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Shedding Some Light in the Dark—A Comparison of Personal Measurements with Satellite-Based Estimates of Exposure to Light at Night among Children in the Netherlands

Anke Huss,[1] Luuk van Wel,[1] Lily Bogaards,[1] Tanja Vrijkotte,[2] Luzian Wolf,[3] Gerard Hoek,[1] and Roel Vermeulen[1,4]

[1]Institute for Risk Assessment Sciences, Utrecht University, Utrecht, Netherlands
[2]Department of Public Health, Amsterdam Public Health Research Institute, Amsterdam University Medical Center, University of Amsterdam, Amsterdam, the Netherlands
[3]Wolf Technologie - Object-Tracker, Perchtoldsdorf, Austria
[4]Julius Center for Health Sciences and Primary Care, University Medical Center Utrecht, Utrecht, Netherlands

BACKGROUND: Exposure to light at night (LAN) can perturb the biological clock and affect sleep and health. Previous epidemiological studies have evaluated LAN levels measured by satellites, but the validity of this measure as a proxy for personal LAN exposure is unclear. In addition, outdoor satellite-measured LAN levels are higher in urban environments, which means that this measure could potentially represent a proxy for other, likely urban, environmental exposures.

OBJECTIVES: We evaluated correlations of satellite-assessed LAN with measured bedroom light levels and explored correlations with other environmental exposures, in particular, air pollution, green space, and area-level socioeconomic position (SEP).

METHODS: We compared satellite measurements with evening and nighttime bedroom measurements of illuminance (in units of lux) for 256 children, and we evaluated correlations between satellite-based measures and other urban exposures such as air pollution, area-level SEP, and surrounding green space for 3,021 children.

RESULTS: Satellite-measured LAN levels (nanowatts per centimeter squared per steradian) were not correlated with measured evening or nighttime lux levels [Spearman correlation coefficients (r_S) −0.11 to 0.04]. There was a weak correlation with measurements during the darkest time period if parents and their children reported that outdoor light sometimes or usually influenced indoor light levels ($r_S = 0.31$, $n = 28$). In contrast, satellite-measured LAN levels were correlated with air pollution ($r_S = 0.76$ with NO_2, $r_S = 0.71$ with PM_{10}), and surrounding green space ($r_S = -0.71$ for green space within 1 km of the home). A weak correlation with area-level SEP was also observed ($r_S = 0.24$).

CONCLUSIONS: Outdoor satellite-assessed outdoor LAN exposure levels were correlated with urban environmental exposures, but they were not a good proxy for indoor evening or nighttime personal exposure as measured in our study population of 12-y-old children. Studies planning to evaluate potential risks from LAN should consider such modifying factors as curtains and indoor lighting and the use of electronic devices and should include performing indoor or personal measurements to validate any exposure proxies. The moderate-to-strong correlation of outdoor LAN with other environmental exposures should be accounted for in epidemiological investigations. https://doi.org/10.1289/EHP3431

Introduction

Exposure to light in the evening and at night has been shown to disrupt circadian rhythms, alter melatonin levels, and affect sleep and health (Cho et al. 2015; Roenneberg and Merrow 2016). Much of the current evidence on effects from short-term exposure to light in the evening or at night comes from experimental studies. Epidemiological studies aiming at evaluating potential effects on health from longer-term exposures can be challenging regarding valid exposure assessment. Exposure proxies that have been applied in previous studies include assessing whether study participants have worked night shifts; self-reports of bedroom light levels (McFadden et al. 2014); or the use of light-emitting electronic devices, particularly tablets, smartphones, or laptops (Cajochen et al. 2011; Hale and Guan 2015); or proxies of outdoor light at night (LAN) levels. For example, studies have reported that outdoor LAN exposure is associated with breast cancer in women (Kloog et al. 2008; Bauer et al. 2013; Hurley et al. 2014; James et al. 2017), prostate cancer in men (Kim et al. 2017), and obesity (Rybnikova et al. 2016) as well as delayed bedtime, shorter sleep duration, and increased daytime sleepiness (Ohayon and Milesi 2016). In India, higher levels of biomarkers of vascular aging were observed among residents with higher LAN levels (Lane et al. 2017).

Many of the studies addressing outdoor LAN exposure used light as measured by satellites such as the U.S. Defense Meteorological Satellite Program DMSP (Kloog et al. 2008) or the Visible and Infrared Imaging Radiometer Suite Day/Night band (VIIRS-DNB) (Lane et al. 2017) or, more recently, photos taken from the International Space Station (ISS) (de Miguel et al. 2014). Advantages of using these images include ease of access, broad geographical coverage, and reasonable spatiotemporal resolution (Elvidge et al. 2013). Satellite measurements, however, have been questioned regarding their validity to capture personal exposure because they measure the light component that is directed upwards (Katz and Levin 2016) and because elevated outdoor light levels do not necessarily translate into higher indoor light levels. A U.S. study in female school teachers compared personal evening exposure (between civil twilight and bedtime) and nightstand exposure (light meters placed next to the bed, facing the ceiling, with measurements between 0000 and 0400 hours) with categories of sky brightness(Cinzano et al. 2001). Using measurements for 58 teachers collected in 2010, they reported an R^2 value of 0.03 for evening and "no apparent relationship" for nighttimes with five sky brightness categories determined from the Operational Linescan System (OLS) carried on the DMSP satellite, respectively (Rea et al. 2011). To the best of our knowledge, there is no validation study available in children. Some experimental studies have suggested that children may be more sensitive to the effects of evening or night light exposure than postpubertal adolescents or adults (Crowley et al. 2015;

Address correspondence to Anke Huss, Institute for Risk Assessment Sciences, Utrecht University, the Netherlands. Email: a.huss@uu.nl

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Higuchi et al. 2014). Outdoor LAN levels are higher in urban environments (Kyba et al. 2015), where concentrations of other environmental exposures, such as air pollution, are often also higher (Fecht et al. 2015). Outdoor LAN levels may correlate better with other urban environmental exposures than with personal evening or bedroom LAN exposures.

For the present study, we assessed satellite-measured LAN levels in about 3,000 children participating in the Dutch Amsterdam Born Children and Development (ABCD) birth cohort (van Eijsden et al. 2011). In a subgroup of 256 children, we measured personal evening and bedroom light exposure at night. The aim of the present study was to evaluate the correlation of satellite-measured outdoor LAN levels with measured personal evening and night light levels and to explore correlations between satellite-measured LAN levels with other environmental exposures such as air pollution and area-level socioeconomic position (SEP).

Methods

Study Participants

Our study was embedded in the ABCD cohort study, which is a community-based prospective cohort study that examines the relationship between maternal lifestyle and psychosocial determinants during pregnancy to various health outcomes in children. The ABCD study has been described in detail elsewhere (van Eijsden et al. 2011). In brief, between January 2003 and March 2004, 8,266 pregnant women were enrolled during their first prenatal visit to an obstetric care provider and filled out a baseline questionnaire. Follow-ups were performed when the children of the study reached 3 months and 5 and 11 y of age. A total of 3,027 children participated in the most recent follow-up at 11 y of age. During this follow-up, subjects were asked if they agreed to be contacted again for a light and physical activity measurement campaign ($n = 786$ agreed). When we contacted these subjects, 368 (47%) were willing to participate. Study participants were selected based on their willingness to participate in the campaign during a usual school week. Our measurement series was thus based on a volunteer sample within the ABCD cohort. At the time point of the measurements, participating children were between 11 and 13 y of age and lived primarily in the larger areas surrounding the cities of Amsterdam and Utrecht, in the Netherlands.

The ABCD cohort has been approved by the Central Committee on Research involving Human Subjects in the Netherlands, the medical ethical committees of the participating hospitals, and the Registration Committee of the Municipality of Amsterdam.

VIIRS-DNB Images and ISS Photos of Outdoor Light at Night Levels

Using Dutch cadastral building data from 2015, we geocoded the home addresses of the ABCD children at the 11-y-of-age follow-up, which resulted in a coordinate within the building outline for each participant. We then used these coordinates to assign satellite-measured LAN values from VIIRS-DNB data. For this, we used yearly averaged VIIRS-DNB data from 2015. VIIRS-DNB satellite pictures are composites of cloud-free night images, with moonlight filtered out. Satellite image pixel size is about 15 arcsec (Kyba et al. 2015). Light ranging from 500 to 900 nm wavelength is covered by VIIRS-DNB and exposure is given as radiance in nanowatts per centimeter squared per steradian. Data are available from the Earth Observation Group, NOAA National Geophysical Data Center (https://ngdc.noaa.gov/eog/viirs/download_dnb_composites.html). As a second approach, we extracted light levels from ISS photos taken in 2012. Corresponding photos were georeferenced and combined into a photo of national coverage. Another reason to also evaluate the ISS photo was its higher spatial resolution with a pixel size of roughly 45×45 m. However, light levels as photographed from ISS were not calibrated; therefore, we grouped light levels in the combined photo in quintiles to derive groups of darker or brighter ambient LAN levels. The composite ISS picture of the Netherlands is accessible at https://www.atlasleefomgeving.nl/.

Light Measurements

We performed light measurements for ABCD participants between December 2015 and July 2017. Participants were asked to wear a light meter (LightWatcher; Wolf Technologieberatung) for 1 week. The LightWatcher is a small ($1 \times 2 \times 5$ cm), lightweight (12 g) device (see Figure S1). LightWatchers were set to capture light exposure continuously once per 2 s and to log the values as 10-s averages. The LightWatcher measures illuminance in units of lux with a resolution of 0.1 lux and a limit of quantification of 0.01 lux. Lux represents a measure of light intensity as perceived by the human eye, where intensity at specific wavelengths is weighted according to human visual brightness perception. This means, for example, that that irradiance of green light (at 555 nm wavelength, where the human eye is most sensitive) contributes more to lux than, for example, blue light. LightWatchers were calibrated before and during the study and were found to be in good working order with a median of -1.4% [interquartile range (IQR): -2.1 to -0.8] difference between the two calibration time points.

The children's exposure was measured for 7 days (8 nights), in order to capture both weekday and weekend patterns. We asked participants to wear the LightWatcher on a cord around their neck during daytime (see Figure S1) and to place it on their nightstand when they went to bed, with the sensor pointing towards their heads. Children were asked to keep a diary to note times when they did not wear the sensor, when they went to bed, and when they got up. After 1 week, diaries and LightWatchers were sent back to the study center, where data were downloaded and processed.

In the subgroup of 50 children who participated between April and July 2017, we administered an additional questionnaire regarding LAN and bedroom features. We asked parents and children to rate the darkness of the child's bedroom at night with lights turned off ("what describes best how dark it is in your bedroom during the night," with answer categories "very dark—can not see a hand in front of my eyes," "dark—reading a book would be impossible," "twilight—could read a book with a lot of effort," "light—can easily read a book"); if they used curtains in the bedrooms; and if there was light from outdoors shining into the bedroom at night ("no, nearly none," "yes, sometimes a little," "yes, usually"). Of these 50 children, one stopped using the light meter within 24 h, three measurement errors occurred (empty measurement files), and two only participated in actigraph measurements but not in light measurements, which meant that bedroom darkness self-reports and light measurements of 44 children were available.

Air Pollution, Area-Level SEP, Population Density, Green Space

For each participant's home address we assessed residential air pollution with land-use regression (LUR) models that have been previously developed for the European Study of Cohorts for Air Pollution (ESCAPE). Details of the LUR models are described elsewhere (Eeftens et al. 2012). In brief, the models use air pollution measurements performed in the Netherlands in 2009, land-use information, traffic information, and population density to predict annual average estimates to various environmental pollutants such as nitrogen dioxide (NO_2) and particulate matter 10 μm or less in aerodynamic diameter (PM_{10}) in micrograms per cubic meter. Models have been validated using leave one out cross validation (LOOCV) validation and coefficients of determination (R^2) between predicted and measured values of 86% and 79% for NO_2 and PM_{10}, respectively, have been reported (Eeftens et al. 2012).

To assess surrounding green, we calculated the area in meters squared covered with vegetation (agricultural green, grassland, forest, trees, tree nurseries, graveyards, other natural areas) in 100- and 1,000-m radii around the participants' homes, extracted from the Dutch cadastral vector topographical map with an underlying scale of 1:10,000 (TOP10) from 2016 (https://zakelijk.kadaster.nl/-/top10nl).

SEP, population density, and degree of rurality of the neighborhood where study participants lived were extracted from a map from 2014 that is available from Statistics Netherlands (CBS, see https://www.cbs.nl). A neighborhood ("buurt") is the smallest geographical unit with area-level statistics provided by CBS. In 2014, the Netherlands had more than 12,000 such neighborhoods. Percentage of low income population in a neighborhood (defined as less than the 40th percentile of the national income distribution) was used as an indicator of SEP. In addition, we evaluated the degree of rurality, which was defined in five classes ranging from very urban (group 1: $\geq$2,500 addresses/km^2) to rural (group 5: <500 addresses/km^2, in steps of 500).

Data Cleaning and Statistical Analysis

Light measurements. We excluded measurements during the hours when the children reported in the diary that they were not wearing the LightWatcher. We evaluated arithmetic means of several time frames of the children's light exposure: during the darkest period of the night, during the time children reported being in bed, during civil twilight, between the start of civil twilight and bedtime, and during the hour before children went to bed. The darkest period of the night (0012 to 0310 hours) was evaluated to minimize possible effects from stray sun- or moonlight because children were usually in bed during this time period and because it corresponds to the start and end time of the darkest period of the shortest night of the year (astronomical twilight the time period when the geometric center of the sun is 18° below the horizon (Spitschan et al. 2016). Light measurements made during the darkest time period were included only when children reported being in bed by 0012 hours. In addition, because we were especially interested in usual bedroom light conditions (without switching on or off indoor lights), we filtered out light measurements during sudden changes in illuminance (lux levels of at least 10 times the median of the usual exposure between 0012–0310 hours) that were likely to be caused by switching on/off bedroom lights. Although the contribution of moonlight would be expected to be low [<0.3 lux for outside light levels (Kyba et al. 2017)], we also excluded measurements taken on full moon nights and on the nights before and after a full moon because moonlit nights are also filtered from VIIRS-DNB pictures. Civil twilight was defined as the time period when the geometric center of the sun is 6° below the horizon (Spitschan et al. 2016). All exposures during this time period were included, independent of whether children were in bed or not. Evening exposure, from the start of civil twilight until they went to bed, was similar to the time period evaluated in a previous study of teachers (Rea et al. 2011).

We calculated the Spearman correlation of outdoor satellite LAN levels with each of the measured light exposure time windows outlined above ($n = 256$). We also calculated the Spearman correlation coefficients for children who answered the additional indoor light questions ($n = 44$) and evaluated whether correlations were stronger if outdoor light was reported to influence bedroom light levels. Finally, we compared the correlations of outdoor satellite LAN levels with indoor light levels of bedrooms facing a street versus those not facing a street. This comparison was based on a question in the 11-y follow-up questionnaire in which mothers were asked if one of the child's bedroom windows was facing a road.

We evaluated intra-individual variability by calculating the intraclass correlation coefficients (ICCs), calculated as $\text{between-participant variance}/(\text{within-participant variance} + \text{between-participant variance})$ of log-transformed lux levels per night.

Correlation of outdoor satellite LAN levels with other exposures for full cohort. For the ABCD cohort participants, we grouped satellite-measured VIIRS-DNB data into tertiles. For all study participants, we also calculated median and IQR of individual characteristics of our study participants (sex proportion, maternal educational level) and of environmental exposure characteristics (air pollution in NO_2 and PM_{10} as well as amount of surrounding green, area-level SEP, population density, and degree of rurality). Differences across groups were tested with chi-square tests for sex and maternal educational level and with Kruskal-Wallis tests for all other variables. We also calculated Spearman correlation coefficients for all environmental exposures.

Results

During the follow-up of the ABCD cohort when participants were 11 y of age, 5,600 children were invited and 3,027 agreed to participate (54%). Of these, 3,021 could be geocoded at building level and were included in the cohort analysis. Of the children participating in measurement campaigns (i.e., actigraph and LightWatcher measurements, $n = 368$), not all could participate in light measurements because we had fewer LightWatchers than actigraphs. Based on the availability of our light meters, we sent out LightWatchers and diaries to a subsample of 297 children and received 294 LightWatchers back. After excluding 38 participants whose light measurements failed, who did not fill in diaries, or who had a measurement period of less than 1 d or because there was an error in the linkage to the cohort data, 256 participants remained in the analysis. The files of another six participants had only 3 d of measurements, which happened to fall into full moon nights; these six participants were excluded from the analysis of the darkest period of the night. Children with a valid measurement were an average of 12.4 y of age [standard deviation (SD) 0.6 y] and 55% were girls.

Characteristics of all 3,021 participants according to individual and area characteristics by groups of outdoor LAN levels are given in Table 1. These characteristics had a similar distribution in the subgroup of children with light measurements (see Table S1); participant characteristics per subgroup are provided in Table S2.

Satellite-measured median outdoor LAN exposures were $22.1\,\text{nW/cm}^2/\text{sr}$ with an IQR of $14.2–32.6\,\text{nW/cm}^2/\text{sr}$. Among children with light measurements, measured median bedroom levels during the darkest period of the night were 0.08 lux with an IQR of 0.03–0.20 lux (see Table S4). The ICC was 0.75, and children contributed, on average, 5.4 nights with observations to the data set (minimum was 1 night that children had to contribute, maximum that occurred was 7).

Correlations between measured light levels and outdoor VIIRS-DNB LAN levels were low or null ($r_S = -0.11$ to 0.04; Table 2). Correlations with ISS photo-captured outdoor LAN levels were very close to 0 for all measurement time periods ($r_S = -0.03$ to 0.02; Table 2). Among the children with additional questionnaire information (see Table S3), the correlation

Table 1. Characteristics of the ABCD cohort at 11 y of age, by satellite LAN levels in tertiles ($N = 3{,}021$).

Characteristic	Low VIIRS-DNB[a]	Medium VIIRS-DNB[a]	High VIIRS-DNB[a]	*p*-Value
n	1,008	1,006	1,007	
Girls [*n* (%)]	514 (51.0)	513 (51.0)	506 (50.3)	0.91
Boys [*n* (%)]	496 (49.0)	493 (49.0)	501 (49.7)	
Age [y (mean ± SD)]	12.4 ± 0.6	12.3 ± 0.6	12.5 ± 0.6	0.30
Maternal education [*n* (%)]				
Low	51 (5.1)	98 (9.7)	102 (10.1)	
Medium	157 (15.6)	213 (21.2)	154 (15.3)	
High	792 (78.6)	677 (67.3)	730 (72.5)	
Missing	8 (0.8)	18 (1.8)	21 (2.1)	<0.001
NO_2[b]	23.3 (20.5–26.5)	28.4 (25.2–31.3)	35.8 (32.6–39.2)	<0.001
PM_{10}[b]	24.6 (24.2–25.2)	25.5 (24.8–26.4)	27.8 (26.8–28.8)	<0.001
Green 100-m buffer[c]	2,364 (418–5,979)	2,201 (427–5,044)	0 (0–2,570)	<0.001
Green 1,000-m buffer[c]	1.19×10^6 (0.79×10^6–1.54×10^6)	0.71×10^6 (0.52×10^6–0.93×10^6)	0.30×10^6 (0.15×10^6–0.53×10^6)	<0.001
Rurality[d]	3 (2–4)	2 (1–2)	1 (1–1)	<0.001
Population density	3,915 (2,165–6,392)	7,030 (5,026–8,990)	11,436 (7,541–18,266)	<0.001
Area SEP	34 (29–38)	35 (29–40)	39 (34–45)	<0.001

Note: Values are medians (25th–75th percentiles) unless otherwise indicated. *p*-Values were derived with chi-square tests (sex) and Kruskal-Wallis tests on all other characteristics. ABCD, Amsterdam Born Children and their Development; LAN, light at night; NO_2, nitrogen dioxide; PM_{10}, particulate matter less than 10 μm in aerodynamic diameter; SD, standard deviation; SEP, socioeconomic position; VIIRS-DNB, Visible and Infrared Imaging Radiometer Suite Day/Night band.

[a] Categories of low, medium, and high satellite-measured LAN exposure based on tertiles of VIIRS-DNB. Cutoffs between tertiles low-medium and medium-high were 16.6 and 28.9 $nW/cm^2/sr$, respectively.

[b] Air pollutants NO_2 and PM_{10} are modeled average values in micrograms per cubic meter.

[c] Green buffer corresponds to the amount of square meters of green in a buffer of 100 and 1,000 m around the place of residence, respectively, based on vegetation cover indicated on the Dutch cadastral map TOP10.

[d] Degree of rurality, population density, and area-level SEP derived from the smallest area unit ("buurt") by Statistics Netherlands. Degree of rurality ranges from 1 (very urban) to 5 (rural), population density to number of inhabitants per square kilometer, and area SEP to the percentage of the population with low income.

coefficients were also low ($r_S > -0.35$ to <0.05, $n = 44$). If parents or children reported the influence of any outdoor light on indoor light levels sometimes or usually, the correlation between measured light levels in the bedroom during the darkest time period (0012–0310 hours) and satellite values increased to $r_S = 0.31$ ($n = 28$; see Figure S2 for scatter plots). Corresponding correlation coefficients were 0.01 for the time period when children were reported to be in bed, 0.001 during civil twilight, −0.32 for the time period between civil twilight and bedtime, and −0.04 for the hour before children went to bed. These correlation coefficients were based on $n = 28$, $n = 28$, $n = 23$, and $n = 28$, respectively. The lower *n* for the comparison of exposure between start of civil twilight and bedtime was based on several children for whom bedtime preceded timing of civil twilight. Nearly all parents and their children reported the use of curtains in the child's bedroom (94%), and we therefore did not further evaluate this factor. Among children with measurements, correlations between LightWatcher-measured and outdoor VIIRS-DNB LAN levels were also low when we restricted the analysis to those children who were reported to sleep in bedrooms facing roads ($r_S = -0.09$ for the darkest period of the night; $r_S = 0.001$ for the time period children reported to be in bed; $r_S = -0.02$ for the time period of civil twilight; $r_S = -0.09$ for the time between civil twilight and bedtime; and $r_S = 0.007$ for the hour before children went to bed, with $n = 137$, 140, 140, 120, and 140, respectively). The correlation between measured light levels during the darkest time period and the four categories of self-reported darkness in the bedrooms was $r_S = 0.12$. Median values of measured lux levels were low and similar for children who self-reported their bedroom darkness as very dark, dark, or twilight (mean lux 0.09, 0.37, 0.30 for 3, 29, and 10 children, respectively), in contrast with 0.85 for two children who self-reported that their bedroom was "light" (see Figure S3 and Table S3).

Among all children at 11 y of age ($n = 3{,}021$), median population density, degree of rurality, and NO_2 and PM_{10} concentrations increased from the lowest to highest tertile of satellite-measured LAN, whereas the median area of green space within each buffer decreased (Table 1). Correlations between satellite-measured outdoor LAN levels and air pollutants or area-level characteristics were strongest for NO_2 ($r_S = 0.76$), degree of rurality ($r_S = -0.74$), and PM_{10} ($r_S = 0.71$) (Table 3; see also Figure S2).

Discussion

Outdoor satellite-measured LAN exposure was not correlated with measured light exposures among children in our study population. In contrast, outdoor satellite LAN exposure was positively correlated with population density and air pollution levels, with correlation coefficients ranging from 0.66 to 0.76. Negative correlation coefficients were found with the amount of surrounding

Table 2. Spearman correlation coefficients between measured light exposure in the evening and at night and proxies of outdoor exposure ($n = 256$).

Time frames of average LAN exposure	VIIRS-DNB	ISS photo[a]
Average bedroom exposure during the darkest period of the night ($n = 250$)[b]	−0.04	0.02
Average exposure in the time children were reported to be in bed[c]	0.03	−0.002
Average exposure during the time period of civil twilight[d]	−0.11	−0.03
Average exposure between start of civil twilight and bedtime ($n = 217$)[e]	−0.05	−0.004
Average exposure in the hour before children went to bed	0.04	0.007

Note: ISS, International Space Station; LAN, light at night; VIIRS-DNB, Visible and Infrared Imaging Radiometer Suite Day/Night band.

[a] ISS photo: composite photo from pictures taken from the ISS.

[b] Between 0012 and 0310 hours, corresponding to the start and end times of astronomical twilight (geometric center of the sun is 18° below the horizon) during the shortest night of the year, the lower *n* is based on six children for whom only measurements during the full moon were available.

[c] Bedtime: self-reported information from diaries.

[d] Civil twilight corresponds to the time period when the geometric center of the sun is 6° below the horizon.

[e] The lower *n* is based on several children for whom bedtime preceded timing of civil twilight.

Table 3. Spearman correlation coefficients between exposures for ABCD cohort ($N = 3{,}021$).

	VIIRS-DNB 2015	NO_2[a]	PM_{10}[a]	Green 100-m buffer[b]	Green 1,000-m buffer[b]	Rurality[c,d]	Population density[c,e]	Area SEP[c,f]
VIIRS-DNB	1							
NO_2	0.76	1						
PM_{10}	0.71	0.91	1					
Green 100-m buffer	−0.33	−0.29	−0.27	1				
Green 1,000-m buffer	−0.71	−0.56	−0.50	0.34	1			
Rurality	−0.74	−0.70	−0.67	0.30	0.67	1		
Population density	0.66	0.52	0.49	−0.40	−0.64	−0.66	1	
Area SEP	0.24	0.20	0.21	0.09	0.08	−0.27	0.18	1

Note: ABCD, Amsterdam Born Children and their Development; NO_2, nitrogen dioxide; PM_{10}, particulate matter less than 10 μm in aerodynamic diameter; SEP, socioeconomic position; VIIRS-DNB, Visible and Infrared Imaging Radiometer Suite Day/Night band.

[a] Air pollutants NO_2 and PM_{10} are modeled average values in micrograms per cubic meter.

[b] Green buffer corresponds to the amount of square meters of green in a buffer of 100 and 1000 m around the place of residence, respectively, based on vegetation cover indicated on the Dutch cadastral map TOP10.

[c] Degree of rurality, population density and area-level SEP derived from the smallest area unit ("buurt") by Statistics Netherlands.

[d] Degree of rurality ranges from 1 (very urban) to 5 (rural).

[e] Population density refers to number of inhabitants per square kilometer.

[f] Area SEP refers to the percentage of the population with low income.

green space, with correlation coefficients of −0.33 and −0.71 for greenness within100- and 1,000-m buffers, respectively, and −0.74 for degree of rurality. This suggests that associations between health outcomes and satellite-based estimates of exposure to LAN may be due to confounding by correlated urban exposures.

Strengths of our study include the relatively large measurement data set of 256 children, with measurements for up to 7 nights per child. In addition, we evaluated several other exposures that are usually clustered by different degrees of rurality, including air pollution, the amount of surrounding green space, and indicators of SEP. There are also limitations to our study. LightWatchers worn on a cord around the neck or placed on a bedside table may not provide accurate measures of light exposure to the retina, although it is unclear how a different placement of the sensors would have impacted correlations with satellite-measured LAN. We found that curtains were used almost universally in our study population. If usage of curtains is different between children and adults, our measurements may not be directly generalizable to adults. However, our findings are similar to a previous study of 58 American school teachers that reported a low correlation between measured light levels during the civil twilight time period a and a five-category measure of sky brightness (Rea et al. 2011). The use of electronic devices, especially in the evenings or at night, would be expected to contribute to LAN exposures (Gringras et al. 2015) and was not assessed in our measurement study. However, information was available for our cohort study, for which we had inquired about average minutes per day of screen time (TV or computer, video gaming, laptop, tablet, or mobile phone use) as well as the use of electronic devices in the hour before children went to bed (see Figure S4). All of these categories were uncorrelated with satellite-based measures of LAN. Given the relatively low participation in our measurement campaign, we cannot exclude that our measurements reflect a selective group of children that may or may not be generalizable to the general population. Because we asked the participants to perform week-long measurements using actigraphy as well as light sensors, it is unclear in which direction such a possible selection would have occurred.

In addition, we compared annual averaged LAN satellite measurements with indoor bedroom light levels measured during the course of 1 week. If there was variation in LAN exposure levels across weeks or months, then this could have further contributed to the low correlations observed. Variation in outdoor light levels could potentially arise from changes in street lighting or moon phases. Although we tried to filter out potential effects from moonlight, this could have nevertheless influenced our findings to some extent.

Light from street lamps can display high spatial variability, especially due to shielding by buildings or vegetation. Such variability is not covered in the satellite pictures, which have a relatively low spatial resolution and which can be seen as another disadvantage of using satellite pictures to extract proxy measures of LAN exposure levels. Finally, VIIRS-DNB measures light in the spectrum of 500–900 nm, which covers most but not the entire visible spectrum. Blue light, for example, is not included in the satellite pictures. All in all, although the aforementioned points may contribute to low correlations between outdoor LAN levels and measured evening or nighttime light levels of our participants, there remains the open question of whether the use of VIIRS-DNB measurements as a proxy for personal LAN exposure is suitable in epidemiological studies. In particular blue light exposure has been discussed as to its effect on melatonin (Wood et al. 2013). Some recent papers have analyzed ISS photos instead of satellite pictures, given that ISS photos have a higher spatial resolution and because ISS photos include information within the blue, red, and green light spectrum (de Miguel et al. 2013). Outdoor LAN levels captured with ISS pictures and with VIIRS-DNB were correlated ($r_S = 0.67$). As for VIIRS-DNB–measured LAN levels, LAN levels assessed using ISS photos were not correlated with the light levels measured by our participants.

Self-reported darkness of bedrooms is also a commonly used proxy for LAN exposure in large epidemiological studies. In our data set, the correlation was low ($r_s = 0.12$) between measured light during the darkest time period and four categories of bedroom light levels reported by 44 children.

Satellite measurements might still be useful for evaluating LAN exposure in outdoor settings [e.g., when evaluating effects on birds (Rodríguez et al. 2015)]. Given previous study findings by Katz and Levin (2016) of low-to-moderate correlation of outdoor-measured light levels at ground level with satellite-measured outdoor LAN levels, it may still be useful to validate satellite-measured outdoor LAN levels with ground measurements.

Clearly, our findings do not counter previous evidence suggesting that exposure to LAN may affect a range of health end points, including sleep. Instead, our findings for 11-y-old children living in the Netherlands suggest that outdoor satellite-measured LAN exposure levels may not be a good measure of evening or nighttime personal LAN exposures but that they may, instead, act as a proxy for other urban exposures. Studies planning to evaluate potential risks from LAN should therefore consider performing indoor measurements to validate their exposure proxies, to additionally collect information regarding the use of electronic devices, and to account for other environmental exposures that could potentially underlie observed effects.

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