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Are we still in the dark? A systematic review on personal daily light exposure, sleep-wake rhythm, and mood in healthy adults from the general population

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ABSTRACT

Insufficient light exposure is assumed to be related to a wide array of health problems, though few studies focus on the role of whole-day light exposure in the habitual setting in the development of these health problems. The current review aims to describe the association between personal light exposure in the habitual setting and sleep-wake rhythm and mood in healthy adults from the general population.

Five databases (Embase, Medline Epub, Web of Science, PsycINFO, and Google Scholar) were searched in June 2019. The inclusion criteria included: assessment directly of light exposure on the participants for at least one full day; reporting on both individual personal light exposure and outcomes. The quality of the papers was assessed using the Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies of the National Heart, Lung and Blood Institute. The current review followed the PRISMA guidelines.

In total, 8140 papers were identified in the database search. Twenty-five papers were eventually included in this review. All included studies were cross-sectional, and individual light exposure was usually measured with a wrist-worn device. Five studies received a "good" quality rating, 16 received a "fair" rating, and the remaining 4 a "poor" quality rating. The overall quality of the included studies was considered low because of the lack of intervention studies and the fact that light exposure was measured on the wrist.

Given the low quality of the included studies, the current review can only provide a first exploration on the association between light exposure and sleep-wake rhythm and mood in healthy adults from the general population. Limited evidence is presented for a positive relationship between the amount and timing of light exposure on the one hand and rest-activity rhythm and some estimates of sleep architecture on the other. The evidence on an association between light exposure and circadian phase, sleep estimates, sleep quality, and mood is conflicting. Data from intervention studies are needed to gain insight into the causal mechanism of the relationship between light exposure and sleep-wake rhythm and mood.

Introduction

Light is as important for perceiving the world as it is for regulating physiological and behavioral rhythms. These follow a circadian rhythm, a rhythm of approximately 24 hours. Circadian rhythms are regulated by the biological clock, which is located in the suprachiasmatic nucleus in the hypothalamus. Circadian rhythms synchronize

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to the external 24h rhythm using external cues called "Zeitgebers," of which light is the strongest.[1]

Alignment of the circadian rhythm with external day-night rhythm is considered essential for the regulation of the sleep-wake rhythm and mood.[2-4] Insufficient, or badly timed, exposure to light can ultimately result in desynchronization of the sleep-wake rhythm and sleep problems, which in turn can result in mood problems.[3] Misalignment of circadian rhythms[2,5] and disturbances of the sleep-wake rhythm[6] and mood[7] are each associated with poor health outcomes.

Research in populations exposed to light patterns that are extremely deviated from the natural dark-light cycle (e.g. shiftwork, jetlag, and a late chronotype) has provided knowledge on the relationship between light exposure, sleep-wake rhythm mood, and other health complaints. For instance, traveling through time zones has been associated with disruption of the circadian rhythm,[8] whereas shiftwork is associated with sleep problems and lower sleep quality,[9] depressed mood,[10,11] cardiovascular diseases, gastro-intestinal and metabolic disorders,[12] as well as cancer.[13-15] The exposure to extremely deviating light patterns is assumed to play a role in the development of these health problems.[11]

To date, evidence on the relationship between light, sleep-wake rhythm and mood is provided by both fundamental studies in humans and studies in populations with extreme deviating light exposure patterns. For the general population in everyday living conditions this relationship is less clear. Associations between light exposure and health in populations prone to extreme deviating light patterns are not necessarily generalizable to the general population. Although not as extremely deviating, the general population might be exposed to suboptimal light as well; for instance due to little bright light exposure,[16-18] poorly lit homes and workspaces,[18-20] or evening light exposure using multimedia devices.[21] So far, we are lacking an overview of the evidence on the relationship between daily light exposure in the habitual setting and sleep-wake rhythm, and mood in the general population.

The aim of the current systematic literature review is to provide an overview of the literature on the association of personal light exposure in the everyday (habitual) setting, with sleep-wake rhythm, and mood in healthy adults from the general population. The current review will focus on personal light exposure as measured directly on the participants, as this is considered more reliable than a proxy such as light exposure measurements in the environment.[22] No restrictions will be made with regard to the features of light exposure; the timing, amount, and spectral distribution will all be described. Also, the outcomes in terms of sleep-wake rhythm and mood will be explored broadly and without restrictions. This way, we aim to determine the potential impact of personal daily light exposure on sleep-wake rhythm and mood.

Methods

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines[23] were followed during this review. This review was registered in the Prospero register under number CRD42016039107.

Search strategy

The search was performed within multiple electronic databases in order to reduce the risk of missing eligible articles. Embase, Medline, Psychinfo, Web of Science, and Google Scholar were searched on June 14, 2019. The database-specific search codes used are shown in Appendix A. In addition, the reference lists in the included papers were examined for further relevant papers.

Definitions and inclusion criteria

The aim of the review is to study the association of personal light exposure in the habitual setting during the day with sleep-wake rhythm and mood in the general population. Personal light exposure refers to the light exposure measured on the participant directly as this is considered more reliable than indirect measurements of light exposure such as light measurements in the environment.[22] Light exposure could be both artificial light and sunlight. All features of light exposure were included; the timing, amount, and spectral distribution will all be described. The habitual setting is defined to include all real-life settings. Studies conducted in a laboratory or experimental setting were excluded. Real-life intervention studies that included baseline analyses of the association between light exposure and outcomes were included. With regard to the population, we aimed for healthy adults from the general population who were not likely to be exposed to extreme deviating light exposure patterns, therefore excluding shift workers, studies of chronotypes, and jetlag. No criteria were formulated for the outcome variables of sleep-wake rhythm, thus 24 hour activity-rest rhythm, sleep estimates or sleep problems could all be included. "Mood" was used as an umbrella term to capture all possible facets of the term; both states and traits (affect vs. temperament) could be included, as well as mood complaints.

Studies had to meet the following inclusion criteria: published in the English language, study sample of healthy adults aged ≥18 from the general population; light exposure was measured directly on the participant for at least one full waking day; the study took place in a habitual setting; sleep-wake rhythm and/or mood, and analyses of the relationship between habitual daily light exposure and sleep-wake rhythm and/or mood were reported.

Studies were excluded if participants were likely to have deviating light patterns (shiftwork, jetlag, chronotype), participants had pre-existing sleep- or mood disorders or other known physical or mental conditions, if the full text was not available through the medical libraries or if the text was a conference abstract. Studies conducted in the controlled environment of a laboratory were also excluded.

Selection process

The selection of papers was carried out by the first and second authors. After the electronic database search, the titles and abstracts were screened for eligibility. Then the full text was read of the eligible papers. Disagreement between the 2 authors was resolved through consensus discussions. The bibliography of selected papers was screened for possible relevant papers that were not included in the electronic database search. These papers were screened in the same manner as papers from the electronic database search (Fig. 1).

Data extraction and management

In the data collection phase, all results were extracted of analyses of the relationship between light exposure and the outcome measures sleep-wake rhythm and mood.

Quality assessments

Selected studies were assessed for methodological quality using the Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies of the National Heart, Lung and Blood Institute.[24] The Quality Assessment Tool consists of 14 items that can be scored as "yes," "no," "not applicable" or "not recorded". Each "yes" was rewarded with one point; studies could score a maximum of 14 points.

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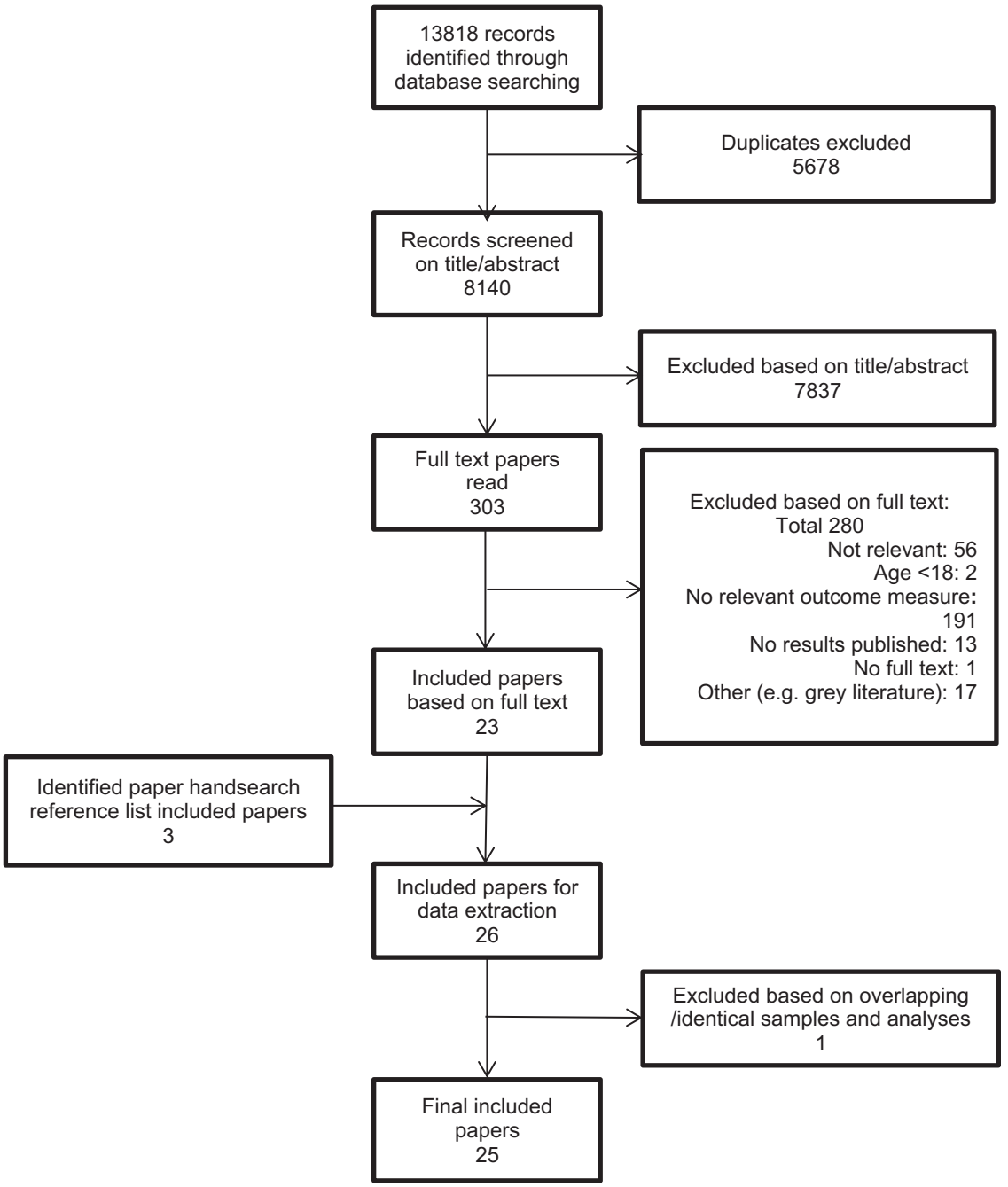

Fig. 1. Flow chart of paper selection.

Based on the quality assessment, an overall rating of "poor," "fair" or "good" was determined. Studies that scored 9 points or more received an overall "good" rating; however, if only basic analyses (such as correlations) were performed the study was assigned a "fair" overall rating. Studies with 8 points with advanced analysis (such as regression analyses) received a "good" rating. Studies with 6-8 points received a "fair" rating, unless they had a small sample size ($N < 30$); those studies were given a "poor" rating. Studies with 5 points or fewer were all rated as "poor."

The quality assessment was done by the first author, who assessed all the included studies and determined the overall rating for the quality of the study. Next, the findings were presented to the second author to check whether the quality assessment of all the studies had been performed in a consistent manner. Disagreements were resolved through a consensus discussion.

The current review itself was not assessed on quality, as to date no appropriate tool exists to do a quality assessment of reviews that include merely observational studies.

Results

Selection of studies

The search for studies on the association between daily light exposure and sleep-wake rhythm and mood generated 8140 unique articles (Fig. 1). Based on title-abstract screening, 303 were considered eligible.

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After reading the full text of these articles, 23 articles were included. Most of the excluded studies (n = 279) were excluded because they did not report on personal light measurements. After including 3 articles from the reference lists of the included papers, a total of 26 articles were obtained for data extraction.

With regard to overlapping populations, 3 papers published results on the same group of post-menopausal women from the Women's Health Initiative.[25-27] In 2 cases, there were 2 different papers that reported on the same group of healthy volunteers.[28-31] For these studies, only the first unique analysis will be reported. Two studies[25,32] described identical populations and data analysis relevant for the current review, therefore one of these—the study of Youngstedt et al (2004)[32]—was excluded.

Of the final 25 articles included, ten focused solely on sleep-wake rhythm,[30,33-41] 4 on sleep-wake rhythm and mood,[19,25,27,42] and the remaining 11 studies focused solely on mood.[26,28,29,31,43-49]

Quality assessment of the included studies

Information needed to rate the items of the Quality Assessment Tool was not always reported in the articles, which restricted the proper assessment of the risk of bias. Five studies received an overall "good" rating.[19,34,36,43,49] Sixteen studies were rated as "fair."[25,27-31,33,35,37,39,41,42,44,46-48] The remaining 4 studies were rated as "poor."[26,38,40,45] No sample size justification was provided for 22 studies, but due to the observational nature of the studies, this was not considered to impact the quality of the studies too much. Twenty studies did not report on the participation rate of eligible persons, which might have resulted in an unrepresentative sample of the target group. Fifteen studies measured the light exposure once or averaged the light exposure over the measurement period, making it not possible to show an effect of changes in light exposure over time, thus resulting in a weaker study design. Fourteen studies measured the light exposure (mostly) at the time of the outcomes rather than prior to the outcomes, which makes it not possible to study a causal relationship between light exposure and the outcomes. Table 1 gives the complete overview of the results of the quality assessment.

Light exposure measurement

Within the 25 studies, 11 different devices were used to measure personal light exposure. Measuring light exposure at eye level is preferred as it is the most reliable way to estimate the amount of light that enters the eye. Three studies measured light exposure at eye level using a device that was attached to glasses that the participants wore.[19,45,46] In one study, the participants wore a lanyard with a light sensor as a necklace[38]; in another study the light cell was pinned as a brooch.[49] In 19 studies, participants wore an accelerometer with an integrated light cell on their wrist.[25-31,33-37,39-44,47,48] New-generation wrist-worn accelerometers, used primarily to measure sleep-wake activity, often come with an integrated light sensor. Although practical, the amount of light exposure measured at wrist-level is less reliable. When compared to eye level, the amount of light exposure measured at wrist level deviates by up to 27%.[50]

All studies measured light at least for one complete waking day of the participants, as this was an inclusion criterion. The duration of the measurements varied between 16 hours and 10 days.

The average intensity of light exposure in lux was reported in 21 studies.[19,25-31,33,34,36,38-43,45-47,49] Duration of light exposure above a predefined threshold in lux was reported in 6 studies.[19,35,37,44,46,48] Two studies grouped participants based on low or high light exposure according to quartiles or by a cut-off value of light exposure defined by the authors.[42,43]

The timing of light exposure was reported in 9 studies.[26,27,31,33-36,38,45,46] These studies reported the average light exposure in the morning or evening, or mentioned the timing of the maximum light exposure (acrophase of the light exposure pattern).

Associations between light exposure and outcomes

Based on the reported light exposure outcome variables, a description will be given of the association between the amount (defined as the average intensity of light exposure in lux, unless specified otherwise), duration, and timing of light exposure on the one hand and the outcome variables sleep-wake rhythm, and mood on the other hand. The results will be described starting with the highest quality study included. In the case of significant results, all the test results and p-values for the light exposure variables reported in the papers are presented in both the text and the tables.

We acknowledge the broadness of our research question, but we are interested in determining the potential impact of personal daily light on sleep-wake rhythm, and mood even if we could not be definitive about the specific conditions and effects. Therefore, in order to qualify the results, the conclusions per domain are drawn based on an adaptation of the Cochrane classification of the level of evidence[51]:

Strong evidence—consistent findings among multiple high-quality studies;
Moderate evidence—consistent findings among multiple fair/low-quality studies and/or one high-quality study;
Limited evidence—consistent findings among multiple low-quality studies;
Very limited evidence—single low-quality study;
Conflicting—inconsistent findings among multiple studies;
No evidence—no studies available.

Sleep-wake rhythm

Assessment of sleep-wake rhythm

Outcomes for the sleep-wake rhythm are described within the domains sleep-wake rhythm and sleep quality. The 12 studies on light exposure and sleep-wake rhythm and 7 studies on light exposure and sleep quality are described in Tables 2 and 3. Of these studies, 5 studies solely used actigraphy to measure sleep-wake rhythm.[27,37,39,41,42] One study used both actigraphy and sleep diaries or questionnaires.[25] Four studies focused on measuring melatonin levels or dim light melatonin onset (DLMO) as indicator of the circadian phase of the sleep-wake rhythm.[30,33-35] Wams et al (2017)[36] used polysomnography (PSG) in combination with actigraphy and DLMO measurements.

Sleep quality was measured in 7 studies, of which 4[36,39,40,42] used the well-validated Pittsburgh Sleep Quality index (PSQI).[52] Two actigraphy studies reported the sleep efficiency as a proxy for sleep quality.[27,39] The self-reported PROMIS Sleep disturbance short form for measuring sleep problems in addition to measuring sleep quality was used twice.[40,42] The last 2 studies[19,25] added questions on subjective sleep quality to the questionnaires.

Association between light exposure and sleep-wake rhythms and sleep quality

Because of the broad variety of outcome measures for sleep-wake rhythms and sleep quality, results are grouped per outcome measure.

Sleep-wake rhythm (Table 2)

Rest-activity rhythm Light exposure and rest-activity rhythms were studied in one fair-quality study[42] and one poor-quality study.[38] Exposure to light of high intensities during the day was associated with higher phasor magnitude ($F_{1,39}$ = 35.38, $p < .0001$)[42] and stability of the sleep-activity rhythm (r = 0.343, $p < .01$).[38]

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Table 1
Quality of the included studies (NIH National Heart, Lung, and Blood Institute Study quality assessment tool)

	aan het Rot et al (2008)[43]	Araki et al (2012)[28]	Asai et al (2018)[48]	Beale et al (2017)[41]	Boubekri et al (2014)[39]	Crowley et al (2015)[35]	Espiritu et al (1994)[44]	Figueiro et al (2016)[40]	Figueiro et al (2017)[42]	Grandner et al (2006)[26]	Hoaki et al (2011)[29]	Hood et al (2004)[37]
1. Was the research question or objective in this paper clearly stated?	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	yes	yes
2. Was the study population clearly specified and defined?	yes	no	yes	yes	yes	yes	yes	no	yes	yes	yes	no
3. Was the participation rate of eligible persons at least 50%?	NR	yes	yes	ND	NR	NR	no	NR	NR	ND	yes	NR
4. Were all the subjects selected or recruited from the same or similar populations (including the same time period)? Were inclusion and exclusion criteria for being in the study pre-specified and applied uniformly to all participants?	yes	no	yes	ND	yes	no	yes	yes	yes	yes	no	NR
5. Was a sample size justification, power description, or variance and effect estimates provided?	no	yes	no	no	no	no	no	no	no	no	no	no
6. For the analyses in this paper, were the exposure(s) of interest measured prior to the outcome(s) being measured?	no	no	NR	no	NR	no	ND	no	yes	yes	no	no
7. Was the timeframe sufficient so that one could reasonably expect to see an association between exposure and outcome if it existed?	yes	yes	NR	yes	yes	yes	yes	yes	yes	no	yes	yes
8. For exposures that can vary in amount or level, did the study examine different levels of the exposure as related to the outcome (e.g., categories of exposure, or exposure measured as continuous variable)?	yes	no	no	yes	yes	yes	yes	no	yes	no	no	yes
9. Were the exposure measures (independent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	yes
10. Was the exposure(s) assessed more than once over time?	yes	no	no	no	no	yes	no	yes	yes	no	no	no
11. Were the outcome measures (dependent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
12. Were the outcome assessors blinded to the exposure status of participants?	NA	no	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	no	NA	NA	NA	NA	no	NA	no	no	NA	NA	NA

(*continued on next page*)

Table 1 (*Continued*)

	aan het Rot et al (2008)[43]	Araki et al (2012) [28]	Asai et al (2018) [48]	Beale et al (2017) [41]	Boubekri et al (2014) [39]	Crowley et al (2015) [35]	Espiritu et al (1994) [44]	Figueiro et al (2016) [40]	Figueiro et al (2017) [42]	Grandner et al (2006) [26]	Hoaki et al (2011) [29]	Hood et al (2004) [37]
13. Was loss to follow-up after baseline 20% or less?												
14. Were key potential confounding variables measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?	yes	no	yes	no	no	no	yes	no	yes	yes	yes	yes
Additional criteria [a]	AA, SS	BA	BA	BA	BA, SS	BA, SS	BA	AA, SS	BA	BA	BA	BA
Total score	9	6	7	6	7	7	8	6	9	5	7	6
Quality rating (poor, fair or good)	good	fair	fair	fair	fair	fair	fair	poor	fair	poor	fair	fair

Hubalek et al (2010) [19]	Itzhacki et al (2019) [49]	Jean-Louis et al (2005) [30]	Jean-Louis et al (2005b) [31]	Koller et al (1993) [45]	Kripke et al (2004) [25]	Martinez-Nicolas et al (2011) [38]	Phillips et al (2017) [33]	Smolders et al (2013) [46]	van der Maren et al (2018) [34]	Wallace-Guy et al (2002) [27]	Wams et al (2017) [36]	Wang et al (2003) [47]
yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
yes	no	yes	no	no	yes	yes	yes	no	no	yes	yes	yes
NR	NR	NR	NR	NR	ND	ND	NR	ND	NR	no	ND	NR
yes	yes	no	no	ND	no	NR	yes	no	yes	yes	no	yes
no	yes	no	no	no	no	no	no	no	no	yes	no	no
yes	yes	no	yes	no	yes	no	no	yes	yes	yes	yes	no
yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Hubalek et al **(2010)** [19]	**Itzhacki** et al **(2019)** [49]	**Jean-Louis** et al **(2005)** [30]	**Jean-Louis** et al **(2005b)** [31]	**Koller** et al **(1993)** [45]	**Kripke** et al **(2004)** [25]	**Martinez-Nicolas** et al **(2011)** [38]	**Phillips** et al **(2017)** [33]	**Smolders** et al **(2013)** [46]	**van der Maren** et al **(2018)** [34]	**Wallace-Guy** et al **(2002)** [27]	**Wams** et al **(2017)** [36]	**Wang et al (2003)** [47]
yes	yes	no	no	no	no	yes	no	no	yes	no	yes	no
yes	yes	yes	yes	yes	yes	no	yes	yes	yes	yes	yes	yes
yes	yes	no	no	yes	no	no	no	yes	yes	no	yes	no
yes	no	yes	yes	yes	yes	no	yes	yes	yes	no	yes	yes
NA	NA	NA	NA	NA	NA	NA	NA	NA	Na	NA	no	NA
NA	yes	NA	NA	NR	NA	NA	NA	NA	NR	NA	NA	NA
yes	yes	yes	yes	no	yes	yes	yes	yes	NA	yes	yes	no
BA, SS	AA	BA	BA	AA, SS	BA	BA	BA, SS	AA	AA	BA	SS	AA
9	10	6	6	5	7	5	7	7	8	8	9	6
good	good	fair	fair	poor	fair	poor	fair	fair	good	fair	good	fair

ND, not determined; NR, not reported; AA, advanced analyses; BA, basic analyses; SS, small sample.

Note. Question 5: Sample size of n < 30 was considered small. Question 6: studies that measured exposure prior to the outcome received a "yes"; if exposure was measured at the same time as or after the outcome, this question was scored "no". Question 7: studies received a "yes" if light exposure was measured for at least 3 days.

Studies that scored 9 points or more received an overall "good" rating; however if only basic analyses (such as correlations) were performed the study was assigned a "fair" overall rating. Studies with 8 points that included advanced analysis (such as regression analyses) received a "good" rating. Studies with 6-8 points received a "fair" rating, unless they had a small sample size (N < 30) — those studies were assigned a "poor" rating. Studies with 5 or less points were all rated as "poor".

[a] Additional criteria for final quality rating. Abbreviations: AA, advanced analyses; BA, basic analyses; SS, small sample (N<30)

Table 2
Characteristics of included studies that examine the association between personal light exposure and sleep-wake rhythm in the general population

Author	Country	Design, sampling, sample size	Participant characteristics (age, gender)	Measurement: Light exposure	Measurement: Sleep-wake rhythm	Light exposure outcome	Sleep-wake rhythm outcome	Results	RoB
Beale et al (2017) [41]	Mozambique	Cross-sectional, volunteer sample N = 74	Adults from an electrified city and an unelectrified rural settlement in the Milange district, Zambézia province, Mozambique. 34.68 years (SD = 8.73) 42% female	ActTrust (AT0503 Condor Instruments, São Paulo, Brazil)	ActTrust (AT0503 Condor Instruments, São Paulo, Brazil)	Total light exposure with most illumination Total light exposure in the 3 hours after sunset (light at night)	Sleep onset Nocturnal activity L5 onset (onset of 5 hours of least activity)	Sleep onset is negatively correlated with amount of daytime light exposure ($r = -0.41$, $t(60) = -3.49$, $p < .001$). More light prior to sleep time resulted in a later sleep onset latency ($r = 0.61$, $t(60)$ 5.93, $p < .001$). L5 onset ($r = -0.23$, $t(60) = -2.58$, $p = .012$) correlated negatively with amount of daytime light exposure. Nocturnal activity was not associated with the amount of evening light when adjusted for age, sex, and location ($R^2 = 0.28$, $\beta_{evening\ light} = -5.6 \times 10{-}5$, $p = .77$, $\beta_{location} = 0.25$, $p = .00005$).	fair
Boubekri et al (2014) [39]	U.S.A.	Cross sectional, convenient sample N = 21	Volunteers from office locations with and without windows. Descriptives of this sample not reported, descriptives below are for the full sample of 49 participants. 19-60+ years 61.22 % female	Actiwatch-L (Minimitter)	Actiwatch-L (Minimitter)	Average light exposure	Sleep onset Sleep onset latency Wake after sleep onset Sleep duration Sleep fragmentation	Workers with access to daylight had a longer sleep duration than workers without access to daylight (476.31 minutes vs. 429.65 minutes, $p < .05$). There were no significant differences between workers with windows and workers without windows in sleep onset time (21:46 vs. 22:04), sleep onset latency (10 min vs 19 min), sleep efficiency (91% vs 89%), wake after sleep onset (30 min vs 37 min), and sleep fragmentation (19 vs 22) on workday nights.	fair

(*continued on next page*)

Table 2 (*Continued*)

Author	Country	Design, sampling, sample size	Participant characteristics (age, gender)	Measurement: Light exposure	Measurement: Sleep-wake rhythm	Light exposure outcome	Sleep-wake rhythm outcome	Results	RoB
Crowley et al (2015) [35]	U.S.A.	Cross-sectional, volunteer sample N = 14	Full-time office workers 28 years (SD = 5) 71% female	Actiwatch Spectrum (Philips Respironics Inc. Bend, OR)	Dim Light Melatonin Onset	Total minutes and timing of exposure above 10, 180, 550 and 1000 lux	Dim Light Melatonin Onset (DLMO)	Total duration of light exposure at any level did not correlate with the DLMO. The DLMO was later if the first exposure to 10 lux (r = 0.55, p = .04) and 180 lux (r = 0.61, p = .02) were also later. Trends were seen for the 550 lux (r = 0.51, p = .06) and 1000 lux (r = 0.52, p = .06) thresholds. Similarly, the DLMO was later if the last daily exposure to 180 lux was also later (r = 0.77, p = .001). A similar trend was seen for the 10 lux threshold (r = 0.49, p = .08), but the last daily exposures to 550 lux and 1000 lux were not associated with the DLMO.	fair
Figueiro et al (2017) [42]	U.S.A.	Cross-sectional, volunteer sample N=67	Workers in 5 buildings of the U.S. General Services Administration in Washington DC (2x), Portland OR, Seattle WA, Grand Junction Colorado Age not reported 63% female	The Daysimeter, (Lighting Research Center, Troy, NY)	The Daysimeter, (Lighting Research Center, Troy, NY)	Morning or workday CS; Magnitude of circadian stimulus calculated using light exposure and circadian illuminance (CS) in the morning or workday (high vs low)	Phasor magnitude Phase angle Sleep onset latency Sleep time Wake time Sleep efficiency	Participants who had high workday CS had greater phasor magnitudes than those who had low workday CS ($F_{1,39}$ = 35.38, p < .0001). Workday CS did not affect the phasor angle. High morning CS was associated with greater phasor magnitudes ($F_{1,45}$ = 41,94, p < .0001). Morning CS did not relate to phasor angle. Sleep onset latency declined as morning CS increased ($F_{1,162}$ = 13.49, p = .002). No effect was found for high vs. low workday CS and sleep onset latency. No association was found between any of the CS measurements and sleep time, wake time, and sleep efficiency.	fair

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Table 2 (*Continued*)

Author	Country	Design, sampling, sample size	Participant characteristics (age, gender)	Measurement: Light exposure	Measurement: Sleep-wake rhythm	Light exposure outcome	Sleep-wake rhythm outcome	Results	RoB
Hood et al (2004) [37]	Australia	Cross-sectional, volunteer sample N = 33	Healthy elderly 74.18 years 66% female	Mini Mitter 2000 Data Logger	Mini Mitter 2000 Data Logger	Light intensity in total minutes above 3,000 lux	Nocturnal immobility	Minutes of light above 3000 lux was positively associated with Nocturnal Immobility data ($R^2 = 0.519$, $t(26) = 2.408$, $p < .023$).	fair
Jean-Louis et al (2005b) [30]	U.S.A.	Cross -sectional, volunteer sample N = 30	Healthy elderly 69.03 years (SD = 6.84) 80% female	Actiwatch-L (Mini Mitter)	Melatonin	Light exposure acrophase Light exposure mesor	Melatonin acrophase Melatonin mesor	When corrected for sleep and race, light exposure acrophase was associated with a lower melatonin mesor ($r = -0.43$, $p = .03$), light exposure mesor was not associated with the melatonin mesor. Light exposure mesor and acrophase were not associated with melatonin acrophase.	fair
Kripke et al (2004) [25]	U.S.A.	Cross-sectional, convenient sample N = 416-450	Menopausal women included in a ancillary study of the Women's Health Initiative (Matthews et al 1997) 67.7 years (SD = 7.9) 100% female	Actillume, Ambulatory Monitoring Inc., Ardsley, NY	Actillume, Ambulatory Monitoring Inc., Ardsley, NY Sleep diary	Mesor Log Lux	Objective sleep duration Subjective sleep duration Daytime sleep Sleep acrophase	There was a negative correlation between objective sleep duration and mesor Log lux ($r_p = -0.20$, $p < .001$). Mesor log lux was not related to subjective sleep duration and daytime sleep. When corrected for age and ethnicity, Mesor Log Lux was positively associated with acrophase of sleep ($r_p = -0.14$, $p < .005$).	fair
Martinez-Nicolas et al (2011) [38]	Spain	Cross-sectional, volunteer sample N = 88	Undergraduate volunteers 18-23 years 64% female	HOBO Pendant Temperature/Light Data Logger UA-002-64 (Onset Computer, Bourne, Massachusetts, USA)	Self-reported sleep diary designed by Chronobiology Laboratory of University of Murcia, Spain.	Mean Intensity Morning light Evening light	Stability of sleep-wake rhythm Sleep fragmentation Midsleep	A higher mean intensity ($r = 0.343$, $p < .01$) as well as more light in the morning ($r = 0.437$, $p < .001$) and evening ($r = 0.304$, $p < .01$) were associated with a more stable sleep-wake rhythm. None of the light exposure measures were associated with the sleep fragmentation. A higher mean intensity was associated with an earlier midpoint of sleep ($r = -0.425$, $p < 0.1$). Stronger morning light exposure ($r = -0.651$, $p < .001$) as well as evening light exposure ($r = -0.287$, $p < .01$) were associated with phase advance measured in terms of sleep midpoint.	poor

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Table 2 (*Continued*)

Author	Country	Design, sampling, sample size	Participant characteristics (age, gender)	Measurement: Light exposure	Measurement: Sleep-wake rhythm	Light exposure outcome	Sleep-wake rhythm outcome	Results	RoB
Phillips et al (2017) [33]	U.S.A.	Cross-sectional, volunteer sample N = 22	Full-time undergraduates (excluding first-years) from Harvard College 20.23 years (SD = 1.27) 48% female	Motionlogger-L (Ambulatory Monitoring, Inc., Ardsley, NY)	Dim Light Melatonin Onset	Light exposure in lux	Dim Light Melatonin Onset (DLMO)	A previously validated model of the human circadian pacemaker, its sensitivity to light, and salivary melatonin concentration was used to predict circadian phase. Modelling the circadian pacemaker showed that irregular sleepers have a 1.7 hour delay of their circadian timing predominantly due to the characteristics of their light profiles ($p < .01$, t-test).	fair
Van der Maren et al (2018) [34]	Canada	Cross-sectional, volunteer sample N = 28	Sleep delayed group: 21.3 years (SD = 1.2) 57 % female Control group: mean age 22.1 years (SD = 2.5) 57 % female	Actiwatch-2 (Philips-Respironics, Andover, MA)	DLMO	Mean white light exposure Mean blue light exposure Light exposure amplitude	Dim Light Melatonin Onset (DLMO)	The association between averaged daily exposure to white light and DLMO was non-significant ($r = -0.29$, $p = .14$). More exposure to blue light was related to an earlier DLMO ($r = -0.46$, $p = .01$). A lower light exposure amplitude was associated with a later DLMO for both white ($r = -0.61$, $p = .001$) and blue light ($r = -0.53$, $p = .004$).	good
Wallace-Guy et al (2002) [27]	U.S.A.	Cross-sectional, convenient sample N = 154	Menopausal women included in a ancillary study of the Women's Health Initiative (Matthews et al 1997) 67.7 years (SD = 7.9) 100% female	Actillume, Ambulatory Monitoring Inc., Ardsley, NY	Actillume, Ambulatory Monitoring Inc., Ardsley, NY	Mesor logLux Light exposure 4 hours prior to sleep onset	Sleep onset latency Waking after sleep onset Total night sleep Total day sleep	Greater 24-hour light exposure was related to shorter sleep latencies ($r = -0.29$, $p < .001$) and waking after sleep onset ($r = -0.19$, $p < .05$), but not with total night or day sleep. Illumination during the 4 hours before bedtime was not significantly related to total sleep time, sleep latency, sleep timing, or amount of daytime napping.	fair

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Table 2 (*Continued*)

Author	Country	Design, sampling, sample size	Participant characteristics (age, gender)	Measurement: Light exposure	Measurement: Sleep-wake rhythm	Light exposure outcome	Sleep-wake rhythm outcome	Results	RoB
Wams et al (2017) [36]	the Netherlands	Cross-sectional, volunteer sample n = 20	Healthy participants 23.4 years (SD = 2.2) 60% female	Motionwatch 8 (8™, MW8™, CamNTech Ltd., UK)	Motionwatch 8 (8™, MW8™, CamNTech Ltd., UK) Polysomnography (PSG)	Light exposure in log Lux Time of first exposure above 10 lux Time of last exposure above 10 lux Time of maximum light exposure	Dim Light Melatonin Onset (DLMO) % Rapid Eye Movement (REM) sleep % stage 1 sleep REM latency Mean awakenings per hour Time in bed Waking after sleep onset No. of transitions Rest duration Sleep onset Sleep offset	Raw maximal light intensity, time of first exposure to >10 lux, time of last exposure to 10 lux, and time of maximal light exposure were not related to DLMO. Higher fitted average light intensity did predict earlier DLMO (R^2 = 0.23, $\chi^2(2) = 10.01$, p < .01). Higher maximal intensity of light on the day before PSG was followed by lower percentages of REM sleep (R^2 = 0.43, χ^2 (2) = 13.90, $p < .001$). Increase in percentage of SWS at higher average light intensities subsequence over the day (R^2= 0.25, χ^2 (2) = 8.8, $p < .05$). A later time of first exposure to >10 lux (R^2= 0.21, χ^2 (1)= 0.36, $p < .05$) and a later timing of maximal light exposure (R^2= .36, $\chi^2(2)$= 11.17, $p < .01$) were associated with a subsequent shorter latency to first REM episode. Lower maximal light intensity was associated with longer rest duration (R^2 = 0.05, χ^2 (2) =4.82, $p < .05$) and fewer awakenings per hour (R^2 = 0.26, χ^2 (2) = 6.98, $p <$ .05). No significant results for waking after sleep onset, number of transitions, time in bed, sleep onset and offset were reported.	good

RoB, risk of bias.

Table 3
Characteristics of included studies examining the association between personal light exposure and sleep quality in the general population

Author	Country	Design, sampling, sample size	Participant characteristics (age, gender)	Measurement: Light exposure	Measurement: Sleep quality	Light exposure outcome	Sleep quality outcome	Results	RoB
Boubekri et al (2014) [39]	U.S.A.	Cross-sectional, convenient sample N = 21	Volunteers from office locations with and without windows. Descriptives of this sample not reported, descriptives below are for the full sample of 49 participants. 19-60+ years 61.22 % female	Actiwatch-L (Minimitter)	Actiwatch-L (Minimitter) Pittsburgh Sleep Quality Index	Average light exposure	Sleep efficiency Sleep quality	There was no difference between workers with and without windows in objectively measured sleep efficiency (with windows: 91%, without windows: 89%, $p < .10$). Workers with windows scores lower on the Pittsburg Sleep Quality Index (5.05 vs. 7.23, $p = .05$), indicating a better sleep quality when compared to workers without windows.	fair
Figueiro et al (2016) [40]	U.S.A.	Cross-sectional, volunteer sample N = 11	Workers of the Building of the U.S. General Services Administration in Grand Junction, Colorado Age not reported 91% female	The Daysimeter (Lighting Research Center, Troy, NY)	Pittsburgh Sleep Quality Index PROMIS Sleep Disturbance Short Form	Magnitude of circadian stimulus calculated using light exposure and circadian illuminance (CS).	Sleep quality Sleep problems	None of the correlations between CS values and self-reports of sleep quality and sleep problems were statistically significant.	poor
Figueiro et al (2017) [41]	U.S.A.	Cross-sectional, volunteer sample N = 67	Workers in 5 buildings of the U.S. General Services Administration in Washington DC (2x), Portland OR, Seattle WA, Grand Junction Colorado Age not reported 63% female	The Daysimeter (Lighting Research Center, Troy, NY)	Pittsburg Sleep Quality index PROMIS Sleep Disturbance Short Form	Morning or workday CS; Magnitude of circadian stimulus calculated using light exposure and circadian illuminance (CS) in the morning or workday (high vs low)	Sleep quality Sleep problems	Participants with high workday CS had significantly better sleep quality ($F_{1,155} = 6.19$, $p = .014$) and fewer sleep disturbances ($F_{1,165} = 4.76$, $p = .031$) than those with low workday CS. No effect was found for high or low morning CS and sleep quality or sleep problems.	fair
Hubalek et al (2010) [19]	Switzerland	Cross-sectional, volunteer sample N = 23	Healthy workers in offices located in or close to Zurich, Switzerland 38.4 years (SD = 10.6) 30% female	LuxBlick (no manufacturer reported)	Sleep Quality Questionnaire	Daily light exposure Light exposure over thresholds 1000 and 2500 lux Vis-nonvis spectrum parameter (ratio image forming and non-image forming light exposure)	Sleep quality	Sleep quality positively correlated with all measures of daily luminous exposure. Spearman's correlations for 25th-90th percentile of illuminance and irradiance were .368 and .963 ($p < .001$). Correlations for duration over thresholds >100 lux, >1000 lux and > 2500 lux were .726, .906 and .915 (all $p < .001$)	good
Kripke et al (2004) [25]	U.S.A.	Cross-sectional, convenient sample N = 416-450	Menopausal women included in an ancillary study of the Women's Health Initiative (Matthews et al 1997) 67.7 years (SD = 7.9) 100% female	Actillume (Ambulatory Monitoring Inc., Ardsley, NY)	Sleep dairy	Mesor Log Lux	Sleep problems Sleep quality	Mesor log lux was positively correlated with sleep quality ($r_p = .17$, $p < .005$) and negatively correlated with trouble falling asleep ($r_p = -0.17$, $p < .005$), waking after sleep onset ($r_p = -0.18$, $p < .001$), early waking ($r_p = -0.09$, $p < .10$) and trouble getting back to sleep ($r_p = -0.11$, $p < .025$).	fair

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Table 3 (*Continued*)

Author	Country	Design, sampling, sample size	Participant characteristics (age, gender)	Measurement: Light exposure	Measurement: Sleep quality	Light exposure outcome	Sleep quality outcome	Results	RoB
Wallace-Guy et al (2002) [27]	U.S.A.	Cross-sectional, convenient sample N = 154	Menopausal women included in a ancillary study of the Women's Health Initiative (Matthews et al 1997) 67.7 years (SD = 7.9) 100% female	Actillume (Ambulatory Monitoring Inc., Ardsley, NY)	Actillume (Ambulatory Monitoring Inc., Ardsley, NY)	Light exposure 4 hours prior to sleep onset	Sleep efficiency	Illumination during the 4 hours before bedtime was not significantly related to sleep efficiency.	fair
Wams et al (2017) [36]	the Netherlands	Cross-sectional, volunteer sample N = 20	Healthy volunteers 23.4 years (SD = 2.2) 60% female	Motionwatch 8 (8™, MW8™, CamNTech Ltd., UK)	Pittsburgh Sleep Quality Index	Light exposure in log Lux Timing of first exposure above 10 lux Timing of maximum light exposure	Sleep quality	Amount of light exposure was not related to sleep quality. Individuals who were first exposed to 10 lux later had significantly lower subjectively reported sleep quality (t=-2.5, p = .02067).	good

RoB, risk of bias.

With regard to the timing of light exposure, the fair study found an association between exposure and the amount of light exposure in the morning and phasor magnitudes ($F_{1,45}$ = 41,94, $p < .0001$).[42] In the poor study, a greater amount of light exposure in the morning (r = 0.437, $p < .001$) and evening (r = 0.304, $p < .01$) was associated with a more stable rest-activity rhythm.[38]

Overall, based on 2 lower-quality studies[38,42] with consistent results, it is concluded that limited evidence is available for a positive relationship between the amount and timing of light exposure and rest-activity rhythms Table 2.

Circadian phase of sleep-wake rhythm One good-quality study found a positive relationship between the amount of light exposure and DLMO (R^2 = 0.23, χ^2 (2) = 10.01, $p < .01$), whereas maximal light exposure in lux was not related to DLMO.[36] Another good-quality study found no relationship between the amount of white light and DLMO, but more exposure to blue light was related to an earlier DLMO (r = −0.46, p = .01).[34] A fair-quality study showed light exposure mesor was not related to timing and mesor of melatonin.[30] Another fair study found that total duration of light exposure above any level of light exposure did not correlate with DLMO.[35]

With regard to timing of light exposure, the good-quality study did not find a relationship between timing of light exposure and DLMO.[36] A fair study found a medium to strong (r = 0.49-0.77) positive relationship between the timing of first and last light exposure and DLMO; later exposure to light was related to later DLMO.[35] Another fair study compared DLMO timing in regular and irregular sleepers, and concluded that the 1.7-hour delay of DLMO in irregular sleepers ($p < .01$) was the result of their delayed timing of light exposure.[33] The last fair study showed later light exposure acrophase was related to lower melatonin mesor (r = −0.43, p = .03) but not to melatonin acrophase.[30]

Given the 2 high-quality studies[34,36] that found a positive relationship between the amount of light exposure and DLMO and 2 fair-quality studies[30,35] that did not find a significant relationship, the available studies provide conflicting evidence on the association between light exposure and DLMO. Given the one high-quality study[36] that did not find a relationship and 3 fair studies that found a positive relationship between timing of light exposure and DLMO,[30,33,35] the evidence for an effect of the timing of light exposure on DLMO is conflicting too.

Sleep architecture The highest-quality study showed exposure to light of higher intensity was associated with a lower percentage of stage 1 sleep (p = .03), shorter REM sleep duration (R^2 = 0.43, χ^2 (2) = 13.90, $p < .001$), and longer slow wave duration on PSG (R^2 = 0.25, χ^2 (2) = 8.86, $p < .05$).[36] The amount of light exposure was not associated with the percentage of stage 2, 3 and REM sleep, N3 latency, and REM sleep latency.[36] A fair study showed that L5 onset, the start of the 5 hours with the least amount of activity during the night, was earlier when participants were exposed to a higher amount of light during the day (r = −0.23, $t(60)$ = −2.58, p = .012).[41] Sleep fragmentation was not associated with the amount of light exposure in one fair study and one poor study.[38,39]

The highest-quality study showed that later timing of first exposure to >10 lux (R^2 = 0.21, χ^2 (1) = 5.77, $p < .05$) and later timing of maximal light exposure (R^2 = 0.36, χ^2 (2) = 11.17, $p < .01$) were associated with a subsequent shorter latency to first REM episode.[36] Timing of light exposure was not associated with the percentage of stage 2, 3 and REM sleep, N3 latency, and REM sleep latency.[36] A fair study found nocturnal activity was not associated with the amount of evening light exposure.[41] A poor study found a higher amount of light exposure in the morning (r = −0.651, $p < .001$) as well as evening light exposure (r = −0.287, $p < .01$) was associated with an earlier sleep midpoint.[38]

The high-quality study[36] as well as the 2 lower-quality studies[38,41] found evidence for a positive relationship between the amount and

Table 4
Characteristics of included studies examining the association between personal light exposure and mood and affect in the general population

Author	Country	Design, sampling, sample size	Participant characteristics (age, gender)	Measurement: Light exposure	Measurement: Mood	Light exposure outcome	Mood outcome	Results	RoB
aan het Rot et al (2008) [43]	Canada	Cross-sectional, volunteer sample N = 53	Mild seasonal individuals, defined by a Global Seasonality Scale score between 6-11 31 years (SD = 8) 54% female	Actiwatch-Light (Mini Mitter, Inc., Bend, OR, USA)	Affect Valence and Affect Arousal Positive Affect	Overall bright light exposure (BLE) Groups: no, low (<19.6min) and high (>19.6 min) Bright light exposure	Affect Valence Affect Arousal Positive Affect	Bright light exposure was positively associated with affect valence ($F_{2, 89}$ = 3.89, p < .03), affect arousal ($F_{2, 89}$ = 10.21, p < .0001) and positive affect ($F_{2,89}$ = 11.66, p < .0001). The difference in affect valence between participants with high and low BLE was significant ($t(89)$ = -2.68, p < .03). The difference between high and no BLE was not significant. Compared to periods without BLE, participants reported higher affect arousal during periods with both low and high BLE (low: $t_{(89)}$ = -4.36, p < .0002; high: $t(89)$ = -3.30, p < .005). After Tukey correction, the difference between low and high BLE was not significant. The differences in positive affect between participants with high, low and zero BLE ($t(89)$ = -2.91, p < .02) and between high and zero BLE ($t(89)$ = -4.81, p < .0001) were significant. The difference between high and low BLE was not significant.	good
Araki et al (2012) [28]	Japan	Cross-sectional, volunteer sample N = 56	Healthy participants (no psychiatric disorders). 26.9 years (SD = 5.9) 30% female	Actigraphy with illuminance measurement (no specs reported)	Japanese standardized version of the Temperament Evaluation of Memphis, Pisa, Paris and San Diego-auto questionnaire version (TEMPS-A)	Average illuminance of daytime	Temperaments: Depressive Anxious Cyclothymic Hyperthymic Irritable	The association between light exposure and cyclothymic temperament was negative (b = −0.33, p = .015), light exposure and hyperthymic temperament scores were positively (b = 0.54, p < .0001) associated. Light exposure was not associated with depressive temperament, or irritable and anxious temperament.	fair
Asai et al (2018) [48]	Japan	Cross-sectional, volunteer sample n = 1005	Elderly Mean age 71.5 (SD= 7.0) 51.9 % female	Actiwatch 2 (Respironics Inc., Murrysville, PA, USA)	Short version of the Geriatric Depression Scale (GDS-15)	Minutes per day exposed to >1000 lux	GDS-score	Time exposed to light >1000 lux did not explain the relationship between farming habits and depressive symptoms. Further adjustment for log-transformed time exposed to bright light (≥1000 lx) and daytime physical activity (model 3 in Table 2) attenuated the significance of OR for depressive symptoms among long farming group (0.66, 95%CI: 0.42-1.03, p = .07); however, OR among short farming group remained significant (0.65, 0.43-0.99, p = .047) with significant trend (p = .048). Indirect association mediated by time exposed to bright light explained 7.2% of the direct association between farming habit and depressive symptoms, but it was not significant (95%CI: −15.6 to 31.0).	fair

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Author	Country	Design, sampling, sample size	Participant characteristics (age, gender)	Measurement: Light exposure	Measurement: Mood	Light exposure outcome	Mood outcome	Results	RoB
Espiritu et al (1994) [44]	U.S.A.	Cross-sectional, volunteer sample N = 106	Inhabitants from the City of San Diego, USA aged 40-64 49 years 50% female	Actillume (Ambulatory Monitoring Inc., Ardsley, NY)	Center for Epidemiologic Studies Depression Scale (CES-D) SAD-related questions from the SIGH-DAS-SR	Percentage time of measurement period at thresholds 10, 100 and 1000 lux. Log lux mesor Log lux amplitude	Total score for CES-D Total score for SAD questions	SAD scores were negatively correlated with every illumination score. Correlations for the amount of time above 10, 100 and 1000 lux were respectively −0.227 (p = .005), −0.252 (p = .013) and −0.217 (p = .013). The correlation with log lux mesor was −0.191 (p = .026), and with log lux amplitude −0.280 (p = .002). Scores for the CES-D did not correlate significantly with any of the light exposure measurements.	fair
Figueiro et al (2016) [40]	U.S.A.	Cross-sectional, volunteer sample N = 11	Workers in the Building of the U. S. General Services Administration in Grand Junction, Colorado. Age not reported 91% female	The Daysimeter (Lighting Research Center, Troy, NY)	Positive and Negative Affect Schedule, Center for Epidemiologic Studies Depression Scale (CES-D)	Magnitude of circadian stimulus calculated using light exposure and circadian illuminance (CS)	Positive affect Negative affect CES-D score	None of the correlations between CS values and self-reports of affect and mood were statistically significant.	poor
Figueiro et al (2017) [42]	U.S.A.	Cross-sectional, volunteer sample N = 67	Workers in 5 buildings of the U.S. General Services Administration in Washington DC (2x), Portland OR, Seattle WA, Grand Junction Colorado Age not reported 63% female	The Daysimeter (Lighting Research Center, Troy, NY)	Center of Epidemiological Studies Depression Scale (CES-D)	Magnitude of circadian stimulus calculated using light exposure and circadian illuminance (CS)	CES-D score	Participants with high workday CS had lower depression scores than those with low workday CS ($F_{1,144}$ = 4.68, p = .026). No association was found for CS and positive or negative affect.	poor
Grandner et al (2006) [26]	U.S.A.	Cross-sectional, convenient sample N = 459	Postmenopausal women included in an ancillary study of the Women's Health Initiative (Matthews et al 1997) 67.68 years (SD = 7.86) 100% female	Actillume (Ambulatory Monitoring Inc., Ardsley, NY)	Quality of life and emotional well-being scales of the self-report questionnaires designed for the Women's Health Initiative	Average light exposure morning light exposure Light acrophase	Quality of Life Emotional Well-being	Emotional well-being scores were positively correlated with mesor light (r = 0.128, p = .05) but not with morning light. Quality of life was positively associated with mesor light (n = 422, r = 0.185, p = .0005) and morning light (when corrected for average light exposure, partial F(1400)=5.760, p = .05, R^2 change=0.013). Light acrophase did not correlate with quality of life and emotional well-being.	poor
Hoaki et al (2011) [29]	Japan	Cross-sectional, volunteer sample N = 56	Healthy participants (no psychiatric disorders) 26.9 years (SD = 5.9) 30% female	Actigraphy with illuminance measurement (no specs reported).	Japanese standardized version of the Temperament Evaluation of Memphis, Pisa, Paris and San Diego-auto questionnaire version (TEMPS-A)	Average illuminance during daytime	Hyperthymic temperaments	Daytime illuminance was positively associated with hyperthymic scores (r = 0.47). When corrected for adrenocorticotropic hormone and sleep time, daytime illuminance was a predictor for hyperthymic temperament scores (b = 0.59, p < .0001)	fair

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Table 4 (*Continued*)

Author	Country	Design, sampling, sample size	Participant characteristics (age, gender)	Measurement: Light exposure	Measurement: Mood	Light exposure outcome	Mood outcome	Results	RoB
Hubalek et al (2010) [19]	Switzerland	Cross-sectional, volunteer sample N = 23	Healthy workers with offices located in or close to Zurich, Switzerland 38.4 years (SD = 10.6) 30% female	LuxBlick (no manufacturer reported)	Pleasure-Arousal-Dominance (PAD)	Daily light exposure, light exposure over thresholds 1000 and 2500 lux and vis-nonvis spectrum parameter (ratio image forming and non-image forming light exposure)	Pleasure Arousal	None of the light exposure measures were related to feelings of pleasure or arousal.	good
Itzhacki et al (2019) [49]	The Netherlands	Cross-sectional, volunteer sample N = 27	mean age 23.7 years (SD= 3.8) 52% female	Daysimeter-D, (Rensselaer Polytechnic Institute, Troy, NY)	Positive and negative mood adjectives of the Daytime Insomnia Symptom Scale	Mean light intensity per timeframe	Mean score of the 5 Positive Mood items Mean score of the 5 Negative Mood items	Within-subject as well as between-subject variability in light intensity did not correlate significantly with positive mood or negative mood.	good
Jean-Louis et al (2005) [31]	U.S.A.	Cross-sectional, volunteer sample N = 70	Healthy elderly 68.27 years (SD= 5.97) 73% female	Actiwatch-L (Mini Mitter)	Geriatric Depression Scale (GDS)	Mesor log Lux Light exposure acrophase	GDS score	Amount and timing of light exposure were not associated with depressed mood.	fair
Koller et al (1993) [45]	Austria	Cross-sectional, stratified sample N = 12	Night and day workers Night: 32.8 year (SD = 6.2) Day: 37.3 year (SD = 8.6) 100% male	Photocell BPW2 1 (Telefunken)	State Questionnaire	Average light exposure Onset of light exposure	Mood Alertness	Higher light dose in day workers associated with a shift in the maximum mood score to later in that same day ($r = 0.90$). Regression analyses showed that 40% of the variation in mood or alertness is explained by the light onset.	poor
Kripke et al (2004) [25]	U.S.A.	Cross-sectional, convenient sample N = 416-450	Menopausal women included in an ancillary study of the Women's Health Initiative (Matthews et al 1997) 67.7 years (SD = 7.9) 100% female	Actillume (Ambulatory Monitoring Inc., Ardsley, NY)	Center of Epidemiologic Studies Depression Scale (CES-D) Structured Clinical Interview for DSM (SCID) for Affective disorders	Mesor Log Lux	CES-D score Affective Disorders	Mesor Log Lux was not associated with CES-D depression scores or SCID mood disorders.	fair
Smolders et al (2013) [46]	The Netherlands	Cross-sectional, volunteer sample N = 42	Office employees and students that all lived, worked, and/or went to university in the Eindhoven region, the Netherlands 25 years (SD = 8.1) 52 % female	Daysimeter (Lighting Research Center, Troy, NY)	Online Questionnaire	Average light level per hour Percentage of minutes above 1000 lux per hour	Vitality Tension Positive affect Negative affect	Hourly light exposure was positively related to vitality: when corrected for chronotype, social interaction, physical effort, prior sleep duration and light sensitivity and subjective chronic fatigue, participants felt more energetic when they had experienced a higher amount of light during the previous hour ($\chi^2(3) = 359.12$; $p < .01$, $B_{\text{hourly light}} = .06$, $p < .01$). Light exposure was not related to feelings of tension, positive or negative affect.	fair

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Table 4 (*Continued*)

Author	Country	Design, sampling, sample size	Participant characteristics (age, gender)	Measurement: Light exposure	Measurement: Mood	Light exposure outcome	Mood outcome	Results	RoB
Wallace-Guy et al (2002) [27]	U.S.A.	Cross-sectional, convenient sample N = 154	Menopausal women included in an ancillary study of the Women's Health Initiative (Matthews et al 1997) 67.7 years (SD = 7.9) 100% female	Actillume (Ambulatory Monitoring Inc., Ardsley, NY)	Screening questionnaire for major depression	Mesor log Lux	Depressed mood	Greater 24-hour light exposure was related to lower depressed mood ($r = -0.21$, $p = .01$).	fair
Wang et al (2003) [47]	U.S.A.	Cross-sectional, volunteer sample N = 37	Postpartum women 15 postpartum Age 32 (SD= 8.43) 100% female	The Actillume (Ambulatory Monitoring, Inc., Ardsley, NY)	Short version of the Center of Epidemiological Studies Depression Scale	Average light exposure	Mood	Average light exposure was not correlated with mood.	fair

RoB, risk of bias.

timing of light exposure and some estimates of sleep architecture, but due to the broad variety of outcomes this evidence is classified as limited.

Sleep timing One high-quality study.[36] and 2 fair-quality studies[41,42] measured sleep onset time (hh:mm, clock time of sleep start); only one fair-quality study found that the amount of light exposure during the day ($r = -0.41$, $t(60) = -3.49$, $p < .001$) and low evening light exposure ($r = 0.61$, $t(60)$ 5.93, $p < .001$) were associated with an earlier sleep onset.[41] The high-quality study found sleep offset time (hh:mm, clock time of sleep end) and time in bed (minutes between getting into bed in the evening and out of bed in the morning) not to be associated with the timing or exposure to high light intensity.[36]

The high-quality study[36] and one study of fair quality[42] found no relationship between light exposure and sleep timing, whereas one fair-quality study[41] did find a significant relationship. Thus the available studies provide conflicting evidence for a relationship between the amount and timing of light exposure and bedtimes.

Nocturnal sleep duration and daytime napping The only high-quality study found lower light intensities to be related to longer nocturnal sleep duration ($R^2 = 0.05$, χ^2 (1) = 4.83, $p < .05$) (Wams et al, 2017). The 3 fair-quality studies found the amount of light exposure and nocturnal sleep duration were positively ($r = 0.483$, $p = .03$),[39] negatively (Kripke et al (2004)[25]: $r_p = -0.20$, $p < .001$) or not[27] associated. Subjective nocturnal sleep duration[25] and duration of daytime napping were not associated with exposure to high light intensities.[25,27]

The single high-quality[36] and 3 fair-quality studies[25,27,39] provide conflicting evidence on the relationship between the amount of light and sleep duration.

Sleep onset latency The single high-quality study found light intensity not to be related to sleep onset latency.[36] One fair study found that exposure to higher light intensities was associated with a shorter sleep onset latency ($r = -0.29$, $p < .001$),[27] whereas another fair study did not find an association.[39]

The high-quality study[36] as well as 2 studies of fair quality[27,39] found no association between timing of light exposure and sleep onset latency. One fair study found high light exposure in the morning to be associated with shorter sleep onset latency in the following night ($F_{1,15} = 10.43$, $p = .005$).[42]

Based on one high-quality study[36] and 3 lower-quality studies,[27,39,42] the evidence on the relationship between amount and timing of light and sleep onset latency is conflicting.

Waking after sleep onset The high-quality study of Wams et al (2017)[36] found that lower maximal light exposure ($R^2 = 0.26$, $p < .05$) and earlier timing ($R^2 = 0.36$, $p < .05$) of light exposure resulted in fewer awakenings measured using actigraphy, but not when using PSG. Fair-quality studies found a longer duration of light exposure ($R^2 = 0.519$)[37] and earlier light exposure (Wallace-Guy et al (2002)[27]: $r = -0.29$, $p < .05$) were associated with fewer nocturnal awakenings. In contrast, the fair-quality study of Boubekri et al (2014)[39] did not find an association between the amount and timing of light exposure and wake after sleep onset (minutes). The single high-quality study[36] and 3 fair-quality studies[27,37,39] provide conflicting evidence on the relationship between the amount and timing of light and waking after sleep onset.

Sleep quality (*Table 3*)

Exposure to higher light intensities was associated with better sleep quality in one high-quality study ($F_{1;81.1} = 6.84$, $p = .01$)[19]; the other high-quality study did not find this relationship.[36] Three fair-quality studies found exposure to higher light intensities to be associated with better sleep quality (Kripke et al (2004)[25]: $r_p = 0.17$, $p < .005$; Figueiro et al (2017)[42]: $F_{1,155} = 6.19$, $p = .014$; Boubekri et al (2014)[39]: $p = .05$). One poor study found no association between the amount of light and sleep quality.[36,40]

One high-quality study found a longer duration of light exposure > 1000 lux ($F_{1;76.2}$ = 4.22, p = .04) and >2500 lux ($F_{1;81.3}$ = 6.82, p = .01) during the waking day to be positively related to sleep quality.[19] The other high-quality study and a fair-quality study found earlier timing of light exposure to be related to better sleep quality (Wams et al (2017)[36]: $t(1)$= -2.5, p = .0267; Figueiro et al (2017)[42]: $F_{1,165}$ =4.76, p = .031), whereas the other fair study did not find timing to be related to sleep quality.[27]

Two fair studies found exposure to higher light intensities to be associated with fewer sleep disturbances (Kripke et al (2004)[25]: falling asleep; r_p = −0.17, p < .005; night waking: r_p = −0.18, p < .001; trouble getting back to sleep r_p = −0.11, p < .025; Figueiro et al (2017)[42]: $F_{1,21}$ = 6.12, p = .022). One study of poor quality found no association between the amount of light and sleep problems.[40]

The available studies provide conflicting evidence for the amount and timing of light exposure and sleep quality and the association between higher light intensities and sleep problems. No evidence is presented for the timing of light exposure and sleep problems.

Mood (Table 4)

Assessment of mood

The 16 studies on light exposure and mood are described in Table 4. All included studies used questionnaires to assess mood.[19,25-29,31,34,40,42-47,49] Depressive symptoms were measured in 9 studies.[25,27,28,31,40,42,44,47,48] Cyclothymic and hyperthymic temperament were measured in 2 studies,[28,29] the presence of mood disorders was measured in one study,[25] and affect in 7 studies.[19,28,40,43,45,46,49] Other mood-related measurements were emotional well-being[26] and quality of life.[26]

Association between light exposure and mood

Depression and temperament. Nine studies looking at depression and temperament were of fair quality, 2 studies were of poor quality.[40,42] Three studies found that exposure to higher amounts of light was associated with fewer depressive symptoms (Wallace-Guy et al (2002)[27]: r = - 0.21, p = .01; Figueiro et al (2017)[42]: $F_{1,44}$ = 4.68, p =.036; Espiritu et al (1994)[44]; r = −0.191, p = .026), 6 studies did not find a significant association.[25,28,31,40,47] Duration of light exposure was not related to depressive symptoms.[48] One study found higher levels of light exposure (r = -1.191, p = .026) and longer duration (>10 lux: r = 0.226, p = .01; >100: r = −0.252, p = .005; > 1000: r = −0.217, p = .013) of light exposure to be associated with fewer Seasonal Affective Disorder symptoms.[44] Exposure to light of higher intensity was related to a more hyperthymic (Hoaki et al (2011)[29]: b = 0.59, p < .0001); Araki et al (2012)[28]: R^2 = 0.32, b = 0.54, p < .0001,) and less cyclothymic state (R^2 = 0.323, b = 0.54, p < .0001),[28] but was not associated with a diagnosis for mood disorders diagnosed using the Structured Clinical Interview for DSM-IV Axis I Disorders (SCID interview).[25,53]

Based on the low quality of the studies, the diversity of the outcomes, and conflicting results, it is concluded that the available studies provide conflicting evidence for an association between the amount of light exposure and depression and temperament.

Affect, overall emotional well-being, and quality of life. One study of good quality found the amount of light exposure was associated with positive affect ($F_{2, 89}$ = 11.66, p < .0001),[43] but in a poor-quality study these were not found to be associated.[42] The amount of light was associated with more vitality (b = 0.08; p < .01).[46] Other measurements of affect, for instance negative affect, were not related to measures of light exposure.[19,28,40,42,43,46,49]

Exposure to a higher amount of light was related to better emotional well-being (r = 0.128, p = .05) and a higher quality of life (r = 0.185, p = .0005), whereas exposure to more light in the morning was associated with quality of life (when corrected for average light exposure, partial $F(1400)$ = 5.760, p = .05, R^2 change=0.013) but not with emotional well-being.[26] Light acrophase was not related to either quality of life or emotional well-being.

Based on the low quality of the studies, the diversity of the outcomes, and the lack of significant results, it is concluded that the available studies provide very limited evidence for an association between the amount of light exposure and affect, emotional well-being, and quality of life.

Discussion

This systematic review describes the association between habitual personal light exposure and sleep-wake rhythm, and mood in the general healthy adult population. The 25 articles included in this review mainly focused on the average light intensity in lux of light exposure during the day and the duration and timing of the light exposure. The quality assessment of the 25 included papers revealed a risk of bias in all studies, largely due to gaps in the information reported and because most of the studies were cross-sectional. Limited evidence is presented for a positive relationship between the amount and timing of light exposure on rest-activity rhythm and some estimates of sleep architecture. For the association between light exposure and circadian phase of the sleep-wake rhythm, sleep estimates, sleep quality, and mood, the evidence is conflicting.

The 2 high-quality studies on light exposure and circadian phase of sleep-wake rhythm provided conflicting results, which is not in line with the laboratory studies conducted previously. These show that light sources of just 8 lux can shift the phase of the sleep-wake rhythm.[54,55] Although circadian phase of the sleep-wake rhythm seems to be affected by light exposure within the laboratory setting, the implications for the real world are yet to be determined. Second, there is no consensus on what “an optimal aligned circadian rhythm is” or what a cut-off point is for desynchronization of the rhythms.[55] As all the studies included were cross-sectional and measured circadian phase as a continuum, this review unfortunately cannot give insight into this matter.

Five out of 6 studies (2 of high quality, 3 of fair quality) on sleep quality found a positive relationship between light exposure and sleep quality, while results for several sleep indicators are conflicting. It is hypothesized that the measurements of sleep quality capture an overall association between light exposure and sleep, whereas the different sleep indicators are possibly too specific. Decades of sleep research show a broad variety in sleep preference; some people feel energetic after 8 hours whereas others report a need for 10 hours of sleep. This subjective experience of sleep quality, even more than the objective sleep, is an important criterion in diagnosing sleep problems.[56] Therefore, it is suggested that the results of the review on light exposure and sleep quality might provide more valuable information than the results of the sleep indicators.

The limited evidence for an association between personal light exposure and rest-activity rhythm and sleep architecture does not seem to translate directly to sleep estimates and mood outcomes. The results of the current review were inconclusive for the effect of light exposure on sleep estimates and mood. In these cases, the personal preference, or “chronotype,” could provide more insight. Roughly 15% of the population identify as an early chronotype or “lark”. Larks are characterized by waking up early in the morning, and falling asleep early in the evening. Another 15% of the population identify as a late chronotype or “owl” and wake up and go to bed later in the day. The remaining 70% have an “intermediate” chronotype.[57,58] Research showed that owls are more prone to depression and anxiety[59,60] and sleep longer[61] than larks. If chronotype is a mediator or confounder for the relationship between light exposure, sleep, and mood, more and earlier light exposure could

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have a positive relationship with outcomes for larks, and a negative one for owls. It is hypothesized that since chronotype was not taken into account in the included studies, the possible different associations between light exposure and sleep for larks and owls offset one another in the results, resulting in the non-significant results found.

Another explanation for the lack of conclusive results on light exposure and sleep might be provided by the age of the study sample subjects. The aging brain is less sensitive to light exposure,[62] possibly resulting in more light needed to affect sleep. For sleep we included 3 studies with an older study sample,[25,27,37] one with a young sample[36] and 2 with a mixed-age study sample.[39,41] Further inspection of the results of these studies did not provide more insight, as studies with both younger and older subjects showed an association between light exposure and sleep for some measures but not for others.

Finally, the ambiguous results might be explained by the fact that the included studies did not correct for other factors that are known to affect the sleep and mood. Whereas most of the studies corrected for age, they did not take into account other "Zeitgebers" and factors that can affect sleep and mood, like physical activity, working times, diet, or medication use.[63,64]

A disadvantage of the included studies is that only a third of the studies measured the light exposure prior to the outcome measurements. Light is shown to have a direct effect on mood and sleep[3,54] in the lab setting, so it is desirable to analyze mood or sleep in respect of the personal light exposure on that same day. Of the 25 papers included in this review, only 5 studies analyzed the data in this manner. Secondly, in order to give a direction to the studied relationship between light exposure, sleep-wake rhythm and mood, it is required that studies measure exposure prior to the outcome and at least at 2 time points. Unfortunately, as all studies were cross-sectional and most just performed correlational analyses, no conclusion can be drawn on the causal relationship between light exposure, sleep-wake rhythm and mood.

In line with the above, most of the included studies were not designed to answer the research question of this review. It is hypothesized that some of the included papers reported baseline data of intervention studies. Other papers were by-catch from other studies that happened to have measured both light exposure and outcomes of interest. This was first noticed in the data extraction; studies would report light exposure and mood or sleep outcomes, but no analyses relating these variables. Second, some study populations were part of a bigger cohort in which the wrist-worn accelerometer was used and the light exposure data was analyzed in an exploratory fashion.

Lastly, 19 studies measured personal light exposure using a wrist-worn light cell, which has been shown to be unreliable. Aarts et al (2017)[50] showed that even within the same wrist-worn devices, the measured light exposure can differ by up to 27% from the actual light exposure. Therefore, measurements of light exposure in the included studies might have been unreliable and might have resulted in the ambiguous results.

Strengths and limitations

Due to the large variation in outcome measures, conducting a meta-analysis was not possible for the current review. In addition, another limitation is that "grey literature" and papers in a language other than English were not included.

One strength of our systematic review is the duplicate study selection and quality assessment, which was performed by 2 authors independently. Second, the current review applied strict inclusion criteria for light exposure measurements and analysis. This way, even though the quality of the included studies was low, this review provides us with more insight into the current evidence on the relationship between personal light exposure, sleep, and mood in the general population.

Future research

Further research should first and foremost be focused on better measurements of personal light exposure. Instead of measuring light exposure on the wrist, it is advised to measure light exposure at eye level or at least chest height as this is more reliable. In addition, measurement of the spectral properties of the light exposure is advised to gain insight into the properties of light that are the most efficient in entraining the circadian rhythm.

In order to gain insight into the causal relationship between light exposure and health, a high-quality, longitudinal intervention study of light exposure, sleep-wake rhythm and mood is needed. In this study, special attention should be given to measuring possible confounders of this relationship, like mental and physical condition, medication use, physical activity, and diet.

Most of the previous work on the association between circadian rhythms and health outcomes was based on populations that are prone to misalignment of the circadian rhythms. The current review provides insight into the relationship between light exposure, sleep-wake rhythm and sleep problems in the general population. This review gives grounds for integrating personal light measurements in research on light exposure and health in the populations that are at risk of extreme misalignment of the sleep-wake rhythm, in order to be able to define the mechanism of this relationship more clearly.

Conclusion

The current review aimed to describe the association between personal light exposure in the habitual setting, sleep-wake rhythm, and mood in the general population. Because the quality of the included studies was generally low, this review cannot do more than provide a first exploration of the available literature on this matter. Based on the available studies, we conclude that there is limited evidence for a positive relationship between the amount and timing of light exposure on the one hand and rest-activity rhythms and some estimates of sleep architecture on the other hand. The evidence on the association between light exposure and circadian phase of the sleep-wake rhythm, sleep estimates, sleep quality, and mood is conflicting. High-quality intervention studies are needed to gain insight into the causal mechanism of this relationship.

Author contribution

All authors made substantial contributions to the design of this study and/or were involved in the interpretation of the data. All authors drafted the work, and reviewed and revised the manuscript critically. All authors approved the final version to be published.

Declaration of conflict of interest

The authors declare that there is no conflict of interest.

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Supplementary materials

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