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Daylight and health: A review of the evidence and consequences for the built environment

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Daylight has been associated with multiple health advantages. Some of these claims are associations, hypotheses or beliefs. This review presents an overview of a scientific literature search on the proven effects of daylight exposure on human health. Studies were identified with a search strategy across two main databases. Additionally, a search was performed based on specific health effects. The results are diverse and either physiological or psychological. A rather limited statistically significant and well-documented scientific proof for the association between daylight and its potential health consequences was found. However, the search based on specific health terms made it possible to create a first subdivision of associations with daylight, leading to the first practical implementations for building design.

1. Introduction

Humans have evolved under the influence of daylight and the light–dark cycle. On the one hand, the human skin provides a layer of pigmentation to protect us from the highest radiation intensities when exposed to daylight almost every day. On the other hand, humans have developed a variety of physiological responses to the varied characteristics of daylight. Daylight was the main light source until electric lighting became reliable and affordable. Since the introduction of electric lighting, a large part of the population started spending most of its time inside buildings. It sometimes even appears as if daylight has only an architectural value, and all other daylight functions have been replaced by electrical lighting solutions.

Solar radiation is filtered through the atmosphere and radiation reaching the Earth's surface is mainly in the wavelength range 200–4000 nm; some visible, some invisible to the human eye. The portion of the spectrum to which the eye is sensitive – commonly referred to as light – is electromagnetic radiation with a wavelength in the range from about 380 nm to about 780 nm. Radiation with wavelength between 100 nm and 400 nm is called ultraviolet (UV) radiation and is usually divided into UV-C (200–280 nm), UV-B (280–315 nm) and UV-A (315–400 nm). Radiation with wavelength between 780 nm and 1 mm is called infrared (IR). UV and IR are invisible to the human

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eye. Daylight is the solar radiation, visible to the human eye, emitted by the sun and perceived during daytime. The duration of daytime depends on our location on Earth and the time of year. Since daylight cannot be artificially replicated, it is often referred to as natural light.

Humans overwhelmingly prefer working and sitting near windows.[1] However, nobody can fully explain why. Potential reasons are the link with the view outside with its inexhaustible supply of information, the quantity of daylight (both high and low), the presence of the full continuous spectrum, the (change in) directionality and/or the dynamics from milliseconds to months. Daylight provides variety and stimulation during the day and it is widely believed that access to daylight reduces stress and increases productivity.[2,3] Weather in general is found to influence people's health and mood.[4–7] In the multivariate study of Denissen *et al.*,[4] the effects of six weather parameters (temperature, wind, sunlight, precipitation, air pressure and photoperiod) on mood (positive affect, negative affect and tiredness) were examined. The results revealed important effects of temperature, wind and sunlight, with sunlight also showing a mediating role.

Daylight, however, because of its variability, intensity and thermal component, can also lead to serious problems. It can cause an uncomfortable level of glare,[8,9] or it makes the building demand excessive amounts of cooling/heating energy if too much/little radiation enters the building. When daylight is the cause of thermal or visual discomfort, the occupants' wish for daylight is diminished. Additionally, people do not switch electric lighting off when there is enough daylight. This suggests that daylight is not superior, but electric lighting is limited in creating necessary variation, the provision of a view and space illumination.[10] Besides, people's preference for daylight may be partly due to their negative view of electric lighting.

Radiation is increasingly administered and studied as a non-pharmacologic treatment for a variety of health-related problems, including skin problems (UV-radiation treatment), seasonal affective disorder (SAD), depression, jetlag, as well as circadian rhythm sleep disturbances and behavioural problems.[11] Light therapy consists of exposure to daylight or to specific types of electric lighting. Exposure is prescribed for a specific duration and time of day. A little more than 50 years ago, it was quite common for sunlight to be prescribed as part of the treatment of tuberculosis in sanatoria.[12]

The World Health Organization defines health as 'a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity'.[13] Daylight is widely believed to influence human health. Daylight and daylighting have been associated with lower absenteeism, reduced fatigue, relief of SAD, decreased depressive symptoms, improved skin conditions, better vision, positive impact on the behavioural disturbances seen in Alzheimer's disease and multiple other health advantages. Some, but hopefully not all of these claims are associations, hypotheses or beliefs. Therefore, the rationale of this paper is to present an overview of studies on the proven effects of daylight exposure on human health, since 'light is the most important environmental input, after food, in controlling bodily functions'.[14] Moreover, we discuss the consequences and applicability of the results of the literature review for the construction and the renovation of buildings from a practical and architectural point of view.

2. Methodology

2.1. Search process

Proven health effects of daylight were examined on the basis of existing literature and the search followed a two-step process. First, studies were identified with a search strategy across two (English language) literature databases: PubMed and Scopus. In Scopus, the initial search terms in the article title, abstract or keywords were: 'daylight', 'sunlight' and 'natural light', in combination with 'health'. In PubMed, 'daylight' was included in all fields and 'health' was entered as MeSH Term. Species was set to 'human' (PubMed) or the word 'human' was included in the search term (Scopus). In order to eliminate most results related to daylight saving time, results with 'saving' and 'accident' (all fields) were excluded, and to eliminate most dental results, terms such as 'oral' (all fields) were excluded, and to eliminate results related to fasting during Ramadan, 'Ramadan' (all fields) was excluded. Table 1 shows the exact search terms used. Bibliographies of selected articles were screened for other relevant articles. Second, searches were performed based on 'daylight' and a specific health effect (for instance, headache), since it could be that only this specific term was used in the article instead of 'health'.

2.2. Inclusion and exclusion criteria

Included were published studies of daylight effects on human health. Actual eligibility was assessed by reading abstracts and, if necessary, whole articles. Due to the large amount of hits in Scopus, a pre-selection based on the journal title (e.g. publications in the *Journal of Accident Analysis and Prevention* or the *Journal of Public Health Dentistry* were excluded) or topic (e.g. 'fasting during Ramadan') was made prior to the eligibility process of studies.

2.3. Data extraction

The following data were extracted from the studies if available: (1) studied health effect(s); (2) light source (daylight only or a combination of daylight and electric lighting); (3) illuminance (including direction if possible); (4) time of exposure (either time at which the exposure occurred or the duration of the exposure); (5) number of subjects; (6) type of study; (7) statistical evidence (including test details and significance level) and (8) conclusions related to daylight and health. Study quality other than completeness of requested data was not further assessed.

2.4. Limitations

The study was limited to daylight only (visible radiation 380–780 nm). Known intra- and interpersonal differences (i.e. gender, photoperiod sensitivity, and daily and monthly rhythms) were not specifically included in this literature search. This also applies for potential health interaction effects, and the results or interactions due to electric lighting.

Table 1 Search terms within the databases 'PubMed' and 'Scopus' (Date of last search: 20 September 2013)

	Search terms
PubMed	(daylight[Title/Abstract] AND health[Title/Abstract]) NOT saving[All Fields] NOT ('oral'[All Fields]) NOT ('Ramadan'[All Fields]) NOT ('accident'[All Fields]) AND (hasabstract[text] AND 'humans'[MeSH Terms] AND English[lang])
PubMed	(natural light[Title/Abstract] AND health[Title/Abstract]) NOT saving[All Fields] NOT ('oral'[All Fields]) NOT ('Ramadan'[All Fields]) NOT ('accident'[All Fields]) AND (hasabstract[text] AND 'humans'[MeSH Terms] AND English[lang])
Scopus	TITLE-ABS-KEY(daylight AND health AND NOT saving AND NOT oral AND NOT Ramadan AND NOT accident) LANGUAGE(English) AND (LIMIT-TO(DOCTYPE, 'ar') OR LIMIT-TO(DOCTYPE, 'ip')) AND (LIMIT-TO(EXACTKEYWORD, 'Humans'))
Scopus	TITLE-ABS-KEY('natural light' AND health AND NOT saving AND NOT oral AND NOT Ramadan AND NOT accident) LANGUAGE(English) AND (LIMIT-TO(DOCTYPE, 'ar') OR LIMIT-TO(DOCTYPE, 'ip')) AND (LIMIT-TO(EXACTKEYWORD, 'Humans'))

3. Results

In this section, an overview is given of health effects related to daylight exposure. After comparing and pre-selecting the literature search results (Table 2), an in depth abstract-based selection showed that 18 unique studies from both literature databases seem to be eligible and were further analysed. Subsequently results of additional studies (and their limitations) are reported.

3.1. Step 1: Databases 'PubMed' and 'Scopus'

Table 3 shows the results from the search within the PubMed and Scopus databases. Mottram *et al.*[15] reported the best sleep timing, duration, efficiency and quality under natural light conditions. The study included questions and measurements (both actigraphy and lighting measurements) and used daylight as a control condition (3-week period at the beginning and end of the Antarctic winter).

Four studies focused on the relationship between daylight hours and physical activity. Three studies[16–18] found no significant effects, while the fourth study[19] found a significant association. Next to the difference in measurement devices between those four studies (pedometers vs. accelerometers), there was also a difference in the amount of daylight hours per day (from 8.7 hours to 15.1 hours). The studies of Feinglass *et al.*[19] and Klenk *et al.*[18] both compared long (15–16 hours) to short (9 hours) photoperiods using accelerometers and found contradictory results. However, corrections for additional weather parameters and the fact that the group of Feinglass *et al.*[19] suffered from arthritis can explain the difference. Since significant (not clinically meaningful) results were found between days with less sunlight and arthritis pain severity, this could also be an explanation for the difference in activity level. It is generally not clear from the existing studies if the mixed results are due to limited statistical power (such as small sample sizes and variability in weather indices).

Bodis *et al.*[20] used also daylight hours to study the effect on heart attack and infarction. They found a (weak) negative correlation: the more daylight hours, the less infarctions. They also found a positive correlation between timing and infarctions. The influence of daylight hours was investigated by Hansen *et al.*[21] and Murray and Hay[22], as well in relation to SAD and mental distress. Both concluded that the (self-reported) depression was most likely not photoperiod specific, since 'human seasonality may have a broader psychological component'.[22] This preliminary conclusion seems consistent with Björkstén *et al.*[23] who tried to relate the daylight photoperiod to suicide levels. Surprisingly the suicide rate in Greenland peaked in midsummer and was lowest in the period with the least daylight hours (winter).

Since month of birth can influence people's life after, Jewell *et al.*[24] researched the season of birth with length of day as a representative variable and postpartum depression. They found no significant relationship.

Electric lighting at night and daylight photoperiod were linked to breast cancer by

Table 2 Hits per search term for the databases 'PubMed' and 'Scopus' (Date of last search: 20 September 2013)

Source	Search term 'daylight' or 'natural light'	Hits	Eligible after pre-selection
PubMed	Daylight	56	16
PubMed	Natural light	12	4
Scopus	Daylight	42	20
Scopus	Natural light	23	7

Table 3 Results of eligible studies (from 1989 until 20 September 2013)

Reference	Health effect	Light source	Illuminance (lx)	Exposure (hour)	Study type	N	Statistical test	Conclusion
Robertson *et al.*[39]	Work-related headache	Natural light and fluorescent electric lighting	Not reported	Not reported	Health questionnaire study	106	Not reported	Those with work-related headache found the lighting less comfortable ($p=0.059$) and perceived more glare ($p<0.05$). The study suggests the need to maximize the use of natural light from untinted windows
Hansen *et al.*[66]	Mental distress	Daylight and electric lighting	Not reported	November to February, including darkness in December and January	Questionnaire study: three questions about depression, coping problems and insomnia (within heart disease study)	7759	χ^2 tests	The prevalence of self-reported depression was surprisingly low in winter considering the lack of daylight.
Murray and Hay[22]	Seasonal affective disorder	Daylight photoperiod (the timing and duration of daylight)	Not reported	Not reported	Questionnaire study: SPAQ, GHQ, CES-D and STAI-T	526	Pearson correlations	Photoperiod cannot underlie the springtime reports of mood problems measured in the CES-D, STAI-T and GHQ scales. The findings of the present study suggest that the diathesis for seasonal affective disorder/seasonality may not be photoperiod-specific. At least in Australia, there is provisional support for the proposal that human seasonality may have a broader psychological component
Hansen *et al.*[21]	Seasonal affective disorder	Daylight Photoperiod (the timing and duration of daylight)	Not reported	Not reported	Questionnaire study with four questions regarding seasonal changes after winter (2 months no daylight) in April/May and after summer (2 months 24 hours daylight) in September/October	3736	Mantel-Haenzel procedure and logistic regression analysis	The prevalence of self-reported depression was surprisingly low in winter considering the lack of daylight.

Continued.

Table 3 Continued

Reference	Health effect	Light source	Illuminance (lx)	Exposure (hour)	Study type	N	Statistical test	Conclusion
Davis *et al.*[25]	Breast cancer	Light at night and daylight photoperiod	No numbers, ambient light measured every 30 seconds	Year around with to measurement moments (three different seasons)	Case control study	203	Linear regression models with correlated error structure to account for the correlation of the repeated measurements on each subject	Light-at-night as an exposure measures was not associated with nocturnal urinary 6-sulphatoxymelatonin concentration Lower nocturnal urinary 6-sulphatoxymelatonin level was associated with more hours of daylight
Björkstén *et al.*[23]	Suicide	Daylight photoperiod (the timing and duration of daylight)	Not reported	Not reported	Database study using official computerized registers on causes of death and population registers (WHO International Classification of Diseases)	833	Rayleigh test	A significant seasonal variation in suicides in West Greenland with a peak about midsummer time and low rates in the winter. Impulsive aggressiveness mediated by a serotonergic imbalance related to seasonal changes in light is proposed to be a biological component
Alimoglu and Donmez[29]	Job burn-out	Daylight	Not reported	Less than 1 hour, 1–3 hours and 3 hours or more	Questionnaire study: the Maslach Burnout Inventory, the Work Related Strain Inventory and the Work Satisfaction Questionnaire	141	χ^2 tests and student t-tests	Daylight exposure showed no direct effect on burn-out but it was indirectly effective via work-related stressand job satisfaction. Exposure to daylight at least 3 hours a day was found to cause less stress and higher satisfaction at work
Park *et al.*[28]	SRSL	Daylight and electric lighting (at home)	Mesor (mm, log10 lx): $M = 1.11 \pm .26$Amplitude (mm, log10 lx): $M = 1.16 \pm 0.62$	6 or 7 days	Questionnaire and actigraphy study	384	Multiple linear regression analysis	The best-fit model to predict SRSL was light exposure, GAF scale and use of anti-hypertensive drugs

Continued.

Table 3 Continued

Reference	Health effect	Light source	Illuminance (lx)	Exposure (hour)	Study type	N	Statistical test	Conclusion
Grimaldi *et al.*[27]	Health related quality of life	Daylight and electric lighting (at home and at work)	Not reported	Not reported	Interview and 12-item GHQ (GHQ-12) study with yes/no question about home lighting and no problem/some trouble/significant trouble about work lighting	7979	Multivariate regression	The HRQoL was influenced by both the seasonal changes in mood and behaviour ($p<0.001$) and the illumination experienced indoors ($p<0.001$). Greater seasonal changes ($p<0.001$) and poor illumination indoors ($p=0.0035$) were associated with more severe mental ill-being
Bodis *et al.*[20]	Heart attack and myocardial infarction	Daylight hours (seasonal variation and time of sunrise)	Not reported	Time of sunrise and sunset from the National Meteorology Service (OMSZ)	Retrospective database study	32 329	Variance analysis (Pearson and Spearman correlative and Kruskal–Wallis and Mann–Whitney nonparametric sampling)	The number of hours with daylight showed a weak negative correlation with the occurrence of myocardial infarction ($r=-0.108$, $p<0.05$) and a positive correlation was found between the time of sunrise and sunset and the occurrence of myocardial infarction ($p<0.01$)
Vreeburg *et al.*[31]	Salivary cortisol levels	Daylight photoperiod (dark months October to February vs. light months March to September)	Not reported	Not reported	Questionnaire study (health and socio-demographic variables) and measurements (salivary cortisol samples)	491	Linear regression analyses and coefficient analysis	Socio-demographic variables (sex, age), sampling factors (awakening time, working day, sampling month (daylight hours), sleep duration) and health indicators (smoking, PA, cardiovascular disease) were shown to influence different features of salivary cortisol levels
Jewell *et al.*[24]	Self-reported postpartum depression	Season of birth or length of daylight at birth	Not reported	Not reported	Cross-sectional database analysis	67 079	Logistic regression for complex survey design	No significant relationship between the season of birth or length of daylight at birth and PPD

Continued.

Table 3 Continued

Reference	Health effect	Light source	Illuminance (lx)	Exposure (hour)	Study type	N	Statistical test	Conclusion
Brown and Jacobs[26]	(Risk for) depression	Self-reported inadequate residential natural light	Not reported	Not reported	Questionnaire study (health and light)	6017	Bivariate-logistic regression model	Participants reporting inadequate natural light in their dwellings were 1.4 times as likely to report depression
Feinglass *et al.*[19]	Physical activity	Daylight hours	Not reported	Monthly daylight hours peaking: July hours/day 15.1 and January 9.1 hours/day	Field study using uni-axial accelerometer counts and interview data	241	Three level random-effects Regression and Restricted maximum likelihoode stimation	Daylight hours, mean daily temperature $<20^{\circ}$ or $\geq 75^{\circ}$, and light or heavy rainfall (but not snowfall) were all significantly associated with lower PA
Mottram *et al.*[15]	General health	17 000 K blue-enriched lamps, standard white lamps (5000 K), natural light	Natural light (3697 ± 1637 lx and 4094 ± 2309 lx) vs. Blue-enriched (1812 ± 652 lx, 2068 ± 4852 lx and 235 ± 1152 lx) and White lamps (2206 ± 746 lx, 1631 ± 487 lx and 1840 ± 727 lx)	General light boxes: 10 hours per day and a 3-week control period before and after	RAND 36-item questionnaire study (health) next to actigraphy and sleep diaries, urine samples and light measurements	15	Repeated measures analysis of variance	There were no differences in health score between the different conditions, only in sleep scores. Analysing all light conditions, control, blue and white, again provided evidence for greater sleep efficiency of blue-enriched light compared with white ($p < 0.05$), but with the best sleep timing, duration, efficiency and quality in control natural light conditions
Baert *et al.*[16]	Physical activity one year post-stroke	Daylight hours	Not reported	10.94 ± 2.68 hours/day	Questionnaire study and PA measurement via a pedometer	16	Spearman rank correlations	Age, gender and hours of daylight were not significantly correlated with PA measured by the several assessments

Continued.

Table 3 Continued

Reference	Health effect	Light source	Illuminance (lx)	Exposure (hour)	Study type	*N*	Statistical test	Conclusion
Duncan *et al.*[17]	Ambulatory PA	Daylight hours	Not reported	8.7 hours/day	Field study including ambulatory PA measurement via a pedometer	536	Repeated measures, analysis of covariance	Hours of daylight at 8.7 hours/day revealed no significant main effects on PA
Klenk *et al.*[18]	Physical activity	Daylight	Not reported	Days with short daylight period (9 hours) and a long daylight period (16 hours)	Population-based cohort study including questionnaires, uniaxial accelerometer data and weather data	1324	Linear regression analyses	Between days with a short daylight period (9 hours) and a long daylight period (16 hours) the walking duration increased by 12.6 minutes in men and 13.3 minutes in women. After adjustment for other weather parameters, daylight was no longer significant

SRSL: Self-reported sleep latency; PPD: postpartum depression; PA: physical activity; SPAQ: Seasonal Pattern Assessment Questionnaire; GHQ: General Health Questionnaire; CES-D: Community Epidemiological Survey for Depression; STAI-T: State-Trait Anxiety Inventory-Trait; HRQoL: health-related quality of life.

Davis *et al.*[25] Exposure levels for either light source were not mentioned. More hours of daylight and subsequently the less hours of darkness were associated with lower nocturnal urinary 6-sulphatoxymelatonin (aMT6s) levels. 6-sulphatoxymelatonin is the metabolic end product of the hormone melatonin.

Three other studies[26–28] did not mention the light levels in their methodology section either. They investigated health-related quality of life, self-reported sleep latency and (risk for) depression, respectively. Grimaldi *et al.*[27] found positive results for poor indoor illumination and an increased mental ill-being in their regression analysis. However, it is not clear what the exact contribution of daylight was to this indoor illumination.

Alimoglu and Donmez[29] based their daylight exposure on questionnaire results (categories <1 hour, 1–3 hours and >3 hours). They investigated the link between burn-out, a psychological term for the experience of long-term exhaustion and diminished interest. Since daylight has an impact on human alertness and cognitive responses, Alimoglu and Donmez[29] investigated if daylight exposure in a work setting could be placed among the predictors of job burn-out, but found no direct effect. They did find an indirect effect via work-related stress and job satisfaction. More daylight exposure leads to less stress and higher satisfaction. If this effect is exclusively related to daylight is not proven, since for example Newsham *et al.*[30] found also positive correlations between the (satisfaction with) lighting (daylight and electric lighting) and job satisfaction.

Vreeburg *et al.*[31] researched a combination of factors (both sampling factors and health indicators) and found that, amongst all, sampling month (daylight hours) influenced salivary cortisol levels. Cortisol is important for the hypothalamic–pituitary–adrenal (HPA) axis regulation: 'The HPA-axis is hypothesized to be one of the key biological mechanisms underlying several stress-related disorders, including somatic and psychiatric disorders'.[31]

3.2. Step 2: Specific health keywords

Table 4 shows the results from the search on specific health keywords. The specific health issues with an association with daylight are divided into three categories: 'positive', 'negative' and 'both positive and negative'. Scientific literature sources were obtained via PubMed, Scopus/ScienceDirect, Google Scholar or at an author's personal website.

The most well-known effect of light is on vision. Human day vision (photopic) is regulated by three cone photoreceptors, while vision in dim light (mesopic) is

Table 4 Specific health associations linked to (interaction with) daylight

Positive association	Negative association	Positive/negative association
Improvement of vision (and reduction of depression)	Triggering of migraines	Influence body height and birth weight
Reduction of myopia	Triggering of epilepsy	Influence bilirubin levels and haem catabolism
Reduction of eyestrain (and improvement of relaxation)	Increase chance for autism	Influence sleep problems for people with autism
Reduction of headaches		Induce/modify changes in human gonadal function
Stimulation of circadian physiology and cognitive performance		Influence breast cancer tumours
Improving sleep quality		
Reduction of ADHD prevalence		
Reduction of SAD depressions		
Prevention of obesity		

ADHD: attention-deficit/hyperactivity disorder; SAD: seasonal affective disorder.

controlled by cone and rod photoreceptors, and (almost complete) darkness (scotopic) is regulated by rod photoreceptors. This light input then triggers a response through the optic nerve to the visual cortex in the brain. The primary transition between scotopic, mesopic and photopic vision – the switch from employing solely rod to solely cone photoreceptors – is a direct response to environmental irradiance.[32] Human vision under daylight conditions is normally better than under electric lighting due to the higher quantity (and often a better colour rendering index), enabling better visual performance. Recently, Zhang[33] concluded that self-reported visual function loss, rather than loss of visual acuity, is significantly associated with depression. This study was based on a cross-sectional, nationally representative sample of adults 20 years of age or older ($N = 10\ 480$). It was not possible from this analysis to determine whether depression is a cause or an effect of visual function loss.

Even though myopia (short-sightedness or near-sightedness) can be corrected with glasses, contact lenses and refractive surgery, according to Morgan *et al.*[34] it has emerged as a public health concern since its prevalence is increasing in Asia, North America and Europe. Surveys have shown that increased amounts of time outdoors protect against the development of myopia[35,36]. In a cross-sectional study of two age samples from 51 Sydney schools, children and their parents completed detailed questionnaires on activity and the children had a comprehensive eye examination. The researchers concluded that higher levels of total time spent outdoors were associated with less myopia ($p = 0.04$) and suggested that light intensity may be an important factor. Due to the higher light levels pupils will be more constricted outdoors, resulting in a greater depth of field and less image blur.[35] Periods of 5–7.5 hours of elevated light levels (15 000–28 000 lx) have been found to reduce the amount of myopia in different animal species[36]. Norton and Siegwart[36] concluded in their review that 'retinal dopaminergic activation seems very likely to play a role in the protective effects of outdoor activities in children and the effects of elevated light levels in the animal studies'.

The most common health effect operating through the visual system is eyestrain. Eyestrain is pain and fatigue of the eyes, due to tightening of the ciliary muscle.[37] Cowling *et al.*[38] found that there were significantly less incidents of eyestrain reported by people whose workstations received large proportions of natural light. A total of 310 questionnaires were distributed in nine different buildings and 254 were returned (response rate 82%). Both chi-squared tests and multiple regression analysis were employed. Headaches, severe fatigue and eyestrain were the three conditions canvassed as having some work environment precursor. The majority of respondents reported suffering from all three symptoms, at least occasionally. The triggering source for eyestrain can be electric equipment, lighting or daylight, although the view that comes with a daylight opening can provide a point of relaxation for the eyes (focus in the distance) and higher incident light can reduce the pain.[37] Eyestrain is often accompanied by headache, resulting from prolonged use of the eyes, uncorrected defects of vision or an imbalance of the eye muscles.[2,37,38] The decrease in headache incidence with daylight illuminance increase was assessed in the study of Wilkins *et al.*[37] using a Jonckheere non-parametric trend test based on the data of $N = 20$ people and corrected for age and seniority (superiority). The illumination from daylight increased with the height of the office above the ground by an average of 80 lx per storey (measured at the work surface on a sunny day). Headaches tended to decrease with increasing storey level ($z = 2.13$, $p < 0.02$, one-tailed, before lighting change). Robertson *et al.*[39] compared two buildings and 106 out of 109 (97%) workers completed a health questionnaire. The researchers found a significantly higher prevalence of work-related headache in the building with less daylight and lower mean luminances and illuminances of the work positions (even with electric lighting on) compared with the other building ($p < 0.001$). The building with less daylight was air conditioned and the headache could therefore be related to either an interaction between daylight and ventilation or related to the ventilation type only.

Migraine is a recurrent moderate to severe headache. The triggering of migraine is hypothesized to start in the visual cortex. Amongst other things, people who suffer from migraine are more sensitive to light than other people (which is also described as photophobia).[37,40] The high level of daylight and often occurring large contrast causing glare makes this light source a potential trigger for migraine.[2] Results of a reviewed study in Mulleners *et al.*[41] indicated that patients with migraine, both with and without an aura, have lower thresholds for visual stress than control subjects. Daylight, especially in the window zone, usually provides much higher light levels than electric lighting.

Photosensitive epilepsy (PSE) is a form of epilepsy in which seizures are triggered by visual stimuli that form patterns in time or space. PSE can start due to lamp flicker (with a frequency of 15 Hz), but this frequency is not dominantly present in daylight. If daylight enters a space through a moving filter, PSE can occur.[2] For example, daylight shining off water or through the leaves of trees can trigger seizures. In their book, Harding and Jeavons[42] show multiple cases and studies where seizures had been precipitated by flickering sunlight.

People with autism have a chronically high level of arousal and high levels of daylight are arousing.[2,43] The variability of daylight can create a stimulating environment, which for most people would be preferable, but not for people with autism. However, exposure to daylight's seasonal variation has positive influences on people with autism. Hayashi[44] reported in a case report on seasonal changes in sleep problems and behavioural problems in an adolescent with autism over the year. Sleep problems decreased from January to June, and disappeared in July and August. Most of the behavioural problems (i.e. crying) decreased gradually from January to June. The subject was one 15-year-old autistic male. Recently, Mazumdar *et al.*[45] showed evidence of seasonality in the risk of conceiving a child later diagnosed with autism. They authors applied a one-dimensional scan statistic (with adaptive temporal windows) on case and control population data from California, USA for the years 1992 through 2000 (with $>$400 000 births per year).

Foster and Roenneberg[46] state that 'despite human isolation from seasonal changes in temperature, food and photoperiod in the industrialized nations, the seasons still appear to have a small, but significant, impact upon when individuals are born and many aspects of health'. Using a large US human male population of 507 125 people, Weber *et al.*[47] found clear evidence for a dependence of body height at age 18 on birth month. Over a period of 10 years there is a sinusoidal variation with a period of 1.0 year with maxima in spring and minima in autumn differing by 0.6 cm, a difference of 0.3% associated with a changing photoperiod (height $M \pm SD = 177.2 \pm 0.33$ cm with 0.057 cm/year secular trend; sunshine duration $M \pm SD = 144 \pm 65$ hours with a trend of 10.69 hours/year). They linearly interpolated both datasets, generated a Fourier spectrum and produced a Lomb–Scargle periodogram. The authors cannot offer definitive explanations but hypothesize that the underlying physiological mechanism might involve the light-dependent activity of the pineal gland. Also Wohlfahrt *et al.*[48] found a circannual variation in length at birth in a population-based cohort of 1 166 206 children born in Denmark. The circannual variation of 2.2 mm in length at birth is compatible with the 6 mm variation of Weber *et al.*[47] Additionally, they showed that discrepancies in measurements over the seasons are not likely, since they also found seasonal variations in birth weight, which is often more accurately measured. Details related to procedures and statistical outcomes are not mentioned. Seasonal variations were also found related to bilirubin levels in newborns. Bilirubin is the yellow breakdown product of normal haem catabolism occurring naturally when red blood cells die. Anttolainen *et al.*[49] found a significantly lower bilirubin value from the fifth day of life onwards in a group of Finnish infants born during the light half of the year (maximum of 22 hours of daylight), compared with infants born during the dark half of the year (maximum of 3 hours of daylight). In total, 86 preterm infants born consecutively during one calendar year were studied.

Many aspects of human physiology and behaviour are adapted to the 24-hour light/dark cycle generated by the Earth's rotation. This 24-hour rhythm has a major impact on human health and well-being,[50] and all peripheral organs have autonomous, light-responsive oscillators. The 24-hour, or circadian, clocks use daylight to synchronize (entrain) to the organism's environment.[51] Studies from Roenneberg *et al.*[52] strongly suggested that the human circadian clock is predominantly entrained by sun time rather than by social time. In 2001, two research groups[53,54] used the effect of light to suppress nocturnal human melatonin secretion as a marker of an effect on the circadian system. The observed action spectrum for melatonin suppression showed short-wavelength sensitivity very different from the known spectral sensitivity of the scotopic and photopic response curves. The non-visual alerting effects of light during night time appear to be related to melatonin suppression.[55] The alerting effects during the daytime (when melatonin is not present) occur through different pathways. According to Cajochen,[56] it is more likely to be the ventromedial preoptic area. Not only blue light ($\lambda_{max} = 460$ nm) but also green light ($\lambda_{max} = 555$ nm) elicits non-visual responses to light, such as resetting circadian rhythms, suppressing melatonin production and alerting the brain.[57] The sensitivity of the human alerting and cognitive response to polychromatic light at levels as low as 40 lx is blue-shifted relative to the three-cone visual photopic system.[58] Daylight intensity is most of the day much higher than 40 lx and will certainly have a significant impact on circadian physiology and cognitive performance (alertness). It also contains the full spectrum, with changing composition over the day. Daylight not only has its impact during the day but also at night daytime light exposure can play a role. Recently, Cheung *et al.*[59] reported their results of workplace daylight exposure on sleep quality (Pittsburgh Sleep Quality Index), physical activity and quality of life. Employees ($N = 49$) with a window in their workplace got significantly more natural light exposure ($p < 0.05$) and their actiwatches registered on average 47 minutes more sleep ($p < 0.05$).

Arns *et al.*[60] studied the relationship between the prevalence of attention-deficit/hyperactivity disorder (ADHD) and solar intensity (SI) on the basis a cross-state (study 1) and multinational study (study 2). In the datasets, a significant relationship between SI and the prevalence of ADHD was found (Study 1: 2003: $p < 0.000$; $r^2 = 0.637$, 34% variance explained; 2007: $p < 0.000$; $r^2 = 0.580$; 41% variance explained; Study 2: $p = 0.018$; $r^2 = -0.758$, 57% variance explained). Approximately, 80% of adult ADHD patients and one-third of children with ADHD suffer from sleep onset insomnia, characterized by a delayed circadian phase and delayed melatonin peak, which could be the result of increased use of modern (social) media (iPads, mobile phones), especially shortly before bedtime. According to the researchers 'the apparent preventative effect of high SI [solar intensity] on ADHD [attention-deficit/hyperactivity disorder] prevalence might thus result from the ability of intense natural light during the morning to counteract the phase delaying effects of modern media in the evening, thus preventing the delayed sleep onset and reduced sleep duration'.[60]

Seasonal changes in day length (photoperiod) and linked night length (scotoperiod) induce changes in the duration of melatonin secretion at night. The duration of nocturnal melatonin secretion is longer in winter than summer and triggers seasonal changes in behaviour.[61–63] In general, alterations in monoaminergic neurotransmission in the brain are thought to underlie seasonal variations in mood, behaviour and affective disorders.[64] SAD is a syndrome characterized by recurrent depressions that recur every autumn/winter. The lack of sufficient natural daylight in winter is often thought to be the reason behind SAD.[63,65] The reduction of depression due to exposure to daylight is not fully understood yet. Several researchers have shown that the prevalence of self-reported depression was surprisingly low in winter (SAD-season) considering the lack of daylight.[21,22,66] The study of Lambert *et al.*[64] showed that the turnover of the monoamine neurotransmitter serotonin by the brain was lowest in the Australian winter (non-SAD-season). Serotonin has a role in the development of seasonal depression. The rate of production of serotonin by the brain was directly related to the prevailing duration of bright sunlight ($r = 0.294$, $p = 0.010$), but it was not related to the hours of sunlight on the day before the study. The authors also found that, irrespective of the month of the year, turnover of serotonin in the brain was affected by acute changes in light intensity, with values being higher on bright days than on dull days.[64]

Season of the year is known to affect the nocturnal rise in melatonin[67]. Melatonin is involved in a variety of diseases, including cancer, insomnia, depression, dementia, hypertension and diabetes. The daylight photoperiod was specifically linked to breast cancer. Women with malignant tumours appeared to have significantly lower 24-hour concentrations of aMT6s (6-sulphatoxymelatonin) compared with women with benign tumours. A study by Obayashi *et al.*[68] showed that daylight exposure (at least 1000 lx between 37 and 124 minutes, mean 72 minutes) in an uncontrolled daily life setting is positively associated with urinary 6-sulphatoxymelatonin excretion in the elderly.

Environmental lighting can induce or modify changes in human gonadal function. A study with blind versus non-blind girls showed that puberty developed earlier than normal in blind girls. In a study with rats, nocturnal animals, puberty developed later than expected in blind laboratory rats. The difference was explained by the fact that humans are active diurnally.[69] A more recent statistical analysis by Flynn-Evans *et al.*[70] was conducted to determine whether differences exist in reproductive measures among blind women ($N = 1392$) with at least light perception (LP) compared with women with no perception of light (NPL) in a cohort study. Student's two-sample *t*-tests and multivariate logistic or linear regression were conducted to get statistical results. The findings suggested as well that lack of LP affects reproductive development in women (odd's ratio NLP vs. LP from birth was 0.88; 95%). A parallel study based on the same group of women by Flynn-Evans *et al.*[71] used multivariate-logistic regression models. These showed that blind women with NPL appear to have a lower risk of breast cancer, compared with blind women with LP (odds ratio, 0.43; 95%), the indirect effect of light may go far beyond the influence on glandular functions only, potentially with a role for urinary 6-sulphatoxymelatonin and melatonin.

Regular physical activity is crucial for human health and it stimulates the level and duration of independence of older people. Weather is widely believed to influence people's health, mood and their physical activity level. Particularly among older people, physical activity levels are much higher in summer than in winter. Day length, sunshine duration and maximum temperature have a significant influence on physical activity levels.[72] Brown adipose tissue (BAT) is present in adult humans and may be important in the prevention of obesity. The study of Au-Yong *et al.*[73] demonstrated a very strong seasonal variation in the presence of BAT relating to ambient temperature and photoperiod. This effect was more closely associated with photoperiod ($r^2 = 0.876$) than ambient temperature ($r^2 = 0.696$). The authors studied 3614 consecutive patients and performed a χ^2 test.

4. Discussion

4.1. The influence of daylight on health: The scientific evidence

Humans have evolved under the influence of daylight and its light–dark cycle. This is probably why people believe that daylight is positively related to human health. Some of the found and investigated studies reported results on 'general health'. More specific health issues reported are either physiological (work-related headache, activity level, heart attack/myocardial infarction, insomnia and breast cancer) or psychological (depression, burn-out, SAD, mental distress and suicide). Objective health measurements that are used are 'activity' (by means of an accelerometer, actiwatch or pedometer), 'salivary cortisol' (samples) and database contents regarding 'heart attack' and 'suicide'. The results found when searched for more specific relations are also either physiological (visual acuity, eyestrain, headache/migraine, epilepsy, autism, body height, birth weight, bilirubin levels, serotonin levels, human gonadal functioning, breast cancer and obesity) or psychological (alerting effects, burn-out and SAD). The fact that effects of daylight were more frequently found when searching under specific medical conditions suggests that much of the current literature is aimed at solving medical conditions instead of providing healthy indoor environments.

The found studies in the two databases search were rather limited. It was expected to find more studies. Moreover, different scientific proof regarding daylight and health effects was actually found by searching on effects directly, which shows there may be a missing link in choice of words for titles, abstracts, search options or key words.

The studies in the two databases were all checked for several information elements, necessary to assess the initial quality of the study. The results show that all but one of the selected studies reported on the used methods and statistical outcomes. It was striking that illuminances or light exposure were only very occasionally documented. Only one paper, by Mottram *et al.*[15], reported actual illuminances with regard to daylight exposure. The lack of daylight levels makes it hard to find a consistent conclusion regarding daylight influence, especially since the intensity and duration of daylight changes over the day and year. Also the distinction between exclusive daylight exposure or a combination of daylight and electric lighting is not documented, which makes a conclusion relating the effect of daylight impossible.

Multiple studies have found a significant influence of the difference in daylight hours per day (photoperiod). The focus of all studies was on daylight in general or the photoperiod specifically. No research was found related to the dynamics of daylight, other than day length.

Multiple studies used techniques that focus on obtaining subjective results (self-reported health effects, SAD-questionnaire answers, etc.). In some cases, questions were not specifically designed for daylight and health research, but were part of a more extensive questionnaire related to general health. The questionnaires reported are, therefore, very different, and in most cases a copy of the questions was not available via the paper. Some studies reported results on 'general health'. No specific questionnaire focusing on daylight and health was found.

Most found studies were executed with daylight as light source; some studies used a combination of light sources (daylight and electric lighting). However, conclusions are not always exclusive to daylight only. For instance, studies that prove that daylight makes people more or more efficiently alert than electric lighting or show the effect on gonadal functioning and breast cancer exclusively related to daylight rather than to electric lighting do not exist (yet).

4.2. Daylight quality

In 1929, the French architect Le Corbusier said that 'the history of architectural material . . . has been the endless struggle for light . . . in other words, the history of windows'. Most architects are devoted to daylight since they know that no other building component has such a significant impact on their design of a building than daylight openings.

People in the Western world spend approximately 80–90% of their time indoors and therefore buildings play an important role in providing a healthy daylight environment. Daylight exposure outdoors means full exposure to solar radiation with all possible positive and negative health effects. Indoors, people's exposure is basically limited to visible and IR radiation, even though glass innovations attempt to limit the IR contribution significantly due to thermal discomfort. The design of the building and its floor plans largely dictates how the building can and will be used. Humans overwhelmingly prefer working, learning and sitting near daylight openings,[1] provided thermal or visual discomfort are absent. The current design of buildings does not allow this for all users.

The reason why people prefer a window seat cannot entirely be explained. It is unknown whether there is a connection or association with health or comfort effects. Potential reasons are the relationship with the view outside with its inextricable supply of information/view, the quantity of daylight (both high and low), the presence of the full continuous spectrum, the (change in) directionality and/or the dynamics from milliseconds to months. The maximal seating distance to the window for a good daylight experience is not known.

The dynamics in daylight availability vary from months to milliseconds. Many health effects are stimulated via ocular light exposure, and the origin of the trigger (i.e. photoperiod) can be far in the past (i.e. before or at birth). The brain structures and functions to measure changes in day length are still present in humans, though mostly not directly apparent. Much stronger is the existence of a circadian rhythm as manifested by the sleep/wake cycle. The endogenous rhythm of the human body clock is usually slightly longer than 24 hours and thus needs a daily morning light signal to reset the clock to entrain with the Earth's 24-hour rotation rhythm and the changing photoperiod. Health effects as a result of different levels of daylight variations are largely unknown. Additionally, variations in light dynamics are introduced by lighting in computer screens, electric lighting or lighting and shading controls. These manmade frequencies can support, substitute or counteract daylight frequencies, and therefore trigger or reduce health effects. Certain effects of daylight are related to the moment of birth and the photoperiod. These effects have no consequences for the design of the built environment, but demonstrate potential unknown influences of the changing photoperiod.

The daylight spectrum represents all wavelengths of the solar visual spectrum. Studies related to isolated parts of the sunlight spectrum are not known, but studies with electric lighting are available. For example, Brainard *et al.*[54] and Thapan *et al.*[53] found effects of the bluish part of the light spectrum ($\lambda_{max} = 459$–482 nm) on the suppression of nocturnal melatonin. Gooley *et al.*[75] found that short-duration (<90 min) exposure to light from the greenish part of the light spectrum ($\pm\lambda = 555$ nm; ≤ 24 lx) was as effective, if not more effective, than an equivalent photon dose of 460-nm light (≤ 2 lx) in causing a circadian phase shift.

Sahin and Figueiro[76] found that a 48-minute exposure to short-wavelength (blue) light (40 lx, $\lambda_{max} = 470$ nm) and long-wavelength (red) light (40 lx, $\lambda_{max} = 630$ nm) equally affected human electroencephalogram measures indicating that acute melatonin suppression is not needed to elicit an alerting effect in humans. Interaction effects between different wavelengths and intensities are not further studied in the study of Sahin and Figueiro.[76] However, Brainard *et al.*[54] and Thapan *et al.*[53] performed a full action spectra analysis for melatonin suppression and both found a greater sensitivity of melatonin suppression to shorter wavelength light. The study of Gooley *et al.*[75] suggested a wavelength-dependent effect on circadian phase shift. This implies that multiple, if not all, parts of the light spectrum, at different intensities play a role in triggering human visual and non-visual effects. Glazing is able to filter certain parts of the radiation spectrum, depending on the type. The question whether full-spectrum electric lighting can replace daylight is not proven. According to some studies[77,78] there is evidence that full-spectrum electric lighting has comparable influence on, for example, cortisol and stress-related effects. However, the review of McColl and Veitch[79] revealed little support for it.

Human vision under daylight conditions is normally better than under electric lighting due to the higher quantity (and often a better colour rendering index), enabling better visual performance. Indirectly, vision can influence the occurrence of depression. The sensitivity of the human alerting and cognitive response to polychromatic light at levels as low as 40 lx is blue-shifted relative to the three-cone visual photopic system.[58] Daylight intensity is much higher than 40 lx during most of the day. Alerting affects general human physiology and behaviour: The human body evolved and adapted in order to react to external triggers, with the 24-hour day/night cycle as one of the most important ones. People tend to prefer the high light levels of daylight, but do not (always) follow the natural variation in daylight.[80] High radiation intensities are not always desired since this radiation contains a lot of energy which influences the heat load of the building. However, high light levels are beneficial for groups such as older adults who require more light to perform well visually, but the opposite is true for people who suffer from migraine or have autism. There is a potential link between daylight and the incidence of migraine. Daylight openings without or with inadequate luminance screening or shading devices can lead to a large contrast between the daylight opening and the interior walls surrounding the opening. Cowling *et al.*[38] concluded that working in a building with highly reflective windows and the presence of blinds/curtains suggested the lowest frequency of severe fatigue and eyestrain. Complaints of eyestrain may be related to those of headache by a common neurological mechanism.[37,80] In order to reduce triggers for neurological attacks due to the high levels of daylight and often occurring large contrast, controllable protection should be provided.

Aries *et al.*[82] found that both view type and view quality had a significant influence on physical and psychological discomfort. In this research, only the view itself was taken into account, despite possible differences in view luminance. Surprisingly, nature views increased discomfort directly while view quality negatively predicted discomfort (better quality view was associated with lower discomfort). In relation to eyestrain, people should have the possibility to focus on distant objects, for example, by means of a view outside. At the same time, the minimum distance is yet unknown. This may be relevant for the further development of (virtual) windows and the basic design of buildings and the surrounding landscape.

4.3. Practical implementations

Even though the majority of relevant information regarding daylight and health design is not known or only very limited and much more research is necessary, some first practical implementations for building design are shown in Table 5. Nevertheless, these first recommendations can be followed by architects and building physicists during the design of buildings and rounds of consultancy.

5. Conclusions

There is only limited statistically significant and well-documented scientific proof for the link between daylight and its potential health consequences, despite the omnipresent attention this supposed relation is receiving. This may sound rather counterintuitive. Nowadays, humans spend the majority of time indoors, where they are often exposed to poor lighting, both in terms of quality and quantity. The amount of daylight people are exposed to indoors via windows is lower than the exposure outdoors. Further research is required to establish the nature of why some people prefer non-visual stimulating lighting and others do not. Also, dose–response curves for alertness, performance and mood to daylight need further investigation. In order to ensure that the effects due to daylight exposure are not only applicable to people with certain (health) conditions, future work should focus on the effect of daylight on the health of the general population.

Fortunately, the search on specific health keywords produced more results, which were divided into three categories according to their association with daylight: 'positive', 'negative' and 'both positive and negative'. Nevertheless, the improvement regarding choice of words in titles, abstracts, search options or key words could help finding scientific evidence or knowledge gaps. If the relation between daylight and health is fully understood and actually

Table 5 First practical implementations for daylight and health building design

Create daylight openings that can be opened to allow occasional exposure to the full radiation spectrum (including ultraviolet and infrared radiation)
Design buildings with floor plans that stimulate people to go outdoors, either via the ground floor or via (protected) verandas and balconies; independent of the weather conditions
Aim for rooms with relatively high daylight levels ($E > 2000$ lx on average vertically) and provide controllable sunlight and luminance protection (blinds, screens, etc.) on all daylight openings. The shading/protection gives people the opportunity to control and dose the entering light for the prevention and reduction of eyestrain, headaches, migraines, discomfort or disability glare, or photosensitive epilepsy, but maintains the option to have enough daylight quality and quantity for, for example, older eyes
Provide automated controls over blinds, luminance screens and shading that allow daylight access to the fullest. Especially in periods with sunrise and sunset during work time (winter time on the northern hemisphere), the daylight opening should be uncovered to expose people to the change in photoperiod. However, users should be able to override the automated control at all times in order to meet personal comfort and health criteria (see also the previous implementation)
Apply glazing that allows the transmittance of full-spectrum light in order to provide indoor lighting with all parts of the visual spectrum represented so interaction effects between different wavelengths and intensities can naturally occur and are undisturbed

scientifically proven, future daylight design in buildings will no longer be a mere recommendation, but an obligation.

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