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Review

Architecture, light, and circadian biology: A scoping review

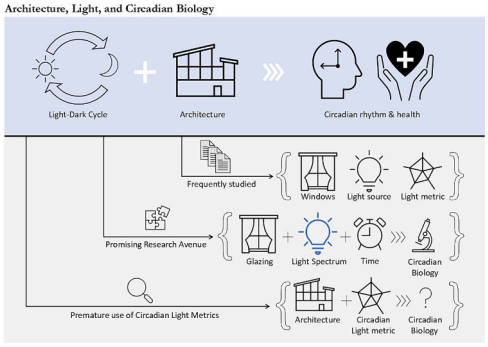
Philip Lewis [a,*,1], Rania Christoforou [b,1], Peiman Pilehchi Ha [b], Ursula Wild [a], Marcel Schweiker [b,c,2], Thomas C. Erren [a,2]

[a] Institute and Policlinic for Occupational Medicine, Environmental Medicine and Prevention Research, Faculty of Medicine and University Hospital of Cologne, University of Cologne, Germany
[b] Healthy Living Spaces Lab, Institute for Occupational, Social, and Environmental Medicine, Medical Faculty, RWTH Aachen University, Aachen, Germany
[c] Chair of Healthy Living Spaces, Faculty of Architecture, RWTH Aachen University, Aachen, Germany

HIGHLIGHTS

- First empirical evidence links architecture, light, and circadian biology.
- Modifiable architectural features (e.g., glazing) affect light exposure and circadian biology.
- The Circadian Stimulus is used in architecture, but applicability is lacking.
- Research gaps include the interactions of conditions provided by and within architectural spaces.

GRAPHICAL ABSTRACT



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ABSTRACT

Light-dark (LD) can support or challenge the circadian organization of physiology and health. As an indoor species, the built environment inevitably influences the patterns and intensities of our LD exposures, thereby affecting health. We reviewed to what extent architectural features have been studied alongside LD and circadian biology. Systematic screening of literature from thirty-one databases identified $n = 11$ relevant human- and $n = 19$ relevant field- and simulation- studies; the latter included exploration of LD and architectural details with pertinent reference to circadian biology. Charting and synthesis concerned architecture, LD sources and metrics, circadian biology-related parameters, and health more generally. Human studies that investigate architecture, LD, and circadian biology together are limited by few participants, few architectural features, and few measurements. Most emphasis is on window-related aspects but must be judged as first explorations (i.e., not suitable to compare e.g., glazing vs shading vs position). Novel findings include the potential for time-specific alteration of blue light transmittance through windows. Circadian-light metrics (e.g., the Circadian Stimulus) are in use but analyses of links between architecture and circadian-light metrics together with biology are lacking. In

* Corresponding author.
E-mail address: philip.lewis@uk-koeln.de (P. Lewis).
[1] Joint first authorship.
[2] Joint senior authorship.

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conclusion, first empirical evidence links elements of LD, architecture, and circadian biology. Novel and necessary avenues of research are discussed.

1. Introduction

Light in general and daylight in particular have been key elements in human evolution, habitation, and culture for millennia (Balter, 1996). Beyond the crucial role of light in health and disease through vitamin D (Holick, 2016), the nascent field of chronobiology has increasingly explored how light regulates human circadian rhythms (i.e., endogenously generated ~24-h cycles in physiological processes); thereby contributing to fostering health and fighting off disease, for instance by allowing physiological restitution via good sleep (Pittendrigh, 1960; Foster, 2022; Menaker, 2007). At the core of such research lies the internal circadian timing system which evolved over millions of years in many species, including humans. Depending on light as key 'time-of-day' information, this system facilitates the organization of highs and lows in circadian rhythms over day (with light) and night (without light) involving, for instance, facets such as sleep, metabolism, and immune system function (Pittendrigh, 1960; Foster, 2022; Menaker, 2007; Pittendrigh, 1993; Foster and Wulff, 2005). Thus, challenge or perturbation of the circadian timing system by inappropriate light and other associated zeitgebers (Aschoff, 1951; Aschoff, 1954; Ehlers et al., 1988; Grandin et al., 2006; Lewis et al., 2018; Lewis et al., 2020) can manifest in jet lag (Rockwell, 1975), impaired physical and cognitive performance (Walker, 2020; Thun et al., 2015), and exacerbation of illnesses in the short term (Walker, 2020). In the long-term, chronic intermittent misalignments, for instance, due to shift work, have been linked with various diseases, including cancer (IARC IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, 2010; IARC, 2019).

Importantly, the way that buildings and spaces are constructed regarding light may impact health. Architecture – here the art and science of designing buildings – covers a multitude of structural, technical, and aesthetic elements that influence the appearance and functioning of both the interior and exterior of buildings. Such design is often based on the decisions and opinions of the occupants who will eventually use the building. Ancient civilizations such as the Greeks and Romans appreciated daylight to create healthy living environments (Baker and Steemers, 2002). The Industrial Revolution with its rise of factories, urbanisation, overcrowding and poor living conditions led to a lack of natural light exposure. Too little time outside and lack of sunlight resulting in insufficient Vitamin D can cause rickets and impair immune systems (Holick, 2023; Kronfeld-Schor et al., 2021). Circumstantial evidence of light benefitting health was noted by Florence Nightingale in the mid-1800s: Patients on a hospital's sunny side had a better mood than those in darker rooms and areas. This led her to demand that "All hospital buildings […] should be erected so that as great a surface as possible should receive direct sunlight" (Mead, 2001; Nightingale, 1863).

Insights from chronobiology suggest that architecture must also be important in affecting the light exposures for our circadian timing systems. Indeed, a healthy "spectral diet" for humans depends on adequate exposure to light and dark at appropriate times of the day and a confusing mix of natural and artificial light input to the circadian timing system should be avoided in built environments (Webler et al., 2019). As we live, and increasingly work, in buildings and cities, how built environments factually allow – or disallow – exposures to light or darkness that affect circadian biology to promote health and prevent disease is relevant.

Two reviews have been published recently related to architecture, light, and circadian biology. Bellia and Fragliasso (2021) reviewed several relevant articles on architectural features and circadian lighting metrics in extensive depth (Bellia and Fragliasso, 2021). Ghaeili Ardabili et al. (2023) systematically focuses on articles concerning windows and circadian light metrics published since 2012 (Ghaeili Ardabili et al., 2023). Differently, our objective was to systematically synthesise the scope, focus, and findings of the literature concerning architecture more generally, light more generally, and circadian biology more specifically and how they are considered together. Indeed, a focus on circadian light metrics may yet be premature. Given the scope of architecture, our approach regarding architecture is inductive; i.e., rather than defining elements of architecture, we implemented a search strategy with broad terms in order to assess and map what has been investigated and how. Similarly, we utilise broad terms concerning both light and circadian biology in our search strategy.

2. Materials & methods

This scoping literature review was developed with guidance from PRISMA and the Joanna Briggs Institute methods (*Ann. Intern. Med.*, 2018; Aromataris and Munn, 2020). The *a priori* protocol can be found at OSF (https://osf.io/z57rd). All steps were conducted by an interdisciplinary team of researchers with architectural and chronobiological backgrounds. The search was conducted in March 2022.

2.1. Search strategy & study selection

Four search engines covering 31 scientific literature databases (Table 1) were used to identify potentially relevant literature using a search string of relevant terms and Boolean operators (Table 1). The returned literature was iteratively screened for relevance against set inclusion criteria (Table 1). Duplicates, non-English or non-German language articles, and articles identified more immediately and clearly about *in vitro*-, non-human experimental (i.e., animal models)-, and plant-models were excluded. Non-human field and simulation descriptive studies were not excluded. Titles and abstracts were then screened against the inclusion criteria, with articles not meeting all inclusion criteria or meeting the exclusion criterion excluded. Full texts of the remaining articles were then screened for fit against a second set of more comprehensive inclusion criteria (Table 1). Endnote software was used to collate literature and track the flow of articles through the various review steps. All steps were performed independently by at least two members (at least one from the architecture working group and at least one from the circadian biology working group involved in this collaboration). Inter-reviewer agreements were tracked. Disagreements were resolved under team discussion. All work was double-checked.

Our selection criteria deliberately narrow the scope of the inclusion. Indeed, there are many studies on the importance of light affecting circadian biology (of course, there is still much to learn) and perspectives describing how architecture may affect light more generally (Bellia and Fragliasso, 2021; Ghaeili Ardabili et al., 2023; Wirz-Justice et al., 2021; Lewis et al., 2018). Specifically, though, we want to know to what extent and how architecture has been studied alongside light and circadian biology together.

2.2. Data extraction & synthesis

Study identifiers, study design, details of architectural features, light sources and metrics, circadian biology-related parameters, health more generally, and data on the populations studied were extracted as appropriate. To keep the scope of the review as broad as possible, all included full texts at least mentioned circadian biology and architecture (at title and abstract level – inclusion criteria, Table 1). It should be noted that mention of a theme does not equate to specific exposure/intervention and/or outcome. Therefore, not all studies were expected

Table 1
Search engines, string, and screening criteria.

Search Engines	PubMed, WoS Core Collection, Scopus, Livivo
Search String	(architect* OR buil* OR construction* OR house* OR home* OR dwelling* OR flat* OR factory OR factories OR hospital* OR office* OR "work place" OR residence OR residential OR block* OR tower* OR urban* OR city OR cities OR town* OR civic OR municipal OR suburban OR "built environment") AND (daylight OR sunlight OR light OR dark* OR LAN OR neon) AND (circadian OR chronobiology* OR "internal clock" OR rhythm OR melatonin)
Screening Criteria	**Title & Abstract Inclusion** 1. English or German, 2. Non-plant, animal, or NICU-related[1], 3. Peer-reviewed, non-conference proceeding, primary research articles (including simulation studies), 4. With title or abstract including at least one of the following words: circadian, rhythm, chronobiology, diurnal, 24-h, sleep, melatonin, clock, non-visual, non-vision forming, light-dark cycle, 5. And includes an indication of assessment of architecture and/or urbanisation contributions to light or darkness in natural (non-laboratory) settings, wherein: a. "Assessment" can refer to a description (or comparison) of the architectural component(s) and/or the light environment(s), b. "Architecture/urbanisation contributions to light or darkness" can refer to an exterior building or interior design using/modifying specific architectural systems or creating/modifying architectural conditions to impact the light environment, c. Explicit mention of the natural setting (e.g., a working/living/socializing space that is not a controlled condition laboratory) or a simulated study of natural setting data must be referred to in the title or abstract. **Title & Abstract Exclusion** 1. Specifying the use of a portable light box or lamp that is not installed in e.g., a nursing home, in studies concerning light therapy. **Full Text Inclusion/Exclusion** 1. A description of architecture and/or urbanisation contributions to light or darkness exposure in natural (non-laboratory) or simulated settings must be provided in the full text. The description need not necessarily be part of study methods but it must not be a description of another study's outcomes. In case the description of architecture and/or urbanisation contribution to light stems from the outcomes of another study, then the original paper should be included in the review. 2. A description of the purpose of the room or the purpose of the building alone will not suffice as a description of architecture. 3. A description of portable lamps or light boxes for individual use alone will not suffice as a description of architecture.

[1] NICU = neonatal intensive care unit. We researched light-dark exposures in NICUs in a separate project (Lewis et al., 2024).

to contain information for all categories, e.g., non-human simulation studies contain no data on population. Counts of studies by architectural features in combination with either specific circadian biology- or health-related features or specific light metrics were performed and the results are illustrated graphically. A narrative synthesis was developed for human studies into light and architecture and circadian biology outcomes and for non-human studies into light and architectural details only (i.e., field and simulation measurements).

3. Results

A total of $n = 36{,}987$ articles were identified using the search engines. Following initial screening steps, $n = 176$ articles were subjected to full-text screening. A total of $n = 65$ articles were deemed eligible for inclusion. Inter-reviewer agreement at the preliminary stages of screening was 72 %, which was due to different definitions and understanding of the two fields of study (i.e., architecture and chronobiology). Common definitions were established, and a 100 % agreement was reached at the end of the screening process. The search results are presented in an adapted PRISMA flow diagram in Fig. 1.

The $n = 65$ articles were first divided into $n = 37$ articles from which pertinent architecture data could be extracted and $n = 28$ articles that only mention architecture features in passing. The n = 28 articles are included in the Supplement. The n = 37 articles from which pertinent architecture data could be extracted were then further divided into three groups: $n = 11$ human studies into light, architecture, and circadian biology; $n = 19$ non-human field and simulation studies into light and architecture with pertinent mention of circadian biology; and $n = 7$ human studies into light, architecture, and other (non-circadian or sleep) outcomes but with mention of circadian biology. The latter n = 7 studies are also included in the Supplement. The studies included in the supplementary material have little bearing on the synthesis, discussion, and conclusions presented here in the main text. They were simply identified as part of our broader initial inclusion criteria and are included in the supplement for reasons of transparency and for interested readers.

The $n = 11$ human studies into light, architecture, and circadian biology and the $n = 19$ non-human field and simulation studies into light and architecture with pertinent mention of circadian biology are synthesised below. Tabulated overviews are provided in Tables 2 and 3, respectively. Building type is included in the tables to inform about building use and when study sample populations will be present in the building (e.g., upon awakening, for work, for evening and sleeping times, etc) and thus, when they are exposed to light (which will be affected by architecture). How building type impacts light depends on the architectural features; thus, building type *per se* is not specified or further discussed in terms of our scope but the architectural features are. For human studies, the comparative count of studies with circadian-related outcomes per identified architectural features and against studies with no circadian biology-related outcome is illustrated in Fig. 2 using different colouring. For all studies, counts of identified studies with circadian light metrics (or none) by architectural components are illustrated in Fig. 3 (also using different colouring).

3.1. Human studies

Outcomes studied include objectively assessed sleep and activity ($n = 9$), subjectively assessed sleep and sleepiness ($n = 7$), melatonin ($n = 6$), and cortisol ($n = 3$); some studies include multiple outcomes. Activity, melatonin, and cortisol are included here due to their pronounced usage in circadian biology. Few architectural features are considered, with most studies only providing details on the existence of windows *per se*, the glazing material used, and the use of shading. Five studies provide example pictures of the rooms of study. The publication years range from 1996 to 2021. Thus, consideration of architecture affecting light and circadian biology has been present in the scientific literature for nearly 30 years but has generally received little attention; however, attention is increasing with almost two-thirds of the studies published in the last 10 years. Oddly, the studies from the last 10 years include ≤20 participants per study while preceding studies contain 100+ participants. Of the eleven studies, eight also include non-circadian biology-related outcomes (discussed in the Supplement), while six involve assessing the Circadian Stimulus (CS) as a light metric (discussion of the applicability of circadian light metrics is provided in the discussion section) (Boubekri et al., 2020; Chen et al., 2019; Figueiro and Rea, 2016; Nagare et al., 2021; Youngstedt et al., 2004; Hraška et al., 2014).

A few studies target spectral transmittance through glass by either the glazing *per se* (e.g., electrochromic glazing or using different glazing colours) or applying, for instance, blue-spectrum suppressing foil. The

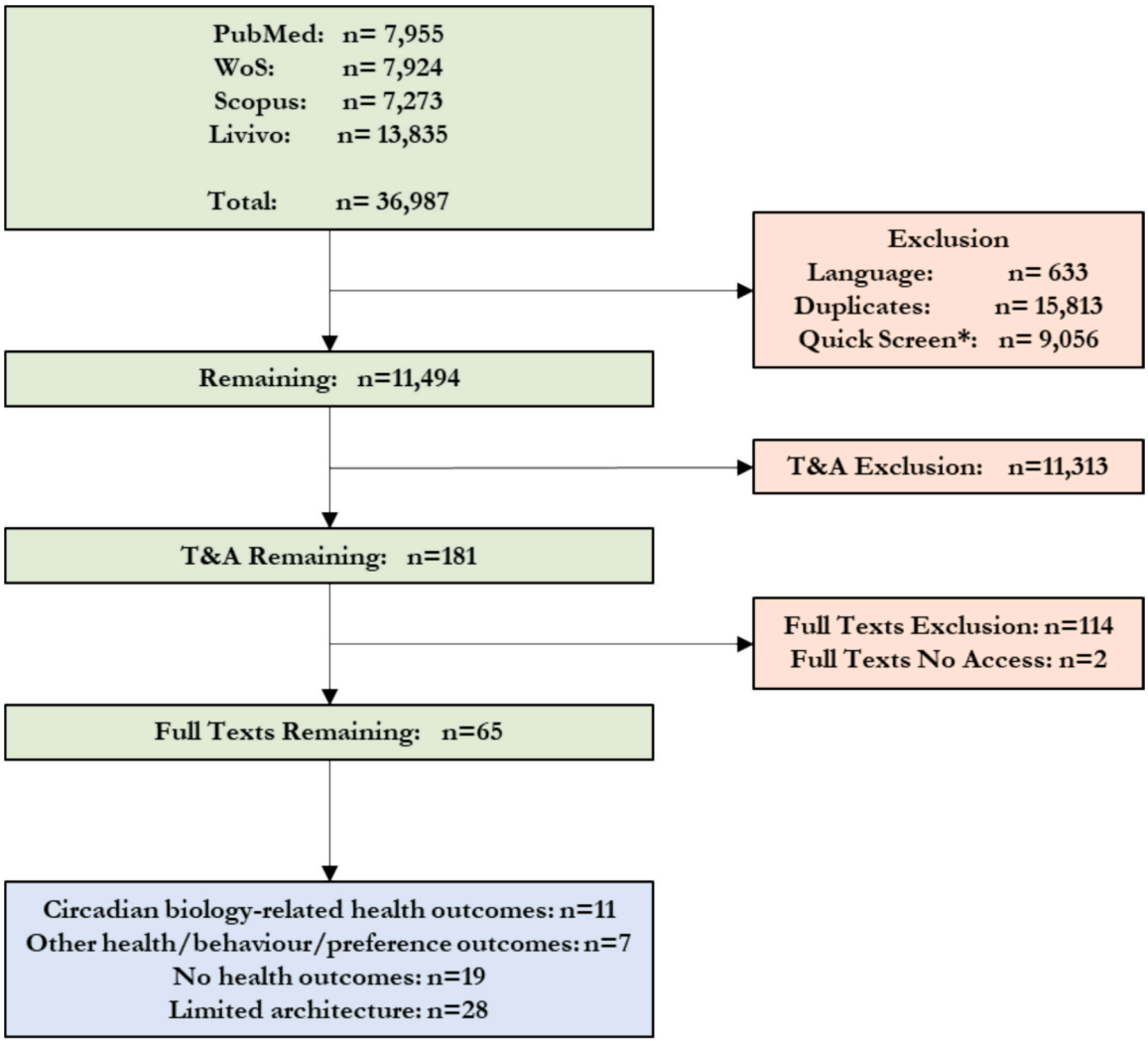

Fig. 1. ***PRISMA Flow Diagram***
WoS=Web of Science Core Collection, T&A = Title and Abstract,
*Articles identified more immediately and clearly as about in vitro-, non-human experimental-, and plant-based models.

transmittance of light through electrochromic glazing can be altered by passing small amounts of electricity through it. Findings include changes to sleep duration, latency, and regularity (Boubekri et al., 2020; Nagare et al., 2021; Stebelová et al., 2014). In one study, ~37mins longer sleep was associated with using EC glazing compared to a control of traditional windows and blinds half-rolled down in a workplace. In the author's words, the changes were "immediate, substantial, and sustained". The study used a cross-over design with 30 participants who spent 1 week in each of the two offices (Boubekri et al., 2020). Another study reported a dim light melatonin onset (DLMO) phase delay with standard windows compared to EC glazing in home-office settings. This study included 20 participants who worked at home and were requested to remain home during the study (Nagare et al., 2021). The EC glazing in both studies had four tints that were based on the presence and timing of sunlight directly on the building façade or based on participant control. The tint states could alter transmittance from 58 % to 0.05 %, with higher tint states filtering out longer wavelengths. The natural setting of these intervention studies has both advantages (observation of real-world differences, i.e., outside of the lab) and disadvantages (greater likelihood of residual confounding, i.e., the causal mechanism could be independent of architecture effects on light). These advantages and disadvantages are also applicable to all the following human studies. As first investigations though, the findings are sufficient to warrant further investigation. The third study of 11 student participants in a 7-day experiment of different glazing colours in the office (different colours each day) found no differences in sleepiness, but this is likely more pertinent to acute alertness rather than involving a circadian mechanism (Youngstedt et al., 2004). Additionally, concerning transmittance of light through windows by using coverings (as opposed to spectral change due to different glazing in the first studies mentioned), a study with $n = 459$ post-menopausal women participants found no association between bedroom window coverings in the home in the morning time and actigraphy-determined sleep parameters. However, there was also no conspicuous difference in illuminance blocking ability between the "heavy coverings (which should block more light)" and "light coverings" categories (Youngstedt et al., 2004). Blackout curtains in bedrooms were associated with longer sleep latency in a study from Japan but it is unclear how sleep latency was assessed and very few participants indicated "no curtains" (Takeuchi et al., 2001).

Six studies assess melatonin (Nagare et al., 2021; Youngstedt et al., 2004; Hraška et al., 2014; Stebelová et al., 2014; Harb et al., 2015; Küller and Wetterberg, 1996). The one described already above is notably the strongest methodologically (Nagare et al., 2021). They took 10 saliva samples in the evening hours to determine dim light melatonin onset (DLMO) (Nagare et al., 2021), as opposed to, for instance, comparing urine metabolite at first-morning void to other times of the

Table 2
11 Human studies into light and architecture and circadian biology & sleep outcomes.

Author (Year)	Study What/Where	When/Who	Architecture	Light	Circadian Biology	Health/Perception
Nagare et al. (2021) (Nagare et al., 2021)	**What:** Study on glazing in an apartment complex. **Where:** Virginia (USA).	**When:** November–December. **Who:** $N = 20$ participants who worked at home and were requested to remain home during the study.	**Building:** One or two-bedroom apartments from ground to 14th floor. **Window:** EC* glass (under voluntary and involuntary control), or functionally standard windows, orientations. **Shading & obstruction:** Blinds were at least half drawn (or down) on standard windows. **Example picture:** Provided.	**Source:** Daylight, no information about voluntary electric light use. **Sensor:** On the wall adjacent to the window, 08:00–17:00. **Metrics:** EC* transmittance, spectral power distributions, illuminance (lux), CS*, mean daytime melanopic lux, and CL_A*.	EC* glass resulted in earlier **sleep** onset (~22 mins) and higher regularity; no clear effect on duration, latency, or efficiency. According to PROMIS-sleep disturbance and sleep-wake impairment were reduced. **Activity** was more aligned with light (greater phasor magnitude). **DLMO** was advanced (~15 mins).	PROMIS statement-anxiety, stress and depression were reduced (albeit not significantly) with EC* glass. Self-reported vitality higher upon awakening.
Boubekri et al. (2020) (Boubekri et al., 2020)	**What:** Study on glazing in offices. **Where:** Durham (USA).	**When:** November. **Who:** $N = 30$ participants who spent 1 week in each of the two offices.	**Building:** Office **Window:** EC* glass or traditional blinds, orientation. **Shading & obstruction:** blinds (1.5 % transmittance at 75 % rolled down [below desk height]). **Example picture:** Provided.	**Source:** Daylight and electric light was controlled. **Sensor:** On desks, 09:00–17:00, central spectrophotometer facing west. **Metrics:** Horizontal task illuminance (lux) and vertical illuminance for both north and south-facing participants, CCT*, CRI*, and photon flux density. EML* and CS* were also determined.	EC glass resulted in longer **sleep** (~37mins) and was stronger than melatonin supplement, opposing the cumulative effect of entering either office from baseline, the largest effect in those considered poor sleepers at baseline.	SMS* cognitive domain scores were consistently higher with EC* glass, differences in acute and cumulative score increases were observed, average score was 42 % higher.
Chen et al. (2019) (Chen et al., 2019)	**What:** Study on glazing in an office. **Where:** Beijing (China).	**When:** November–January. **Who:** $N = 11$ student participants in a 7-day experiment with 1 glazing type per day.	**Building:** Office **Room:** Dimensions, reflectance. **Window:** Dimensions, orientation, transmittance, various glazings. **Shading & obstruction:** None/ no details **Example picture:** Provided.	**Source:** Daylight only. **Sensor:** On working plane and at participants' eyes. **Metrics:** Illuminance (lux), Spectral distribution, CCT* (K), CL_A*, CS*.	No effect of glazing on **sleepiness** (KSS*).	More neutral glazing (clear, bronze, blue) was associated with higher mood (PANAS*), faster response times (GO/NOGO), and higher satisfaction (survey).
Figueiro and Rea (2016) (Figueiro and Rea, 2016)	**What:** Study of personal light exposures in offices. **Where:** Colorado (USA).	**When:** Winter vs Summer. **Who:** N = 11 participants. 7-day period of measurement.	**Building:** Office **Room:** varied by private (sitting facing the window) and open plan (close to the window but sitting with back to window or perpendicular to the window). **Window:** Orientation. **Example picture:** Provided.	**Source:** Natural experiment. **Sensor:** Daysimeter worn as a pendant, 08:00–17:00 on working days. **Metrics:** Illuminance (lux), CL_A*, CS*.	Summer **sleep** (actigraphy and diary) efficiency was higher and latency was shorter compared to winter. No difference in other sleep and **activity** parameters (PSQI*, PROMIS*, Sleep Logs, Actigraphy) Sleep duration was generally short regardless. **Phasor magnitudes** were low.	No summer vs. winter differences in mood (PANAS*, CES—D*).
Stebelová et al. (2014) (Stebelová et al., 2014)	**What:** Study on blue spectrum-suppressing foil on windows vs. none. **Where:** Bratislava (Slovakia).	**When:** January–February. **Who:** $N = 16$ participants in a 7-day experiment (2 days control, 5 days intervention).	**Building:** High-rise building with office on 7th floor. **Room:** No details. **Window:** Several, orientation. **Shading & obstruction:** With/ without blue spectrum suppressing foil (transmittance). **Example picture:** Not provided.	**Source:** Daylight only (computers and tablets were used but covered with experimental foil). **Sensor:** Middle of room and on headsets, 08:00–16:00. **Metrics:** Irradiance (W/m^2/s), Illuminance (lux), CL_A*, CS*.	No difference in urine **6-sulphoxymelatonin** at first morning void, 09:00, 13:00, or 16:00, including within chronotypes when using blue light suppressing foil. Estimated **sleep** parameters and **sedentary times** were different between intervention and control for neutral chronotypes but not morning chronotypes.	N/a.

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Table 2 (*continued*)

Author (Year)	Study What/Where	When/Who	Architecture	Light	Circadian Biology	Health/Perception
Harb et al. (2015) (Harb et al., 2015)	**What:** Study of work environments with vs. without windows. **Where:** Porto Alegre (Brazil).	**When:** Month unknown. **Who:** N = 20 participants.	**Building:** Hospital **Room:** No details. **Window:** Some workplaces with and some without (control). **Shading & obstruction:** None/ no details. **Example picture:** Not provided.	**Source:** Daylight and electric light (control = electric only). **Sensor:** Wrist-worn, 5–10 days **Metrics:** Device algorithmic units converted to adjusted cosine rhythm.	Lower **salivary melatonin** at 8 am and higher at 10 pm and no difference at 4 pm with windows. No difference in **activity** acrophase or light acrophase but mesor and amplitude were higher for the light rhythm. Improved **sleep** (PSQI*) correlated with higher 10 pm melatonin (1/12 correlations).	Few (6/24) correlations between depression-associated scores (SRQ*, MA*, BDI*, Hamilton scale) and cortisol and melatonin.
Hraška et al. (2014) (Hraška et al., 2014)	**What:** Study of spectral filter on windows in hospital wards. **Where:** Klasov (Slovakia).	**When:** December. **Who:** N = 4 bedridden dementia patients (7 intervention days, 4 control days).	**Building:** Social Services Centre **Room:** Floor dimensions **Window:** Width. **Shading & obstruction:** With/ without **b**lue light blocking filter. **Example picture:** Provided.	**Source:** Daylight, no information about voluntary electric light use. **Sensor:** Luxmeter and Daysimeter in centre of the room at 850 mm height and additional luxmeter outside (by the window) at the same height. **Metrics:** CS*	Stated decreased ratio of morning void to 2 pm **urinary melatonin metabolite** following removal of the filter, but no formal statistics were used and the result is not clear from the graph.	N/a.
Thayer et al. (2010) (Thayer et al., 2010)	**What:** Study of working in individual office/old cubicle vs. modern workspace. **Where:** Rocky Mountain region (USA).	**When:** 17 months. **Who:** *N* = 60 office workers.	**Building:** Government facility **Room:** No details. **Window:** Modern office included transparent windows and skylights. **Shading & obstruction:** Modern office included no ceiling height partitions, < 64-in. furniture partitions, open aisle along the window. **Example picture:** None provided.	**Source:** Natural experiment. **Sensor:** None. **Metrics:** None.	Although there was no main effect of office, **diurnal heart rate variability** appears higher and night and lower during the day in modern office workers compared to older office workers, indicated by time trend and office space interactions. Higher **cortisol** levels were associated with the older office space. Time trends and office space interactions were observed.	New office space workers scored higher in satisfaction with the amount of light in the workspace, the amount of daylight in the workspace, and access to a window.
Youngstedt et al. (2004) (Youngstedt et al., 2004)	**What:** Study of the amount of morning window covering in homes. **Where:** San Diego (USA).	**When:** All seasons. **Who:** *N* = 459 postmenopausal women at home.	**Building:** Homes. **Room:** Bedrooms. **Window:** Most participants had bedroom windows. **Shading & obstruction:** Window coverings are categorized as uncovered, light, or heavy. **Example picture:** None provided.	**Source:** Natural experiment. **Sensor:** "Actillume" wrist-worn monitor, 5–7 days. **Metrics:** Device algorithmic units converted to lux and then to either log mean illumination in the first 4 h upon awakening or cosine rhythm.	Although significant correlations were detected between the degree of window covering and **4-week recall sleep quality** and **awakenings**, the mean values are not conspicuously different. There was no correlation with other **4-week recall, diary, or actigraphy-determined sleep parameters** or **melatonin acrophase**.	No correlation between the degree of window covering and CES—D—6 mood was detected.
Takeuchi et al. (2001) (Takeuchi et al., 2001)	**What:** Study of curtain usage. **Where:** Kochi and Nangoku City (Japan).	**When:** October–June. **Who:** *N* = 381 students.	**Building:** Not specified. **Room:** Bedroom. **Window:** Not specified. **Shading & obstruction:** No/half transparent curtain, usual curtain, black-out curtain. **Example picture:** None provided.	**Source:** Light-at-night from outside (depending on the curtain), ceiling or desk light usage at night, low illumination bulb at night, no light. **When & where:** No measurements **Metrics:** No measurements	**Sleep latency** was longer with the blackout curtain compared to the usual curtain only. There was no association with **peak activity time** or **wake-up time.**	N/A
Küller and Wetterberg (1996) (Küller and Wetterberg, 1996)	**What:** Study of underground vs. over-ground work. **Where:** South Sweden.	**When:** No details. **Who:** *N* = 132 workers.	**Building:** Military base. **Room:** Various over-ground or underground work rooms. **Window:** None underground. **Shading & obstruction:** No/half	**Source:** Artificial and/or daylight **When & where:** No measurements **Metrics:** No measurements	Morning **cortisol** was generally lower underground except in January (seasonal rhythm was dampened), with higher **melatonin** for those below ground and clearer seasonal pattern, more **sleep** and easier sleep in the underground workers.	Above ground: lighting was more pleasant and brighter, disease incidence was not different but seasonal peaks were shifted. Underground workers did not seem

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Table 2 (*continued*)

Author (Year)	Study What/Where	When/Who	Architecture	Light	Circadian Biology	Health/Perception
			transparent curtain, usual curtain, black-out curtain. **Example picture:** None provided.			to mind working underground.

* BDI = Beck Depression Inventory, CES-D = Centre for Epidemiological Studies Depression scale, CCT = Correlated colour temperature, CL_A = Circadian light, CS = Circadian stimulus, CRI, DLMO = dim light melatonin onset, EC = electrochromic, EML = Equivalent melanopic lux, KSS = Karolinska Sleep scale, MA = Montgomery-Asberg scale, PANAS = Positive and Negative Affect scale, PROMIS = Patient Reported Outcomes Measurement Information System, PSQI = Pittsburgh Sleep Quality Index, SMS = Strategic Management Simulation assessment, SRQ = Self-reporting questionnaire-20.

day.

Three more studies complete this section but are all very different. A natural experiment assessed the diurnal heart rate and cortisol of 60 participants working in either old offices/cubicles or more modern, open, and brighter offices with transparent windows and skylights (Thayer et al., 2010). A main effect of brighter office space associated with decreased cortisol (cubic time trend of cortisol across the day based on 5 measurements) but no effect on heart rate was observed. Time (months in the workplace)*office interactions indicative of a more pronounced diurnal variability in heart rate (specifically, higher at night and lower during the day) and lower cortisol levels with increasing months in more modern offices were observed (Thayer et al., 2010). However, no light metrics are provided (Thayer et al., 2010). The oldest study from 1996 compared underground workers with over-ground workers at a military base in South Sweden and observed longer sleep duration and greater diurnal difference in urine melatonin metabolite in the underground workers over ten months (Küller and Wetterberg, 1996). This observation is in contrast to what might be expected, as there were no windows to provide daylight to the underground workers (Küller and Wetterberg, 1996). Lastly, a descriptive study of personal light exposures in office workers during work revealed that sleep in summer compared to winter was associated with higher efficiency and shorter latency; however, mean illuminance was ~178 lx in summer in a building designed to improve light exposure, possibly indicative of poor daytime light exposures and/or circadian entrainment (Figueiro and Rea, 2016).

As mentioned, all studies have the advantage of measuring real-world differences following an architectural intervention but any causal inference is unwarranted due to the possible extent of residual confounding. Simply, it cannot be assumed that architecture triggered a change in light which triggered a change in the circadian biology-related outcome. Nonetheless, the possibility of glazing that can alter light transmission affecting real-world changes in circadian biology, including sleep and melatonin parameters, warrants further investigation.

3.2. Non-human studies

In this section are $n = 8$ field studies and n = 8 simulation studies with $n = 3$ being combinations of both. Circadian light metrics considered include the CS metric, the EML (equivalent melanopic lux) metric, and the Circadian Action Factor metric (further discussion on the applicability of metrics in the discussion). Otherwise, assumptions of influence on circadian processes were provided in studies that used photopic light metrics. Window elements considered in field studies include orientation ($n = 4$), size (n = 3), glass ($n = 2$), distance to the window ($n = 1$), window-to-wall ratio (n = 1), and presence of a roof light (n = 1). Additionally, indoor surface reflectance (n = 4), presence of electric light (n = 3) or light pipe (n = 1), roof transmittance (n = 1), dirt accumulation on building elements (n = 1), and internal (n = 1) and external obstructions (n = 1) were considered. Simulation studies focused on window size ($n = 5$), orientation (n = 3), glass (n = 2), position (n = 1), and distance to the window (n = 1). Also, indoor surface reflectance (n = 5) was featured more prominently. Less prominent were external obstructions (n = 1) and furniture layout (n = 1). Extracted data of the 19 articles can be found in Table 3.

Unsurprisingly, field studies are mostly descriptive and confirmatory that architectural features affect the lighting conditions indoors that may be important for circadian biology. Most focus is on the characteristics of windows, line of sight, and whether sufficient light is achieved (Bellia et al., 2014a; Bellia et al., 2014b; Daniel, 2003; Zeng et al., 2021; Babilon et al., 2021). Many studies indicated that sufficient light for circadian biology was not always achieved. Four studies include circadian light metrics (Bellia et al., 2014a; Bellia et al., 2014b; Zeng et al., 2021; Babilon et al., 2021). Worth mentioning, though, is one study finding that spectral distributions of light depended more on the reflectance of the internal and external surfaces and not on the window glass (Bellia et al., 2013), one study considered light pollution and unshielded light fixtures and surrounding reflectance (Hebert, 2011), and one study demonstrated the potential of the utility of light pipes to bring daylight into buildings (Malet-Damour and Fakra, 2021). Regarding the latter, it was demonstrated that the light pipe can provide full spectrum daylight inside on clear and on overcast days. Although there will be less light compared to what might be achieved with a window, such an additional source of directed daylight may prove more beneficial than supplementation with electric light (Malet-Damour and Fakra, 2021). One study found a sky-lit atrium should reduce the need for electric lighting in a large plaza despite surrounding high-rise buildings (Daniel, 2003). Moreover, the calculations took into consideration light obstructions such as glazing bars, wall surface reflectance, transmittance, and dirt accumulation on building elements. The next steps of study should include assessment of association between features, including for instance the light pipe, that affect daylight indoors (using both photopic and circadian-related units) and circadian biology-related parameters.

The eleven simulation studies lead to debate about what architectural features are best to achieve certain light thresholds for circadian biology. Four studies did not consider circadian light metrics like CS or EML but did consider other light measures for circadian biology (Abidi and Rajagopalan, 2020; Andersen et al., 2013; Pechacek et al., 2008; Araji and Boubekri, 2011). The other seven – published since 2017 – used CS or EML with CS $\geq$ 0.3 generally considered the desirable lower threshold (Ezpeleta et al., 2021; Yao et al., 2020; Busatto et al., 2020; Acosta et al., 2019; Acosta et al., 2017; Potocnik and Kosir, 2021; Aguilar-Carrasco et al., 2021).

Window size and orientation are considered most important for light for circadian biology by only one study. They used real window sizes, orientations, and external obstructions (of small apartments in Melbourne, Australia), and simulated surface reflectance to reach this conclusion (Abidi and Rajagopalan, 2020). Others describe limitations of window size and highlight the importance of window size to wall ratios (WWR) alongside surface reflectance and at particular latitudes. A simulated study of educational spaces finds that rooms with low reflectance of inner surfaces or work planes provide insufficient CS values, regardless of window size, orientation, or location (Acosta et al., 2019). White or pale blue colour but not light wood was recommended

Table 3
19 non-human field and simulation studies into light and architecture.

Author (Year)	Study What/Where/Type	When/Which software	Architecture	Light
Zeng et al. (2021)) (Zeng et al., 2021)	**What:** Non-visual effects in office environments **Where:** Chongqing (China) **Type**: Field study	**When:** April 2020	**Building:** Office **Space:** three open-plan offices & 1 private office **Window:** orientation, depth from the window, line-of-sight direction **Shading & obstruction:** Sky conditions **Example picture:** Provided	**Source:** Daylight with or without electric light **Sensor:** EVERFINE SPIC-300 spectrum & illuminance meter **Metrics:** Illuminance, SPD* at eye level, EML* & CS* models
Potocnik and Kosir (2021) (Potocnik and Kosir, 2021)	**What:** Importance of WWR*, glazing transmissivity, wall, ceiling and floor reflectance, room depth, width & view orientation on indoor non-visual and visual content **Where:** Ljubljana (Slovenia) **Type**: Simulation & field study	**When:** not specified **Software:** Rhinoceros 6 & ALFA	**Building:** Simulated office **Window:** WWR* **Other building parameters:** room depth, room width, wall reflectance, ceiling reflectance, floor reflectance, glazing transmissivity, and occupant view direction. **Example picture:** Provided	**Source:** Simulated **Metrics:** melanopically weighted reflectivity, and transmissivity, E_v*, E_m* and Cl_A*.
Malet-Damour and Fakra (2021) (Malet-Damour and Fakra, 2021)	**What:** The impact of Mirrored Light Pipe on thermal & spectral conditions **Where:** Reunion Island (France) **Type**: Field study	**When:** April 2018 – end of 2019	**Building:** Experimental cell **Window:** Presence of window **Shading & obstruction:** overcast sky, clouds **Example picture:** Provided.	**Source:** Daylight from Light pipe **Sensor:** 3 x CMP11 pyranometers, 2xCGR3 pyrgeometers, 1 x JazRad spectrophotometer **Metrics:** I_G*, I_d*, L_{net}*, L_D*, outdoor and indoor spectral irradiance.
Ezpeleta et al. (2021) (Ezpeleta et al., 2021)	**What:** Evaluation of lighting in classrooms **Where:** Zaragoza (Spain) **Type**: Simulation	**When:** n/a	**Building:** Not specified **Space:** Four classrooms **Simulated features:** furniture, walls, windows, & ceiling **Example picture:** Provided.	**Source:** Simulated light **Sensor:** Calibrated spectroradiometer **Metrics:** photopic illuminance (lux), EML*, CCT*, EDI* melanopic lux, CRI*
Babilon et al. (2021) (Babilon et al., 2021)	**What:** To report the amount of circadian-effective light in a senior care facility **Where:** Frankfurt (Germany) **Type**: Field study	**When:** December 2020	**Building:** Single Nursing home **Window:** Window size **Shading & obstruction:** Curtains were open – no further information **Example picture:** Provided.	**Source:** Daylight & Artificial light **Sensor:** HCT-99D handheld photometer **Metrics:** Ev* (lux), CCT* (K), CS* value
Aguilar-Carrasco et al. (2021) (Aguilar-Carrasco et al., 2021)	**What:** Calculation of CS* **Where:** Sevilla (Spain) **Type**: Simulation & field study	**When:** Throughout the year	**Building:** Hospital laboratory area **Window:** window-to-facade ratio, surface, dimensions, glass surface, glass surface/total surface, visual transmittance **Shading & obstruction:** sky coverage **Example picture:** Provided.	**Source:** Natural & Electric light **Sensor:** n/a **Metrics:** Illuminance, CS*
Yao et al. (2020) (Yao et al., 2020)	**What:** Validation of equation for the dependence of daylight corneal illuminance on room surface reflectance and WWR **Where:** Chongqing (China) **Type:** Simulation	**When:** Throughout the year (particularly on October 15th, November 14th, December 1st)	**Building:** n/a **Space:** Artificial sky lab **Window:** size of openings, window-to-floor ratio, WWR **Shading & obstruction:** overcast sky **Example picture:** Provided.	**Source:** Daylight **Sensor:** n/a **Metrics:** illuminance, CS* value
Busatto et al. (2020) (Busatto et al., 2020)	**What:** Comparison of 3 circadian assessment metrics **Where:** Venice (Italy) **Type**: Simulation	**When:** Morning (09:00–10:00), afternoon (15:30–19:30)	**Building:** Healthcare residence **Space:** Gym used for rehabilitation **Window:** presence of window **Shading & obstruction:** overcast sky **Example picture:** Provided.	**Source:** Daylight & artificial light **Sensor:** Spectrascan PR-650 **Metrics:** spectral radiance, a_{cv}*, CS*, EML*
Abidi and Rajagopalan (2020)) (Abidi and Rajagopalan, 2020)	**What:** Analysis of annual conditions in rooms in the southern hemisphere **Where:** Melbourne (Australia) **Type**: Simulation & field study	**When:** 9 am-3 pm in November	**Building:** Residential **Space:** 12 apartment bedrooms **Window:** size and orientation of window, window-to-floor ratio **Shading & obstruction:** Yes, not specified (blinds in photo). **Example picture:** Provided.	**Source:** Daylight **Sensor:** Daylight simulations using a tool in Revit software. **Metrics:** lux
Acosta et al. (2019) (Acosta et al., 2019)	**What:** Determination of suitable window size to promote a proper CS* **Where:** London (UK); Paris (France); Madrid (Spain) **Type**: Simulation	**When:** n/a	**Building:** Institutional (Educational) **Space:** Virtual classroom **Window:** joinery reflectance, joinery reflection and glass transmittance **Shading & obstruction:** n/a **Example picture:** Provided.	**Source:** Daylight & electric light **Sensor:** n/a **Metrics:** lux, CS*
Acosta et al. (2017) (Acosta et al., 2017)	**What:** Use of CS to select appropriate window characteristics **Where:** London (UK); Madrid (Spain) **Type**: Simulation	**When:** n/a **Software:** DAYSIM 3.1	**Building:** Institutional (Medical) **Window:** window/facade (%), window area, window dimensions, glass area, glass factor (visible transmission) **Shading & obstruction:** varying sky	**Source:** Daylight **Sensor:** n/a **Metrics:** CS*

(*continued on next page*)

Table 3 (*continued*)

Author (Year)	Study What/Where/Type	When/Which software	Architecture	Light
			conditions **Example picture:** Provided.	
Bellia et al. (2014b) (Bellia et al., 2014b)	**What:** Confirmation of previous findings on desk illuminances and circadian impact **Where:** Naples (Italy) **Type:** Field study	**When:** late November 2013 and early February 2014	**Building:** Commercial (Office) **Space:** Offices located on the 7th floor **Window:** window dimensions **Shading & obstruction:** External obstructions shown in pictures **Example picture:** Provided.	**Source:** Daylight **Sensor:** Konica Minolta: CS 2000 spectroradiometer & T10 luxmeter **Metrics:** CS*, CL_A*
Bellia et al. (2014a) (Bellia et al., 2014a)	**What:** Daylight characteristics of offices **Where:** Naples (Italy) **Type**: Field study	**When:** May 2013 – July 2013	**Building:** Commercial (Office) in urban area **Window:** window dimensions, glass characteristics, WWR **Shading & obstruction:** pictures of the area provided **Example picture:** Provided.	**Source:** Daylight **Sensor:** Konica Minolta: CS 2000 spectroradiometer & T10 luxmeter **Metrics:** CS*, CL_A*
Bellia et al. (2013) (Bellia et al., 2013)	**What:** Model development for predicting non-visual responses **Where:** Naples (Italy) **Type**: Field study	**When:** 2 typical winter days (1 with overcast sky & 1 with clear sky)	**Building:** Institutional (Educational) **Space:** Classroom on the 6th floor **Window:** window orientation, glass characteristics, window frame **Shading & obstruction:** curtains & pictures of external obstructions **Example picture:** Provided.	**Source:** Daylight & Electric light **Sensor:** spectroradiometer **Metrics:** Illuminance (lux), CCT* (K)
Andersen et al. (2013) (Andersen et al., 2013)	**What:** Effects of housing design on appropriate daylight exposure for the circadian system **Where:** Boston (USA) **Type**: Simulation	**When:** Throughout the year **Software:** DAYSIM software (version not specified)	**Building:** 20 houses within the Boston South End district **Window:** Floor/window configuration, orientation, distance from window **Shading & obstruction:** blind usage **Example picture:** Provided.	**Source:** Daylight **Sensor:** n/a **Metrics:** Daylight Autonomy (%)
Hebert (2011) (Hebert, 2011)	**What:** The effects of optical radiation at university housing sites. **Where:** mid-western USA **Type:** Field study	**When:** October – November 2010	**Building:** Residential (College campuses) **Space:** five student housing sites **Window:** window position but not specified **Shading & obstruction:** not specified **Example picture:** Provided.	**Source:** Electric light **Sensor:** GTE Sylvania DS-2000 m **Metrics:** Visible light (fc*), lux
Araji and Boubekri (2011) (Araji and Boubekri, 2011)	**What:** Predictor variables for enhancing visualisation for facade design **Where:** Chicago (USA) **Type:** Simulation	**When:** 08:00 am – 05:00 pm **Software:** MATLAB	**Building:** Simulated room **Window:** window height **Shading & obstruction:** Exterior obstructions not considered **Example picture:** Provided.	**Source:** Daylight **Sensor:** n/a **Metrics:** Vertical illuminance at the eye level in Klux
Pechacek et al. (2008) (Pechacek et al., 2008)	**What:** Characteristics of light that promote human health **Where:** Boston (USA) **Type:** Simulation	**When:** not specified **Software:** MATLAB, RELUX	**Building:** An imaginary patient room in Boston. **Window:** window size, glazing fractions, window transmissivity **Shading & obstruction:** shading devices and blinds considered. **Example picture:** Provided.	**Source:** Daylight & Artificial light **Sensor:** n/a **Metrics:** lux
Daniel (2003) (Daniel, 2003)	**What:** Energy-saving properties of top-lit Atrium **Where:** Hong Kong (China) **Type:** Field Study	**When:** August 1999	**Building:** Commercial - New Town Plaza **Window:** not specified **Shading & obstruction:** nearby buildings **Example picture:** Provided.	**Source:** Daylight & Electric light **Sensor:** Solar pyranometer **Metrics:** lux, flux transfer

SPD = spectral power distribution, EML = equivalent melanopic lux, CS = circadian stimulus, WWR = window-to-wall ratio, E_v = visually weighted, E_m = melanopically weighted, Cl_A = Circadian Light, l_G = global irradiance, I_d = diffuse irradiance, L_{net} = net radiation, L_D = longwave radiation, CCT = correlated colour temperature, a_{cv} = circadian action factor, fc = footcandles, CRI = Colour Rendering Inde.

to promote a minimum CS value (Acosta et al., 2019). Rooms in London with WWR ranging from 30 % to 60 % and mean room surface reflectance close to 0.55 were able to meet the CS criterion ≥0.35 for at least 1 h in the morning for 75 % of the year (Acosta et al., 2017). In Madrid, rooms with WWR ≥ 40 % and mean surface reflectance close to 0.55 were capable of meeting the CS criterion for over 90 % of the year (Acosta et al., 2017). Windows with an area exceeding 40 % of the facade offered a uniformly distributed CS and window-to-facade ratios of 60 % and 80 % yielded similar CS values, suggesting diminishing returns with larger windows (Acosta et al., 2017). Bringing glazing into consideration, one study that considered WWR to be the most influential geometric building parameter also considered glazing transmissivity to be the most influential optical building parameter in terms of achieving desirable CS values (Potocnik and Kosir, 2021). The impact of increasing WWR at a given transmissivity was greater than vice versa (Potocnik and Kosir, 2021). Another study describes a more important role for window transmittance in achieving illumination levels desirable for the circadian system when the glazing fraction is below 50 % and diminishing returns of increasing transmittance when the glazing fraction is above 50 % (Pechacek et al., 2008). Furthermore, larger windows may be required to achieve similar illumination for circadian systems when windows are tinted (with transmittance ≤0.6) (Pechacek et al., 2008).

In terms of reaching circadian system-desirable light levels, the individual's viewpoints within the architectural space can also be important, especially at earlier and later times of day (Andersen et al., 2013). For instance (and albeit counter-intuitive), tall, reflective urban masking (e.g., surrounding houses) appeared to facilitate more light reaching the back of a room in a south-facing apartment with a partition but would only serve to block daylight if the partition was absent in one simulation (Andersen et al., 2013). Surface reflectance was also shown

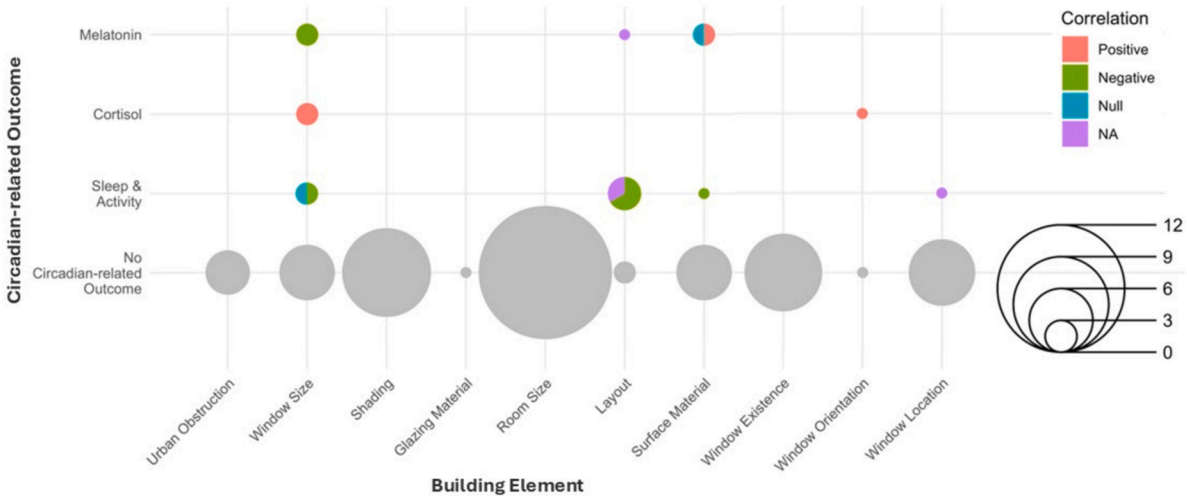

Fig. 2. ***Counts of identified studies including respective circadian-related outcomes and architectural features.*** The circle size indicates how many studies mentioned or investigated the architectural feature. The red, green, and blue colouring indicate what features are investigated in relation to circadian biology and whether the association is positive, negative, or null, respectively. The purple colour indicates the circadian-related outcome was studied but not in regard to the architectural feature mentioned. The grey colouring indicates what features are mentioned or described but no circadian biology outcome is studied (albeit circadian biology is mentioned in the study as important).

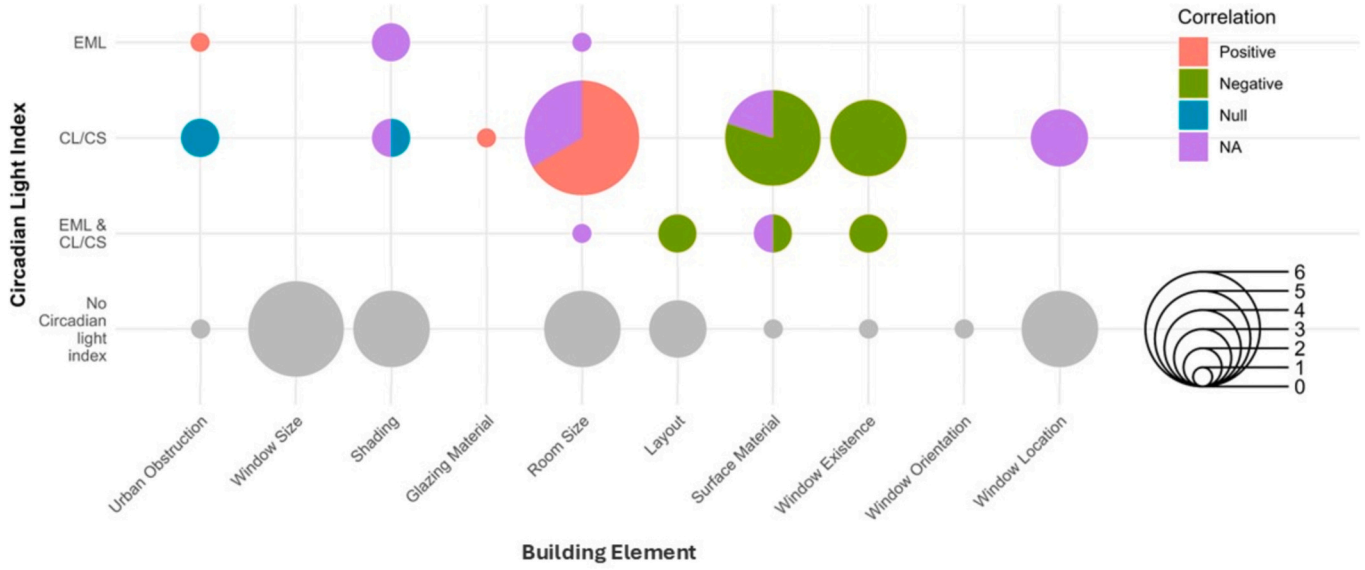

Fig. 3. ***Counts of identified studies including respective circadian light metrics and architectural features.*** The circle size indicates how many studies mentioned or investigated the architectural feature. The red, green, and blue colouring indicate what features are investigated in relation to circadian light metrics and whether the association is positive, negative, or null, respectively. The purple colour indicates the circadian light metric was studied but not in regard to the architectural feature mentioned. The grey colouring indicates what architectural features are mentioned or described but no circadian light metrics are mentioned.

to play a role in terms of optimising indirect corneal illuminance (Andersen et al., 2013). A study of four classrooms with different window characteristics and different surfaces reflectance and positions also considered eye level height and head orientation as important in the simulations (Ezpeleta et al., 2021). The authors also determine improvements can be made to complement available daylight but will likely require higher electricity consumption (Ezpeleta et al., 2021).

Overall, a stepwise consideration of features by architectural importance to light (and circadian light) may be useful when designing and redesigning architectural spaces, but personal viewpoints for tasks performed within the architectural space should be considered. Applicable light limit values for different times of day (for a given architectural space and what it is used for) may be useful, with the use of (currently debatable - see discussion) light metrics providing proof of principle that such metrics can become of utility.

4. Discussion

In summary, this review identified a small number of studies fitting our scope. The architectural emphasis in the different types of studies appears different, with human studies focusing more on glazing transmittance and non-human field and simulation studies focusing more on

window characteristics relative to rooms and on surfaces reflectance. The human studies describe outcomes in real (non-lab) settings, but residual confounding could be rife. The most important finding is perhaps the lack of clear associations regarding architecture, light, and circadian biology together. Nonetheless, novel investigations such as of electrochromic glazing to alter the spectral transmissivity of light through windows at different times of day to benefit circadian biology are identified as warranting further study. Non-human field and simulation studies identify additional architectural features and dimensions that may be beneficial or detrimental to circadian light for humans but their impact requires corroboration by human studies. They also point to the possibility of diminishing returns when developing features for increased light in isolation. Applicable light limit values for different times of day (for a given architectural space and what it is used for) may be useful. Overall, many studies of architecture mention their importance for circadian biology but few and limited real-world studies exist.

From the architectural perspective, first studies exist that include considerations of individual products such as specific glazing types, skylights, light pipes, etc.; however, these must be judged as first explorations with restricted foci and not suitable to compare e.g. the benefits of specific glazing types with those of shading systems or window positions. In general, a lack of investigations of architectural features, such as external and internal shading, is observed, not to mention the interaction of human behaviour with such features and the influence on light and dark exposures. From the chronobiological perspective, studies of the direct effects of architecture on circadian biology are very limited, with most focus on sleep. For instance, there are no conclusive investigations of whether changes in architecture leading to a change in light result in changes of – or affect – circadian biology *per se*; but there is at least evidence to suggest that this could be the case. There is increasing use of the circadian light metrics and CS in particular; yet, demonstration of the applicability of CS is still in the early days. Achieving CS $\geq$ 0.3 is considered the aim in most studies reviewed, but as with circadian biology, it is the timing of exposure that is important. That such timing for circadian biology is important was only stressed in comparatively few simulation studies. For now, increasing daylight exposure during daylight hours and lowering illumination from evening times of day into non-daylight hours (in the blue spectrum in particular) can suffice as a goal.

Indeed, what CS and EML represent can be difficult to understand. In 2005 (and revised in 2010, 2012 and 2018), Rea et al. developed the CS metric that indicates how well a one-hour exposure to a light source producing a certain light level and wavelength of light stimulates the circadian system, based on its ability to suppress the hormone melatonin (Rea and Figueiro, 2018; Rea et al., 2010; Rea et al., 2012; Rea et al., 2005). Circadian light (CL_A), oftentimes provided alongside CS, involves units of circadian spectrally weighted irradiance whereas CS is defined as the relative effectiveness of CL_A for producing a meaningful circadian response. EML was developed by Lucas et al. (2014) by weighting photopic lux for the photosensitive melanopsin-containing retinal ganglion cells that detect and transmit ambient light information to the circadian timing system in the brain (Lucas et al., 2014). The Circadian Action factor (CAF) is the ratio between the integrals of the circadian and the photometric quantities (Gall, 2003). The CIE α-opics (see reference Schlangen, 2019) were not mentioned in any of the included studies. Of course, stimulation of photoreceptors by light to elicit non-image-forming effects also depends on the circadian phase of these cells and on recent light history, so any light thresholds may need to be adjusted to the time of day and nature of the working space (e.g., whether the space is for shift workers who are not long awake and beginning a late shift or who are long awake and ending their middle shift).

Confounding is an issue in the reviewed studies and can be an issue in the future. Even when the dimension of scale is low (i.e., many studies consider an individual design feature as opposed to e.g., an urban context), which should permit more stringent control of potentially confounding factors, circadian biology parameters and related outcomes and health are influenced by many stimuli deriving from the individual, their behaviour, and their environment. Assessment of real-world impacts of modifications of architectural features and space is necessary; thus, crossover studies may be best suited to this. The combination of the dimensions of season (Bellia et al., 2014a), daytime (e.g., morning, evening, night) (Andersen et al., 2013; Pechacek et al., 2008; Ezpeleta et al., 2021; Busatto et al., 2020), and building type (e.g., residential, office) highlights the variety in requirements, needs, and behaviours (Yang et al., 2021; Figueiro et al., 2019; Figueiro et al., 2017; Lo Verso et al., 2021) involved in the relation between architecture, circadian biology, and health. This combination also needs to be reflected when exploring and determining suitable solutions. Also, the interaction between conditions provided by and within architectural spaces and human behaviour starting from as small as head movements changing exposure to daylight within a given space is a point requiring further work (Zeng et al., 2021; Bierman et al., 2005). So far, this possible effect modifier has been largely neglected especially in simulation studies. Also, other behaviours like the use of blue light emitting displays in the evening appear to be less considered as potential confounders in studies focussing on architectural features (Cajochen et al., 2011).

Considering some of the possible sources of confounding and limitations of the circadian light metrics together, the CIE position generalising statement is worth mentioning: “A high melanopic EDI during the day is usually supportive for alertness, the circadian rhythm and a good night’s sleep. A low melanopic EDI in the evening and at night facilitates sleep initiation and consolidation” (Schlangen, 2019).

In terms of future research, simply put, more is needed on architecture, light, and circadian biology together. That architectural modifications can affect the circadian biology of individuals by influencing their light exposures is expected but is not clearly demonstrated. Moreover, to what extent it can have an influence (i.e., effect size), for whom, and in what situations remains open. That light may attain a circadian light metric “threshold” value at a particular time or time of day is not demonstrative of an effect on circadian biology per se either. Circadian biological outcomes must also be better researched, albeit we note that this comes with difficulty.

In conclusion, first evidence is available, while much more research is required to determine the effects of specific elements of architectural design on our circadian biology, health, and well-being. In closing, the following quote encapsulates how applying insights from architecture and chronobiology may shape differences for individual and population health (Rose, 1985): “Belief in the significance of architecture is premised on the notion that we are, for better or worse, different people in different places” (De Botton, 2012: The Architecture of happiness) (De Botton, 2012).

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Ethics

N/A

CRediT authorship contribution statement

Philip Lewis: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Rania Christoforou:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Peiman Pilehchi Ha:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data

curation. **Ursula Wild:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Marcel Schweiker:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Thomas C. Erren:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare no conflicts of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.177212.

Data availability

No data was used for the research described in the article.

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