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A Quantitative General Population Job Exposure Matrix for Occupational Daytime Light Exposure

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Abstract

High daytime light levels may reduce the risk of affective disorders. Outdoor workers are during daytime exposed to much higher light intensities than indoor workers. A way to study daytime light exposure and disease on a large scale is by use of a general population job exposure matrix (JEM) combined with national employment and health data. The objective of this study was to develop a JEM applicable for epidemiological studies of exposure response between daytime light exposure, affective disorders, and other health effects by combining expert scores and light measurements. We measured light intensity during daytime work hours 06:00–17:59 for 1–7 days with Philips Actiwatch

Spectrum® light recorders (Actiwatch) among 695 workers representing 71 different jobs. Jobs were coded into DISCO-88, the Danish version of the International Standard Classification of Occupations 1988. Daytime light measurements were collected all year round in Denmark (55–56°N). Arithmetic mean white light intensity (lux) was calculated for each hour of observation (n = 15,272), natural log-transformed, and used as the dependent variable in mixed effects linear regression models. Three experts rated probability and duration of outdoor work for all 372 jobs within DISCO-88. Their ratings were used to construct an expert score that was included together with month of the year and hour of the day as fixed effects in the model. Job, industry nested within job, and worker were included as random effects. The model estimated daytime light intensity levels specific for hour of the day and month of the year for all jobs with a DISCO-88 code in Denmark. The fixed effects explained 37% of the total variance: 83% of the between-jobs variance, 57% of the between industries nested in jobs variance, 43% of the between-workers variance, and 15% of the within-worker variance. Modeled daytime light intensity showed a monotonic increase with increasing expert score and a 30-fold ratio between the highest and lowest exposed jobs. Building construction laborers were based on the JEM estimates among the highest and medical equipment operators among the lowest exposed. This is the first quantitative JEM of daytime light exposure and will be used in epidemiological studies of affective disorders and other health effects potentially associated with light exposure.

Keywords: epidemiology; job exposure matrix; light exposure; mixed effects model; occupational

Introduction

Sufficient levels of light are essential to perform visual tasks efficiently and accurately, and standards are set for illuminance requirements during indoor and outdoor work (European Standards, 2011; European Standards, 2014; International Organization for Standardization, 2018), but no health-based standards are set. Low daytime light levels are suggested as responsible for the onset of seasonal affective disorder (SAD), other mental diseases, and depressive symptoms during winter (Magnusson, 2000; Levitan, 2007; Hahn *et al*., 2011; Ayers *et al*., 2013; Geoffroy *et al*., 2014). Being exposed to low daytime light intensities may disturb the circadian rhythm (Stothard *et al*., 2017) and circadian disturbance has been proposed to affect the occurrence of breast cancer, cardiovascular, metabolic, and other chronic diseases (IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2010; Bonmati-Carrion *et al*., 2014; Smolensky *et al*., 2015; Lemmer and Oster, 2018; Mason *et al*., 2018). Low daytime light exposure has also been associated with reduced sleep during night (Hubalek *et al*., 2010; Figueiro and Rea, 2016) and decreased alertness (Cajochen *et al*., 2010; Lok *et al*., 2018) and bright light exposure during the day has been associated with better mood (aan het Rot *et al*., 2008).

Light therapy with intensities above 2500 lux may alleviate seasonal and other affective disorders (Golden *et al*., 2005; Al-Karawi and Jubair, 2016; Tseng *et al*., 2016), improve vitality, and reduce depressive symptoms in healthy people during winter when applied in the morning (Partonen and Lonnqvist, 2000). Moreover, outdoor, morning sunlight exposure reduces depressive symptoms in SAD patients with effects comparable to those seen following light therapy (Wirz-Justice *et al*., 1996).

Studies of occupational light exposure at the northern hemisphere between 40° N and 50° N have reported average daytime light levels about 100 and 300 lux during office work in winter and summer, respectively (Hubalek *et al*., 2010; Figueiro and Rea, 2016), 100–800 lux during hospital work, 800–2000 lux during factory and railway work (Papantoniou *et al*., 2014) and about 3000 lux for people working mostly outdoors during summer (Dumont and Beaulieu, 2007). Hospital and office workers spend about 15 min above 1000 lux during summer, daytime working hours (Heil and Mathis, 2002; Hubalek *et al*., 2010), whereas people working mostly outdoors during summer spend about 3 h at more than 1000 lux (Dumont and Beaulieu, 2007). In a recent study in Denmark, latitude 55–56°N, with a partly overlapping study population with that of the current study, we showed that outdoor workers on average spent most daytime working hours above 2500 lux during summer and only briefly during winter, while this did not occur for indoor workers (Daugaard *et al*., 2019).

A way to study occupational daytime light exposure and health in large populations is by use of a job exposure matrix (JEM) classifying workers in different jobs according to their exposure profile combined with employment and health data e.g. from national registers. In order to create a daytime light JEM, valid estimates of occupational exposure to light in the daytime for each subject in the study population are required.

In recent years, several JEMs not related to daytime light assessment have been developed combining quantitative information on exposure levels in a limited number of jobs with expert ratings for all jobs in the workforce. Expert ratings are introduced as informative prior information about the parameters in the mixed effects model (Wild *et al*., 2002; Peters *et al*., 2011; Friesen *et al*., 2012). This approach provides a way of combining expert knowledge with measurement data and allows for estimation of exposure levels for jobs with no measurements. This is especially of interest in situations where a limited number of measurements with high variability in few jobs would otherwise result in high uncertainty in exposure levels.

The objective of this study is to develop a general population quantitative JEM for occupational daytime light intensity. The JEM will be applicable to epidemiological studies of exposure–response relations between daytime light exposure and affective disorders and other health effects in the population of Denmark and other countries at comparable latitude and with comparable industrial structure.

Methods

Expert score

Three experts (V.S., J.H.A., H.A.K.), all specialists in occupational medicine, rated the extent of daytime outdoor work, the predominant predictor of daytime light exposure, during a regular work day for all 372 occupational job titles (hereafter referred to as jobs) of the Danish version of the International Standard Classification of Occupations 1988 (DISCO-88) on a four-digit level. For every job, each expert independently rated probability of daytime outdoor work on a four-point scale (0. 0%, 1. 1–24%, 2. 25–49%, and 3.50–100%) and duration of daytime outdoor work on a four-point scale (0. 0 h, 1. 1–2 h, 2. 3–4 h, 3. > 4 h). For a probability of 0% by default the duration was assigned 0. The experts initially rated probability and duration of outdoor work separately for winter and summer. However, the correlations between summer and winter ratings were high and they therefore proceeded with the summer ratings only. The experts discussed disagreements after their initial ratings and then independently rated each job again. Kappa statistics showed overall agreements (second ratings) between the experts of 0.67 for probability and 0.63 for duration of outdoor work. The three expert rating point scales of probability of outdoor work were averaged for each job and this was also done for duration of outdoor work. Both ratings were categorized into four levels, based on rounding upwards to the nearest integer. Thus, an average rating between 1 and 2 would be assigned a score of 2 and so on. An expert sum score was created by adding the scores for probability and duration for the 372 DISCO-88 codes resulting in six expert sum scores between 0 and 6. A sum score of 1 was not possible because this would require a score of 0 for probability and 1 for duration of outdoor work or the opposite, and these combinations were not possible as specified above. A score of 0 implied a 0% probability of outdoor work and 0 h spent outdoors, and 6 implied at least 50% probability of outdoor work and at least 4 h spent outdoors during a regular work day. Alternative scores were evaluated, such as a product term, but the expert sum score as described above (hereafter referred to as expert score) resulted in the best fit of the of the mixed effects model.

Recruitment of participants for light measurements

Recruitment of participants for personal light measurements took place in Copenhagen and Aarhus, Denmark during two rounds 2011–2012 and 2015–2016. The strategy for the first round was to recruit an equal number of night workers, indoor day workers, and outdoor workers evenly distributed by summer and winter season. These data were collected to study health effects of night-time and daytime light exposure (Daugaard *et al*., 2017; Daugaard *et al*., 2018). The night workers provided data to the current study during the day portion of a night shift (typically 6:00–6:59) or during days with day shifts because most night workers were working rotating shifts. Workplaces employing rotating night shift workers (nurses, nursing assistants, laboratory technicians, midwifes, and physicians), indoor day workers (physiotherapists, primary and secondary school teachers, secretaries, social workers, welders, car mechanics, and machinists) and daytime outdoor workers (child care workers, mail carriers, gardeners, bricklayers, carpenters, and industrial workers) were selected at random from complete lists of businesses by industry provided by the Central Business Register, City of Aarhus, City of Copenhagen and the Central Region of Denmark. Workplaces were contacted and informed about the study protocol, and asked to provide a list of all employees within a specified job. However, only few workplaces complied with this, and in most cases we distributed leaflets and posters to the workplaces informing about the study. Participants signed in in response to these or following requests by foremen or managers and were included irrespective of their job. Eighty-eight workplaces of the 448 approached (20%) agreed to participate and 555 employees were recruited of which 535 provided diaries and readable light measurements.

Participants were at study start asked to sign informed consent and to fill in a questionnaire about job title, life style factors and chronotype. For seven consecutive days they were requested to wear a Philips Actiwatch Spectrum® light recorder (Actiwatch) continuously and in a diary report work hours for work days, days off and for each hour of the day state if the Actiwatch was not worn. They were also asked to provide saliva and blood samples (Daugaard *et al*., 2017; Daugaard *et al*., 2018).

The strategy for the second round was to recruit workers selected at random from targeted industries representing a range of outdoor jobs as defined by the expert scores and taking the prevalence of the jobs as reported by Statistics Denmark into account to avoid infrequent jobs. For each outdoor job, we aimed at recruiting equal numbers of workers during summer and winter. We were, however, unable to recruit participants from jobs with an expert score of 3. Participants were requested to wear the Actiwatch during hours awake for three to five consecutive workdays, provide basic questionnaire information, and fill in a diary. Sixty-four workplaces identified from the Central Business Register were contacted and 31 of them (48%) agreed to participate. Due to time restrictions, only 20 workplaces of the 64 were finally included (31%). Recruitment of participants followed the same procedure as for the first round. Ten of the recruited workplaces provided lists of all employees for random approach. All 235 employees from these lists were approached at random by the study team and 78 (33%) participated. Workers not recruited at random included 155 workers during the second round.

At both rounds, workplaces and employees were informed that the study focus was the possible health effects of light, e.g. if outdoor work may prevent certain diseases. A total of 788 workers were enrolled, 555 during round one and 233 during round two. Of the 788 participants from the two rounds, 695 completed the study protocol, provided readable light measurements and diaries for identification of work hours and hours during the workday where Actiwatches were not worn. The final 695 participants represented 114 workplaces, 39 different industries at the six-digit level according to the Danish Industrial Classification of All Economic Activities 2007 (Statistics Denmark, 2002) and 71 jobs as defined by four-digit DISCO-88 job codes. For 24 participants, light measurements were provided during both summer and winter.

Light measurements

Light measurements were collected with Actiwatch. Participants were instructed to wear the Actiwatch on the upper arm with a sagittal angle of 45° on the outermost layer of clothes throughout the day. The Actiwatch sensor measures irradiance every minute in the red, blue, and green wavelength bands and calculates white light intensity (lux) by integrating the input from the three colored light sensors. The white light output of all recorders was calibrated under overcast sky conditions against a cosine corrected photometer with a spectral sensitivity that closely relates to the luminosity function V (λ) established by the International Commission on Illumination (CIE) as described in Markvart *et al*. (2015). In the diary, the participants reported beginning and end of all work shifts and we included only measurements during daytime work that were defined as any hour of work between 06:00 and 17:59. The participants also recorded any hours during which the Actiwatch was worn for less than 40 min. These measurements were excluded from the data (2.4%). This was also the case for measurements where the actigraphy module of the Actiwatch had shown no activity for the last 20 min (6.9%), which we assumed did not represent actual personal light exposure.

Statistical model

Based on the 1-min light measurements, we calculated 1-h arithmetic mean white light intensities (lux) for each work hour between 6:00 and 17:59 for all participants. The 1-h metric was decided upon to assess specific light estimates for each hour during the day because timing of exposure may be of relevance for health risks (Wirz-Justice *et al*., 1996; Partonen *et al*., 2000). These values were natural log-transformed to obtain a normal distribution of data and the log daytime light intensity levels served as the dependent variable in the statistical model.

The statistical model was developed with the 'Proc Mixed' routine in SAS v9.4 (SAS Institute Inc., Cary, NC, USA). Restricted maximum likelihood (REML) was used to estimate variance components and fixed effects. Compound symmetry was the default assumption and we assumed constant within- and between-worker variance across fixed effects (expert score, month, and hour) and jobs. Final model fixed effects terms (β) included expert score (E), month (M), and hour (H). Job (J), industry nested within jobs (IJ), and subject (S) were included as random effects (b).

The model structure:

$$\mathrm{Ln}\,(\mathrm{Y}) : \beta_0 + \beta_e \mathrm{E} + \beta_m \mathrm{M} + \beta_h \mathrm{H} + b_{j1-71}\mathrm{J} + b_{i1-39}\mathrm{I}(_{j1-71}\mathrm{J}) + \mu + \varepsilon$$

The model terms:

Ln(Y): Natural log-transformed work daytime light intensity (lux)

β_0: Model intercept

$\beta_e E_i$: Categorical variable for expert score (0–6)

$\beta_m M_i$: Categorical variable for calendar month (1–12)

$\beta_h H_i$: Categorical variable for each hour between 06:00 and 17:59 (6–17)

$b_{j1-71}J$: Random effect term for job (b_{1-71})

$b_{ij1-39}I(_{1-71}J)$: Random effect term for industry (b_{1-39}) nested within job (b_{1-71})

μ: Error term for each estimate

ε: Error term

The model includes actual exposure measurements and the output was used to create an algorithm to assign an exposure value to each job in the JEM, regardless of whether exposure measurements were available for that job. The model uses the measurements within all jobs with the same expert score to estimate the overall mean light intensity for that expert score, while also obtaining the deviation in mean exposure of each job within the same score from the overall mean exposure. Random effects for job and industry nested within job are estimated by best linear unbiased predictors (BLUPs). The BLUP for a job with few measurements or high variance will be close to zero, whereas a job with more measurements or lower variance will differentiate the final estimate from the intercept. Information on gender, age, and smoking was available, but were not included, as they did not contribute statistically significantly to the model. No measurements were conducted in jobs with an expert score of 3. This category included jobs such as general managers in construction, glaziers, police inspectors, and detectives. Jobs with this score were in the JEM assigned the interpolated value between scores 2 and 4 from the statistical model. To provide all daytime, all year exposure estimates to each job, we computed the arithmetic means of the hour and month specific geometric means as estimated from the model and assigned the same estimates for jobs with an identical expert score. BLUP estimates were additionally added to jobs with measurements.

The study is a part of the Danish Occupational Cohort (DOC*X) project (http://doc-x.dk/).

Results

A total of 15,272 1-h measurements were collected during 2199 workdays from the 695 participants. Table 1 shows characteristics of the light measurements according to parameters included in the final model (job and industry represented by the main categories and not the detailed levels included in the statistical model). About 42% of the measurements were conducted in jobs with an expert score of 0 and most other measurements were performed in jobs with expert scores of 4 and higher. Overall, there was a monotonic increase in geometric mean (GM) light intensity with increasing expert score. Main DISCO-88 job category 6 showed the highest light intensity and was based on measurements obtained for gardeners and agricultural workers. A high daytime light intensity level was also observed for main DISCO-88 job category 1 representing a small number of owners of farms and craftsman businesses. The agricultural industry showed the highest daytime light intensity based on measurements for farm managers, crop and animal producers, gardeners, and farm workers. Measurements were evenly distributed across months and hours, as expected due to the sampling strategy. Light intensity was highest in August and lowest in January and highest at 12:00 h and lowest at 6:00, also as expected. The number of 1-h light measurements available per four-digit DISCO-88 code varied between 8 and 1657, whereas the average number (range) of 1-h light measurements per participant was 28 (1–69) (data not shown) and the average number of repeated measurements per participant across fixed and random effect parameters ranged between 2 and 33 (Table 1).

Table 2 presents the estimated variance components from the statistical model. In the basic model, that only included the random effects of job, industry nested within job and subject, the variance between jobs, between industries nested within jobs, and between workers within jobs constituted 18, 11, and 18%, respectively of the total variance. Together they made up the total between-worker variance of 48% of the total variance corresponding with a between- to within-worker variance ratio of 0.92. When we in the intermediate model introduced month and hour as fixed effects, the within-worker variance was reduced by 15% and the total between-workers variance by 41% (the weighted average of 35, 49, and 43%). Inclusion of expert score in the final model further reduced the variance between jobs and between industries nested within jobs and now explained 83 and 57% of the variance in the basic model. As expected, inclusion of the expert score did not influence the between-worker and within-worker variance as no participants changed job during the measurement period.

Table 3 presents the estimates (β), standard errors (SE) and geometric mean ratios (GMR) for the fixed effects of the final model of daytime light intensity. Daytime light intensity was 12-fold higher at 12 h compared with at 6 h and 9-fold higher in July compared

Table 1. Characteristics of 15,272 personal 1-h daytime light measurements during work (lux, geometric mean) from 695 individuals followed for 1–7 work days, Denmark, 2011–2016.

Characteristics	Number of workers	Number of measurements	Average number of repeated measurements	Light intensity (lux), GM[a] (GSD)[b]
Expert score				
0 (0 % probability + 0 h)	338	6377	19	207 (4.2)
2 (1–24% + 1–2 h)	38	742	20	414 (6.5)
3 (25–50%+1–2 h or 1–24% + 3–4 h)	0	0	0	-
4 (25–50% + 3–4 h)	131	3093	24	867 (3.6)
5 (25–50% + >4 h or >50% + 3–4 h)	68	1788	26	1719 (3.6)
6 (>50% + >4 h)	120	3272	27	2623 (2.9)
Main job category[c] (Number of jobs represented)				
1. Legislators, senior officials, and managers (3)	<20[d]	112	-	2918 (1.5)
2. Professionals (11)	73	1821	25	906 (3.0)
3. Technicians and associate professionals (16)	255	4886	19	192 (4.6)
4. Clerks (6)	41	965	24	333 (2.3)
5. Service workers and shop and market sales workers (6)	46	942	20	465 (4.7)
6. Skilled agricultural and fishery workers (3)	46	1377	30	3483 (2.3)
7. Craft and related trades workers (13)	153	3319	22	846 (4.7)
8. Plant and machine operators and assemblers (5)	<20[d]	423	-	1522 (6.6)
9. Elementary occupations (8)	57	1427	25	1771 (5.1)
Main industry[d] (Number of jobs represented)				
A. Agriculture (6)	15	492	33	3497 (2.0)
C. Manufacturing (15)	34	685	20	232 (2.4)
E. Water supply, sewerage and waste management (1)	6	198	33	3218 (1.8)
F. Construction (15)	144	3490	24	1617 (4.1)
G. Wholesale and retail trade (3)	14	270	19	547 (5.1)
H. Transportation (3)	12	275	23	2495 (2.5)
M. Scientific research and development and other technical business services (6)	27	293	11	126 (4.3)
N. Services to buildings, cleaning and landscape activities (9)	54	1541	29	3031 (2.7)
O. Public administration, defense and compulsory social security (4)	7	230	33	996 (2.1)
P. Education (10)	69	1689	24	819 (3.1)
Q. Human health and social work (20)	313	6109	20	223 (4.6)
Month				
January	68	1349	20	186 (2.7)
February	49	1177	25	562 (4.7)
March	79	1713	22	835 (3.0)
April	90	1978	22	1276 (6.8)
May	107	1908	18	1060 (6.6)
June	97	1997	21	770 (3.4)
July	23	454	21	980 (4.1)
August	39	842	21	1408 (4.7)
September	38	659	17	483 (4.2)
October	76	1344	18	394 (6.5)

Table 1. Continued

Characteristics	Number of workers	Number of measurements	Average number of repeated measurements	Light intensity (lux), GM[a] (GSD)[b]
November	78	1230	16	108 (3.2)
December	29	621	21	280 (3.5)
Hour				
6	330	640	2	49 (7.2)
7	544	1354	2	148 (6.6)
8	597	1566	3	296 (5.3)
9	608	1707	3	493 (4.9)
10	607	1742	3	690 (5.6)
11	604	1725	3	776 (5.1)
12	602	1661	3	865 (4.8)
13	599	1587	3	811 (5.6)
14	582	1483	3	719 (5.5)
15	463	1061	2	579 (5.9)
16	267	469	2	351 (8.4)
17	173	277	2	234 (11.6)

[a]GM: geometric mean. [b]GSD: geometric standard deviation. [c]DISCO-88 first digit. [c]Danish Industrial Classification of All Economic Activities 2007. [d]<20 is used here in order to ensure GDPR (General Data Protection Regulation) compliance due to small numbers in some of the main job categories.

Table 2. Variance components from the mixed effects model for personal 1-h daytime light measurements during work (*n* = 15,272), Denmark, 2011–2016.

Variance components	Basic model[a]		Intermediate model[b]			Final model[c]		
	Variance component (%)	SE[d]	Variance component	SE[d]	% reduction[e]	Variance component	SE[d]	% reduction[e]
Between jobs	0.82 (18)	0.25	0.53	0.16	35%	0.14	0.08	83%
Between industries nested within jobs	0.49 (11)	0.16	0.25	0.09	49%	0.21	0.08	57%
Between workers	0.82 (18)	0.06	0.47	0.04	43%	0.47	0.04	43%
Within worker	2.32 (52)	0.03	1.97	0.02	15%	1.97	0.02	15%
Total variance	4.45 (100)		3.22		28%	2.79		37%

[a]Basic model includes job, industry, and subject as random effects. [b]Intermediate model includes job, industry, and subject as random effects, and month and hours as fixed effects. [c]Final model includes job, industry, and subject as random effects and expert score, months, and hours as fixed effects. [d]Standard error. [e]% reduction compared to basic model.

with December. Additionally, daytime light intensity increased monotonically with higher expert score and was 5-fold higher for a score of 6 compared with a score of 0.

Table 4 presents model-based all daytime, all year light intensity estimates for the 10 job–industry combinations showing the highest and the lowest light intensity levels. Jobs in the construction industry were among the highest exposed jobs and jobs in hospital and office work were among the lowest exposed. The light intensity level of the highest exposed job–industry combination was 15-fold that of the lowest exposed.

Table 5 shows the model-based light intensity estimates by hour and season for the highest and lowest exposed jobs–industry combinations. The highest light intensity of 7318 lux was seen for building construction laborers working in the construction of utility projects for fluids industry at 12–15 h between June and August. This was 30-fold the intensity of 232 lux for medical equipment operators/hospital activitiesduring the corresponding hours and months.

Table 3. Fixed effects model parameters from a mixed effects model for personal daytime light measurements during work (*n* = 15,272), Denmark, 2011–2016.

Model parameters		β-estimate	Standard error	Geometric mean ratio	95% CI
Intercept		5.33	0.26		
Expert score	0	−1.70	0.23	0.18	0.11–0.29
	2	−1.46	0.34	0.23	0.12–0.46
	4	−1.24	0.30	0.29	0.16–0.54
	5	−0.38	0.30	0.68	0.37–1.24
	6	Ref.		1.00	
Month	January	0.34	0.18	1.40	0.99–1.99
	February	1.24	0.17	3.46	2.49–4.81
	March	1.57	0.17	4.83	3.48–6.70
	April	1.90	0.17	6.67	4.76–9.35
	May	2.00	0.15	7.39	5.50–9.93
	June	1.79	0.16	5.96	4.34–8.20
	July	2.19	0.21	8.96	5.99–13.41
	August	2.06	0.19	7.86	5.39–11.47
	September	1.50	0.18	4.49	3.13–6.45
	October	1.09	0.18	2.98	2.12–4.21
	November	0.49	0.16	1.63	1.19–2.24
	December	Ref.		1.00	
Hour	6	−1.57	0.11	0.21	0.17–0.26
	7	−6.66	0.10	0.52	0.43–0.63
	8	−0.005	0.09	0.99	0.83–1.20
	9	0.48	0.09	1.62	1.34–1.94
	10	0.78	0.09	2.17	1.81–2.61
	11	0.87	0.09	2.39	1.99–2.87
	12	0.96	0.09	2.60	2.16–3.13
	13	0.92	0.09	2.52	2.10–3.03
	14	0.81	0.09	2.24	1.86–2.70
	15	0.62	0.10	1.86	1.54–2.25
	16	0.34	0.11	1.40	1.14–1.73
	17	Ref.		1.00	

For several jobs the measured light intensity differed considerably from the modeled estimates. For example, for production and operation department managers in agriculture, hunting, forestry, and fishing (DISCO code 1221) working in landscape service activities (Danish Industrial Classification of All Economic Activities 2007 code 813000) the measured GM light intensity was 3095 lux whereas the modeled all daytime, all year GM light intensity was estimated to 366 lux. This almost 10-fold difference was seen because we only had 50 measurements collected from 2 workers in late August and early September. The modeled estimate was thus shrunk towards the all year, all day mean light intensity seen for an expert score of 4 (geometric mean, 309 lux), which was the rating assigned to this job–industry combination (data not shown).

The occupational daytime light exposure JEM will be made freely available at the DOC*X homepage (http://doc-x.dk/).

Discussion

We describe an empirical JEM for 372 different jobs in Denmark with estimates of daytime light intensity specific for time of the day and month of the year. The model is based on repeated individual measurements from two field studies combined with an *a priori* expert score. This approach allowed us to use the expert score to assign an exposure estimate to jobs with no available exposure information. The model will provide quantitative exposure assessment for epidemiological studies of the general population of Denmark addressing exposure–response

Table 4. Model-based, personal, all daytime, all year light intensity (lux) estimates (geometric mean) during work for the 10 highest and the 10 lowest exposed job–industry combinations, Denmark, 2011–2016.

Job[a]	Job title	Industry[b]	Industry title	Number of measurements (subjects)	Light intensity (lux), geometric mean	Range (lux)
Ten highest exposed job–industry combinations						
9313	Building construction laborers	422 100	Construction of utility projects for fluids	211 (7)	2064	320–3995
8332	Earth-moving and related plant operators	429 900	Construction of other civil engineering projects n.e.c.	53 (<5)	2050	318–3967
9312	Construction and maintenance workers: roads, dams and similar constructions	429 900	Construction of other civil engineering projects	107 (<5)	2001	310–3871
8332	Earth-moving and related plant operators	422 100	Construction of utility projects for fluids	11 (<5)	1967	305–3806
9162	Garbage collectors	812 900	Other cleaning services	21 (<5)	1612	250–3119
7123	Concrete placers, concrete finishers, and related workers	422 100	Construction of utility projects for fluids	137 (<5)	1503	233–2909
7122	Bricklayers and stonemasons	812 900	Other cleaning services	91 (<5)	1439	223–2785
9313	Building construction laborers	412 000	construction of buildings	86 (<5)	1385	215–2679
9211	Farm-hands and laborers	11 900	Growing of other nonperennial crops	54 (<5)	1321	205–2556
6112	Tree- and scrub crop growers	813 000	Landscaping	683 (23)	1319	205–2552
Ten lowest exposed job–industry combinations						
3133	Medical Equipment operators	861 000	Hospital activities	87 (<5)	66	10–127
2230	Nursery and midwifery professional	861 000	Hospital activities	78 (5)	99	15–186
3224	Optometrists and opticians	861 000	Hospital activities	53 (<5)	109	17–211
7136	Plumbers and pipe fitters	432 200	Plumbing, heat and air-conditioning installation	46 (7)	110	19–234
5220	Shop salespersons and demonstrators	471 130	Discount stores	37 (5)	121	19–237
3211	Life science technicians	861 000	Hospital activities	278 (15)	123	19–237
4115	Secretaries	853 120	Upper secondary schools, adult upper secondary level schools and higher preparatory examination	105 (<5)	123	19–238
3231	Nursing associate professional	861 000	Hospital activities	1655 (124)	123	19–241
4222	Receptionists and information clerks	861 000	Hospital activities	726 (28)	125	20–239
5149	Personal services workers	205 900	Manufacture of other chemical products	31 (<5)	133	21–258

[a]DISCO-88 code (four-digit level). [b]Danish Industrial Classification of All Economic Activities 2007.

Table 5. Model-based, personal daytime light intensity (lux) estimates (geometric mean) for the highest and lowest exposed job–industry combinations by hour of day and season, Denmark, 2011–2016.

Hour of day	Light intensity (lux) by season			
	March–May	June–August	September–November	December–February
Building construction laborers/construction of utility projects for fluids				
6:00–8:59	1176	1422	531	322
9:00–11:59	5025	6074	2267	1374
12:00–14:59	6054	7318	2732	1655
15:00-17:59	3405	4116	1536	931
Medical equipment operators/hospital activities				
6:00–8:59	37	45	17	10
9:00–11:59	159	193	72	44
12:00–14:59	192	232	87	53
15:00–17:59	108	131	49	30

relations with affective disorders and other health effects possibly associated with daytime light exposure.

The study was performed in workplaces selected at random from targeted industries in order to provide estimates of daytime light intensity for a wide range of occupations. Workplace selection followed a research protocol and was not affected by criteria related to exposure levels that may bias workplace measurements, e.g. obtained by working environment authorities to control compliance with exposure threshold levels (Sarazin *et al.*, 2016). From the workplaces, most participants were not selected at random but signed up or were recruited by managers or supervisors and thus we have no information on participation rate on the employee level except for the smaller proportion of round two participants who were approached at random (33%). Participants may not represent the light exposure of the source populations but it is difficult to say if differential participation has resulted in over- or underestimation of daytime intensities.

All measurements were obtained with personal recorders and thus took account of activity, place and surroundings of the participants during work unlike, e.g. measurements obtained with stationary recorders (Cherrie, 2003).

In order to achieve the best estimate of the true light exposure, we excluded measurements with 20 min or more with no concomitant activity according to actigraphy recordings because we assumed these measurements did not represent personal light exposure. We also excluded measurements that, according to diary information, were obtained when the participants did not wear the recorders as instructed. Still we cannot exclude that shorter time periods not representable of personal light recordings are included. This type of measurement error would probably tend to underestimate the light intensity because an Actiwatch left for example on a table would tend to lie with the light sensor facing downwards.

The ratio of the between- and within-workers variance components was close to one. A comparable ratio was seen in a general population exposure study of benzene (Friesen *et al.*, 2012). Comparable and lower ratios were found in several industry based exposure studies (Kromhout *et al.*, 1993; Scheeper *et al.*, 1995; Vinzents *et al.*, 2001). Twenty-nine percent of the variance was seen between jobs and industries nested within jobs which is more than seen in large datasets of measurements of chromium-VI, nickel, benzene, and respirable crystalline silica (Peters *et al.*, 2011; Friesen *et al.*, 2012).

Hour of the day and month of the year explained a high proportion of the variance between jobs, between industries nested within jobs, and between workers. Adding the expert score increased the explained variance between jobs and between industries nested in jobs significantly and this was considerably more than found for crystalline silica and benzene (Peters *et al.*, 2011; Friesen *et al.*, 2012). Hour, month, and expert score explained 15% of the within-worker variance. This mainly reflects the hour-to-hour and day-to-day variation because most measurements for a given worker were collected during consecutive days within a week and expert scores were constant. This finding indicates that additional factors have substantial impact on daytime light intensity level and stresses the appropriateness of a group based exposure strategy, as applied in this JEM, contrary to individual exposure measures, to reduce attenuation of risk estimates when applied in epidemiological studies (Armstrong, 1998; Burdorf, 2005).

The experts rated the extent of outdoor work for each job and not light exposure as such, because sunlight is the predominant predictor of light intensity. This was confirmed by the JEM that showed monotonically increasing light intensity by increasing expert score and a 5-fold higher light intensity for the highest score compared with the lowest. This indicates that we can be quite confident with the light intensity estimates provided for jobs with no measurements that relied solely on the expert scores.

The experts were not able to rate differences in indoor light intensity during day and night-time work. For this reason and because little work is carried out outdoor during the night in Denmark, we did not include night-time light intensity in this general population JEM. However, we recently reported light intensity levels during night, outdoor and indoor work based on data from the first round of the current study (Daugaard *et al.,* 2019).

The BLUP estimates for job and industry nested within job further differentiated exposure estimates and increased the ratio between the highest and lowest exposed job 3-fold. The complete JEM that also included hour of the day and month of the year increased the contrast further and predicted a 30-fold ratio of the highest versus the lowest exposed jobs during identical months and hours. This suggests that this JEM may be reliably assist in detecting differences in health risks attributable to daytime light exposure, if they are present at light intensities present in Denmark.

The International Commission on Illumination (CIE) standard predicts peak sunlight intensity levels of 100,000 lux on a horizontal plane in Denmark on a clear midsummer day (International Organization for Standardization, 2018). Our model showed the highest 3-h average light intensity for building construction laborers around noon during June–August, reaching a geometric mean of about 7000 lux. This large difference from the predicted level is, apart from the different light metrics, expected to reflect variable factors such as meteorological conditions, shadow from buildings and vegetation, and that workers move between workplaces with different light levels, e.g. between outdoor and indoor locations. Furthermore, we measured light on the upper arm and thus mainly on a vertical plane that show lower levels of sunlight compared with the horizontal plane values predicted by the CIE standard.

Our JEM estimates are also expected to be lower than the intensities recorded at the eye that are relevant for effects mediated by the eye (Figueiro *et al*., 2013). We did not have information on the use of sunglasses, headgear, respirators or other equipment during work that may affect light exposure reception at the eye and differ between jobs and thus bias light intensity estimates for the eyes.

The lowest daytime light intensities were estimated for medical equipment operators in hospitals who we expect to work indoors throughout the day. Still, light intensity varied considerably across the day and the year, which probably reflects light from windows because windowless workplaces are generally not permitted in Denmark. This finding is also in accordance with the findings from Sander *et al.* (2015).

The JEM predicted a GM all daytime, all year light intensity of about 120 lux for secretaries and shop salespersons. Earlier field studies of daytime office work between 40 and 50°N have shown average light intensities of approximately 70 lux during winter and 120–300 lux during summer work hours (Hubalek *et al*., 2010; Figueiro and Rea, 2016) in agreement with the levels estimated from our model. Among indoor hospital workers in Spain, higher summertime intensities (approximately 600 lux) have been reported than the all year intensity of 123 lux we observed for nursing associate professionals (Papantoniou *et al*., 2014). For building construction laborers and garbage collectors, expected to work mainly outdoors, we observed all daytime, all year light intensities between approximately 1600 and 2000 lux. We are only aware of a single field study from Montreal, Canada, reporting that persons who mostly worked outdoors were exposed to about 3000 lux during summer (Dumont and Beaulieu, 2007). The differences between ours and the findings from Spain and Canada could, in addition to a seasonal effect, at least partly be explained by differences in latitude.

Due to precise time logging of all measurements, we could include hour of the day and month of the year in the models. This is expected to increase the specificity and applicability of the JEM as timing of exposure during the day and the year may have significant impact on health as suggested for affective disorders and circadian rhythm (Rosenthal *et al*., 1984; Magnusson, 2000; Dumont, 2007; Levitan, 2007).

This JEM provides quantitative estimates of light exposure that impossibly could be obtained by self-reports. The JEM furthermore provides objective measures of light intensity that are unaffected by reporting style, personality, current symptoms, or disease status that are likely to bias associations between light exposure, affective disorders, and other health effects if based on self-reports (Fonn *et al*., 1993; Kolstad *et al*., 2011).

The study was carried out at 55–56° northern latitude, which will affect the generalizability to other locations not only because of seasonal differences in length of the day and the angle of the sun, but also differences in climate, e.g. degree of overcast, rain, and bright sunlight.

Conclusions

This is the first quantitative JEM of personal daytime light exposure and estimates exposure intensities that are comparable with those reported from a limited number of other available daytime light exposure data. The JEM is designed for epidemiological studies in the general population, as light exposure is ubiquitous and not restricted to specific industries. Furthermore, the JEM provides exposure intensities for time of the day and time of the year and may thus provide exposure metrics tailored for specific susceptible time periods in studies of health effects of light exposure. This is a novelty in occupational exposure assessment.

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References

Al-Karawi D, Jubair L. (2016) Bright light therapy for nonseasonal depression: meta-analysis of clinical trials. *J Affect Disord*; **198**: 64–71.

Armstrong BG. (1998) Effect of measurement error on epidemiological studies of environmental and occupational exposures. *Occup Environ Med*; **55**: 651–6.

Ayers JW, Althouse BM, Allem JP *et al*. (2013) Seasonality in seeking mental health information on Google. *Am J Prev Med*; **44**: 520–5.

Bonmati-Carrion MA, Arguelles-Prieto R, Martinez-Madrid MJ *et al*. (2014) Protecting the melatonin rhythm through circadian healthy light exposure. *Int J Mol Sci*; **15**: 23448–500.

Burdorf A. (2005) Identification of determinants of exposure: consequences for measurement and control strategies. *Occup Environ Med*; **62**: 344–50.

Cajochen C, Chellappa S, Schmidt C. (2010) What keeps us awake? The role of clocks and hourglasses, light, and melatonin. *Int Rev Neurobiol*; **93**: 57–90.

Cherrie JW. (2003) The beginning of the science underpinning occupational hygiene. *Ann Occup Hyg*; **47**: 179–85.

Daugaard S, Garde AH, Bonde JPE *et al*. (2017) Night work, light exposure and melatonin on work days and days off. *Chronobiol Int*; **34**: 942–55.

Daugaard S, Markvart J, Bonde JP *et al*. (2019) Light Exposure during Days with Night, Outdoor, and Indoor Work. *Ann Work Expo Health*; **63**: 651–665.

Dumont M, Beaulieu C. (2007) Light exposure in the natural environment: relevance to mood and sleep disorders. *Sleep Med*; **8**: 557–65.

European Standards. (2011) Light and lighting - lighting of workplaces Indoor workplaces. *European Standards*; **1**: 1.

European Standards. (2014) Light and lighting - Lighting of work places - Part 2: Outdoor work places. *European Standards*; **2**: 1.

Figueiro MG, Hamner R, Bierman A *et al*. (2013) Comparisons of three practical field devices used to measure personal light exposures and activity levels. *Light Res Technol*; **45**: 421–34.

Figueiro M, Rea M. (2016) Office lighting and personal light exposures in two seasons: impact on sleep and mood. *Light Res Technol*; **48**: 352–64.

Fonn S, Groeneveld HT, deBeer M *et al*. (1993) Relationship of respiratory health status to grain dust in a Witwatersrand grain mill: comparison of workers' exposure assessments with industrial hygiene survey findings. *Am J Ind Med*; **24**: 401–11.

Friesen MC, Coble JB, Lu W *et al*. (2012) Combining a job-exposure matrix with exposure measurements to assess occupational exposure to benzene in a population cohort in shanghai, china. *Ann Occup Hyg*; **56**: 80–91.

Geoffroy PA, Bellivier F, Scott J *et al*. (2014) Seasonality and bipolar disorder: a systematic review, from admission rates to seasonality of symptoms. *J Affect Disord*; **168**: 210–23.

Golden RN, Gaynes BN, Ekstrom RD *et al*. (2005) The efficacy of light therapy in the treatment of mood disorders: a review and meta-analysis of the evidence. *Am J Psychiatry*; **162**: 656–62.

Hahn IH, Grynderup MB, Dalsgaard SB *et al*. (2011) Does outdoor work during the winter season protect against depression and mood difficulties? *Scand J Work Environ Health*; **37**: 446–9.

Heil DP, Mathis SR. (2002) Characterizing free-living light exposure using a wrist-worn light monitor. *Appl Ergon*; **33**: 357–63.

Hubalek, S, Brink M, Schierz C. (2010) Office workers" daily exposure to light and its influence on sleep quality and mood. *Light Res Technol*; **42**: 33.

IARC Working Group on the Evaluation of Carcinogenic Risks to Humans. (2010) Painting, firefighting, and shiftwork. *IARC Monogr Eval Carcinog Risks Hum*; **98**: 9–764.

International Organization for Standardization. (2018) ISO/CIE 8995-3:2018. Lighting of work places -- Part 3: lighting requirements for safety and security of outdoor work places.

Kolstad HA, Hansen AM, Kærgaard A *et al*. (2011) Job strain and the risk of depression: is reporting biased? *Am J Epidemiol*; **173**: 94–102.

Kromhout H, Symanski E, Rappaport SM. (1993) A comprehensive evaluation of within- and between-worker components of occupational exposure to chemical agents. *Ann Occup Hyg*; **37**: 253–70.

Lemmer B, Oster H. (2018) The role of circadian rhythms in the hypertension of diabetes mellitus and the metabolic syndrome. *Curr Hypertens Rep*; **20**: 43.

Levitan RD. (2007) The chronobiology and neurobiology of winter seasonal affective disorder. *Dialogues Clin Neurosci*; **9**: 315–24.

Lok R, Smolders KCHJ, Beersma DGM *et al*. (2018) Light, alertness, and alerting effects of white light: a literature overview. *J Biol Rhythms*: 748730418796443.

Magnusson A. (2000) An overview of epidemiological studies on seasonal affective disorder. *Acta Psychiatr Scand*; **101**: 176–84.

Markvart J, Hansen ÅM, Christoffersen J. (2015) Comparison and correction of the light sensor output from 48 wearable light exposure devices by using a side-by-side field calibration method. *LEUKOS*; **11**: 155–171.

Mason IC, Boubekri M, Figueiro MG *et al*. (2018) Circadian health and light: a report on the national heart, lung, and blood institute's workshop. *J Biol Rhythms*; **33**: 451–7.

Papantoniou K, Pozo OJ, Espinosa A *et al*. (2014) Circadian variation of melatonin, light exposure, and diurnal preference in day and night shift workers of both sexes. *Cancer Epidemiol Biomarkers Prev*; **23**: 1176–86.

Partonen T, Lönnqvist J. (2000) Bright light improves vitality and alleviates distress in healthy people. *J Affect Disord*; **57**: 55–61.

Peters S, Vermeulen R, Portengen L *et al*. (2011) Modelling of occupational respirable crystalline silica exposure for quantitative exposure assessment in community-based case-control studies. *J Environ Monit*; **13**: 3262–8.

Rosenthal NE, Sack DA, Gillin JC *et al*. (1984) Seasonal affective disorder. A description of the syndrome and preliminary findings with light therapy. *Arch Gen Psychiatry*; **41**: 72–80.

aan het Rot M, Moskowitz DS, Young SN. (2008) Exposure to bright light is associated with positive social interaction and good mood over short time periods: a naturalistic study in mildly seasonal people. *J Psychiatr Res*; **42**: 311–9.

Sander B, Markvart J, Kessel L *et al*. (2015) Can sleep quality and wellbeing be improved by changing the indoor lighting in the homes of healthy, elderly citizens? *Chronobiol Int*; **32**: 1049–60.

Sarazin P, Burstyn I, Kincl L *et al*. (2016) Trends in OSHA Compliance Monitoring Data 1979-2011: statistical Modeling of Ancillary Information across 77 Chemicals. *Ann Occup Hyg*; **60**: 432–52.

Scheeper B, Kromhout H, Boleij JS. (1995) Wood-dust exposure during wood-working processes. *Ann Occup Hyg*; **39**: 141–54.

Smolensky MH, Sackett-Lundeen LL, Portaluppi F. (2015) Nocturnal light pollution and underexposure to daytime sunlight: complementary mechanisms of circadian disruption and related diseases. *Chronobiol Int*; **32**: 1029–48.

Statistics Denmark. (2002) *Danish Industrial Classification of All Economic Activities 2003*. Copenhagen, Denmark: Danmarks Statistiks trykkeri.

Stothard ER, McHill AW, Depner CM *et al*. (2017) Circadian entrainment to the natural light-dark cycle across seasons and the weekend. *Curr Biol*; **27**: 508–13.

Tseng PT, Chen YW, Tu KY *et al*. (2016) Light therapy in the treatment of patients with bipolar depression: a meta-analytic study. *Eur Neuropsychopharmacol*; **26**: 1037–47.

Vinzents PS, Schlünssen V, Feveile H *et al*. (2001) Variations in exposure to inhalable wood dust in the Danish furniture industry. Within- and between-worker and factory components estimated from passive dust sampling. *Ann Occup Hyg*; **45**: 603–8.

Wild P, Sauleau EA, Bourgkard E *et al*. (2002) Combining expert ratings and exposure measurements: a random effect paradigm. *Ann Occup Hyg*; **46**: 479–87.

Wirz-Justice A, Graw P, Kräuchi K *et al*. (1996) 'Natural' light treatment of seasonal affective disorder. *J Affect Disord*; **37**: 109–20.