep disturbances in later life (Smagula et al., 2016), our findings suggest that the mental wellbeing benefits associated with nature visits (White et al., 2021) may support healthier sleep durations.

The lack of association between physical activity and insufficient sleep is at odds with meta-analyses indicating that greater physical activity supports better sleep (Atoui et al., 2021; Kredlow et al., 2015). The null results may relate to the inclusion of multiple mediators within the current study. It may be that physical activity is simply a less important determinant of insufficient sleep, once mental wellbeing is accounted for. However, we recognise that the complex, potential bidirectional, links between wellbeing, physical activity and sleep are difficult to capture using cross-sectional linear models. Notably, from a theoretical perspective, physical activity may improve mental wellbeing and sleep

(Schuch et al., 2019; Kredlow et al., 2015), better sleep aids mental wellbeing (Rezaei et al., 2018); and both low activity level and poor sleep can adversely affect mental health (Ji et al., 2019). Further longitudinal work capable of disentangling these potential inter-relationships is therefore a vital next step for nature-sleep research.

With prior research on adults exclusively using single country data, the current study furthers our understanding of country-level differences in nature-sleep associations. Our country-specific models indicate that positive associations between a) streetscape greenery, b) green space visits and c) blue space visits, and mental wellbeing were largely consistent across countries/regions. However, perhaps due to the relatively small effects and the reduced sample sizes at the country level (Deng et al., 2018), a number of these pathways were not statistically significant. Moreover, the extent to which nature exposure variables and mental wellbeing, in turn, inversely predicted insufficient sleep varied substantially between countries/regions. This is broadly consistent with Feng et al.'s (2020) finding that the strength of the relationship between greenspace and insufficient sleep among 10 year old participants varied substantially between German and Australian samples.

Given that country-level heterogeneity in nature-sleep associations was accounted for within our whole sample model, variation in the strength of associations between countries within the current study is unlikely to be caused by country-specific differences in sleep duration (National Sleep Foundation, 2013). They may, however, be attributable to cultural differences in environmental preferences and recreational use of natural spaces (Kaplan and Herbert, 1987; Kaplan and Talbot, 1988; Todorova et al., 2004; Van den Berg et al., 1998; White et al., 2014; Loukaitou-Sideris, 1995). Further cross-cultural research is therefore needed to explore these factors and their relationship to insufficient sleep.

Country/region heterogeneities notwithstanding, the findings from our full-sample models indicate that multiple types of nature exposure (streetscape greenery, blue view, green space visits, blue space visits) were associated with lower rates of insufficient sleep. This finding is consistent with additive effects of different types of nature exposure observed for broader health and wellbeing outcomes (Shanahan et al., 2016; White et al., 2017). Moreover, each association was upheld after adjusting for a broad range of covariates, including known risk factors for insufficient sleep (area-level deprivation, Hale et al., 2010; socio-economic status, Gellis et al., 2005) and country/region effects. This suggests that the presence of/access to streetscape greenery, blue views from home, green space visits and blue space visits are all robust and independent predictors of insufficient sleep within an international population.

5.2. Limitations

Whilst providing insights into the relationships between nature exposure and insufficient sleep, the current study is not without its limitations. First, the cross-sectional data limit our ability to make causal inferences. Despite experimental evidence demonstrating improved mood following exposure to natural environments (McMahan and Estes, 2015; Browning et al., 2020) and prospective studies identifying affective disorders as a risk factor for sleep disturbances in later life (Smagula et al., 2016), reverse causality cannot be ruled out. For example, individuals with healthier sleep habits may selectively migrate towards more natural settings, or simply choose to spend more recreational time within them.

As noted previously, we recognise that relationships between wellbeing, physical activity, and sleep are likely to be complex and potentially bidirectional. For instance, we place nature contact at the beginning of our path diagrams, but there is evidence of automatic negative thinking patterns (Collins et al., 2020) and sleep disturbances (Smagula et al., 2016) amongst those struggling with their mental health. It is feasible that people already experiencing lower mental wellbeing simply perceive their surroundings (e.g. streetscapes) to be less green and have greater risk of insufficient sleep for reasons unrelated to nature exposure. This especially the case for subjective (*vs.* objective) nature contact measures. Indeed, it is important to recognise that cross-sectional data can yield evidence of an indirect effect when none may be present with a comparable longitudinal designs (Maxwell and Cole, 2007). Although mediation analyses with cross-sectional data is certainly not uncommon in this field (Elliott and White, 2020; Vitale et al., 2022 ; Dzhambov et al., 2020; Wang et al., 2019) and our modelling is consistent with proposed theoretical frameworks (Astell--Burt and Feng, 2020; Hartig et al., 2014), we encourage a cautious approach to interpreting our findings.

Second, our results are largely based on self-report data. Whilst there is good evidence that self-reported subjective wellbeing, physical activity, and sleep duration are associated positively with objective measures (Diener et al., 1999; Kyffin et al., 2004; Milton et al., 2011; Lauderdale et al., 2008), possible misclassifications in these reports due to social desirability bias cannot be ruled out. There is, however, less clarity regarding the accuracy of self-reported visit frequency, so it is somewhat unclear whether there are any biases within these measures. Further, despite consistency in the pattern of associations observed in robustness checks using categorical indicators (Supplementary Materials 2) our nature visit measures are based on estimated numerical values from discreet response categories, and it is also probable that some respondents 'double-counted' some visit locations (i.e., when they had one visit that included two or more different types of natural spaces), so again we remain cautious in over-interpreting the exact details, rather than the general patterns, of our findings. Equally, with evidence of within-person variability in physical activity (Olsen et al., 2022), doubling the weekly physical activity item for temporal consistency with other items, may not provide an accurate measure of respondents fortnightly physical activity.

Third, survey data was collected several years after the Global Land Cover dataset used to assign neighbourhood greenspace values. Consequently, it may be that levels of neighbourhood greenspace actually experienced at the time of self-reported outcomes differed from the values used here, which may have added error to our models. Ideally, future work would include temporally consistent exposure and outcome metrics, although this is not always easy to establish, especially at the international scale explored here.

Forth, examination of the potential mitigating pathways (e.g. reduced noise, air pollution and heat island effects) by which nature contact may be linked to better sleep outcomes were beyond the scope of the current study. As an established predictor of poor sleep (Patel, 2019; Cupertino et al., 2023), light pollution represents an interesting, and often overlooked (Stanhope et al., 2021) area of future greenspace research. In light of Stanhope et al.'s (2021) research identifying light pollution as a potential confounder of nature-sleep associations, we conducted a robustness check controlling for Artificial light at night (ALAN) in our main model (Supplementary Materials 6, Table S22). ALAN did not significantly predict insufficient sleep ($b = 0.0000$; 95% CIs $= -0.0000$, 0.0000, $p = 0.968$), mental wellbeing ($b = -0.0001$; 95% CIs $= -0.0003$, 0.0001, $p = 0.543$), or physical activity ($b = 0.0000$; 95% CIs $= 0.0000$, 0.0001, $p = 0.304$). Moreover, the associations between nature contact indices and: a) mental wellbeing; b) physical activity; and, c) insufficient sleep were largely consistent between models, indicating that light pollution did not affect our overall pattern of findings. Nonetheless, several uncertainties remain over how best to conceptualise its role in nature-sleep relationships. Is it best described as a mediator, with streetscape greenspace buffering light pollution in a similar manner to which it's purported to clean the air of particular matter? Or a moderator, with the provision ample trees shielding street lamps, or light from adjacent residential areas, but low-level greenspace having little effect? Moreover, how do we best account for behavioural adaptations to environmental issues into our analyses of nature-sleep relationships? For instance, the effectiveness of commonplace behavioural adaptations to outdoor light pollution on sleep cycles (e.g. curtains); as well as the role of indoor electronic devices (e.g. smartphones, Cupertino et al., 2023). Work capable of examining these issues further, and disentangling the potential inter-relationships between these factors, is therefore needed.

Studies utilizing longitudinal designs, more comprehensive measures of nature contact, sleep and a greater range of potential mediators, are therefore needed to assess the robustness of our findings.

5.3. Implications

Whilst recognizing the cross-sectional nature of the dataset, should further research corroborate that the associations observed here are causal, our findings have a number of potential practical implications.

Improvements to the provision and maintenance of natural features close to the home, for instance, through greener infrastructure or urban greening strategies, represents a promising place-based strategy for improving sleep duration at the population-level. Given competing demands for land use and widespread budgetary constraints (Public Health England, 2020), the 'streetscape' initiatives currently being implemented with urban cities to mitigate flood risks and urban heat island effects (e.g. Mayor of London, 2019) might usefully be extended to residential areas to promote healthier sleep habits. If the inverse associations between visits to green and blue spaces and insufficient sleep are causal, then targeted nature-based interventions could potentially assist individuals who are most affected by insufficient sleep. Current nature-based social prescribing initiatives aimed at improving mental health and physical activity (Robinson et al., 2020; Astell-Burt et al., 2022), for instance, might be extended to support such individuals.

5.4. Conclusion

Affecting non-trivial proportions of the population worldwide, insufficient sleep (<6 h per day, National Sleep Foundation, 2013) constitutes a significant public health issue (Chattu et al., 2019). The current study provides evidence that nature visible from home (streetscape greenery, blue views) and recreational visits to green and blue spaces were independently associated with lower rates of insufficient sleep. These associations were mediated, to varying degrees, by better mental wellbeing. If further evidence can corroborate that these associations are causal, then improved provision and maintenance of residential blue and green spaces may offer a viable strategy of improving mental wellbeing and promoting healthier sleep duration at the population-level. Further, more targeted nature-based interventions may be an appropriate strategy to assist people who are most affected by insufficient sleep.

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CRediT authorship contribution statement

Leanne Martin: Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Mathew P. White:** Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Lewis R. Elliott:** Writing – review & editing, Project administration, Methodology, Data curation. **James Grellier:** Writing – review & editing, Project administration, Methodology, Data curation. **Thomas Astell-Burt:** Writing – review & editing, Conceptualization. **Gregory N. Bratman:** Writing – review & editing, Funding acquisition. **Maria L. Lima:** Writing – review & editing, Funding acquisition. **Mark Nieuwenhuijsen:** Writing – review & editing, Funding acquisition. **Ann Ojala:** Writing – review & editing, Funding acquisition. **Anne Roiko:** Writing – review & editing, Funding acquisition. **Matilda van den Bosch:** Writing – review & editing, Funding acquisition. **Lora E. Fleming:** Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.118522.

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