DLA
DAYLIGHT ACADEMY

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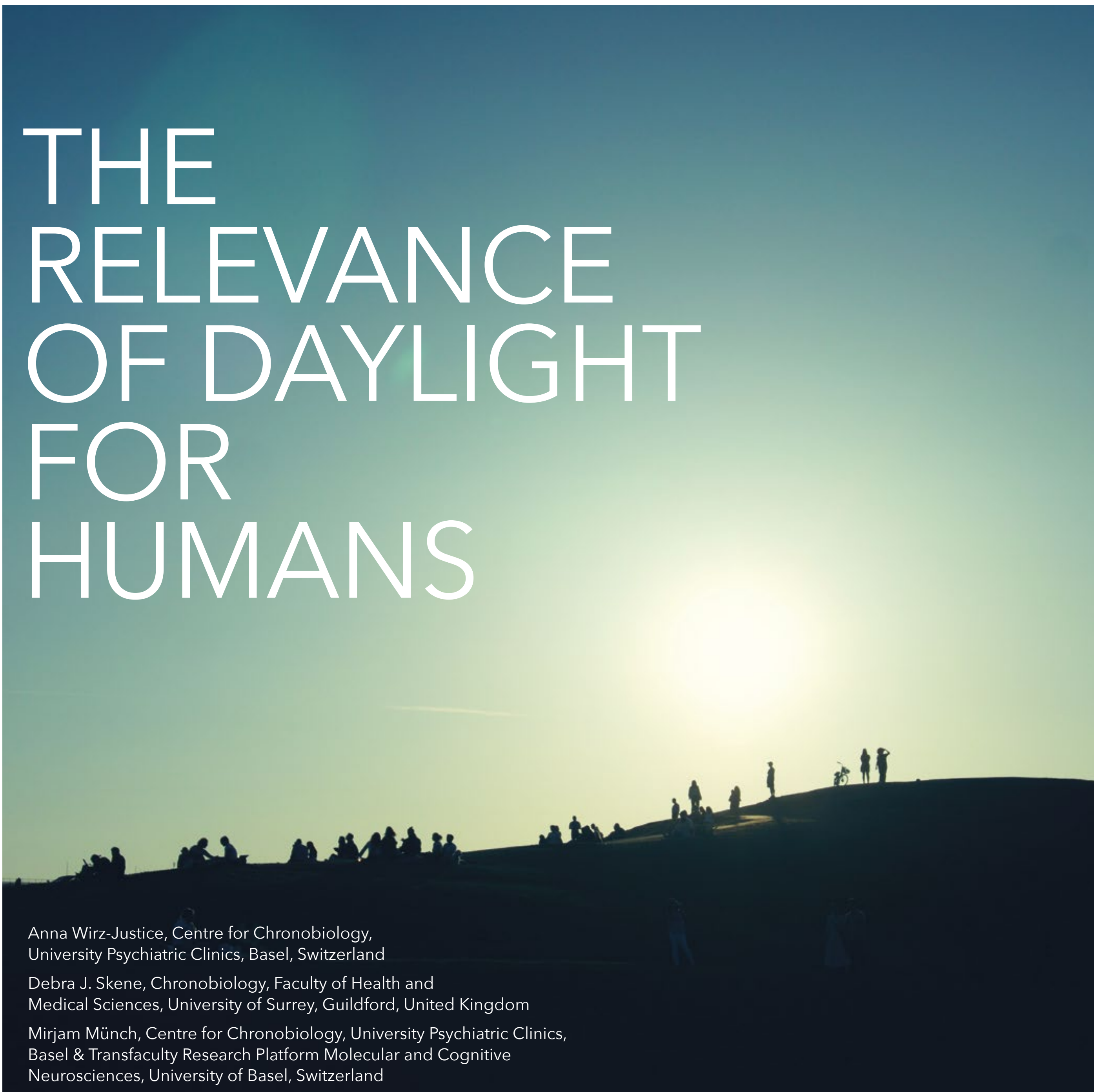


THE RELEVANCE OF DAYLIGHT FOR HUMANS

Anna Wirz-Justice, Centre for Chronobiology,
University Psychiatric Clinics, Basel, Switzerland

Debra J. Skene, Chronobiology, Faculty of Health and
Medical Sciences, University of Surrey, Guildford, United Kingdom

Mirjam Münch, Centre for Chronobiology, University Psychiatric Clinics,
Basel & Transfaculty Research Platform Molecular and Cognitive
Neurosciences, University of Basel, Switzerland

Daylight is ubiquitous and is crucial for mammalian vision as well as for non-visual input to the brain via the intrinsically photosensitive retinal ganglion cells (ipRGCs) that express the photopigment melanopsin. The ipRGCs project to the circadian clock in the supra-chiasmatic nuclei and thereby ensure entrainment to the 24-hour day-night cycle, and changes in daylength trigger the appropriate seasonal behaviours. The ipRGCs also project to the perihabenular nucleus and surrounding brain regions that modulate mood, stress and learning in animals and humans. Given that light has strong direct effects on mood, cognition, alertness, performance, and sleep, light can be considered a "drug" to treat many clinical conditions. Light therapy is already well established for winter and other depressions and circadian sleep disorders. Beyond visual and non-visual effects via the retina, daylight contributes to prevent myopia in the young by its impact on eye development, and is important for Vitamin D synthesis and bone health via the skin. The sun is the most powerful light source and, dependent on dose, its ultraviolet radiance is toxic for living organisms and can be used as a disinfectant. Most research involves laboratory-based electric light, without the dynamic and spectral changes that daylight undergoes moment by moment. There is a gap between the importance of daylight for human beings and the amount of research being done on this subject. Daylight is taken for granted as an environmental factor, to be enjoyed or avoided, according to conditions. More daylight awareness in architecture and urban design beyond aesthetic values and visual comfort may lead to higher quality work and living environments. Although we do not yet have a factual basis for the assumption that natural daylight is overall "better" than electric light, the environmental debate mandates serious consideration of sunlight not just for solar power but also as biologically necessary for sustainable and healthy living.

Content

1. Introduction

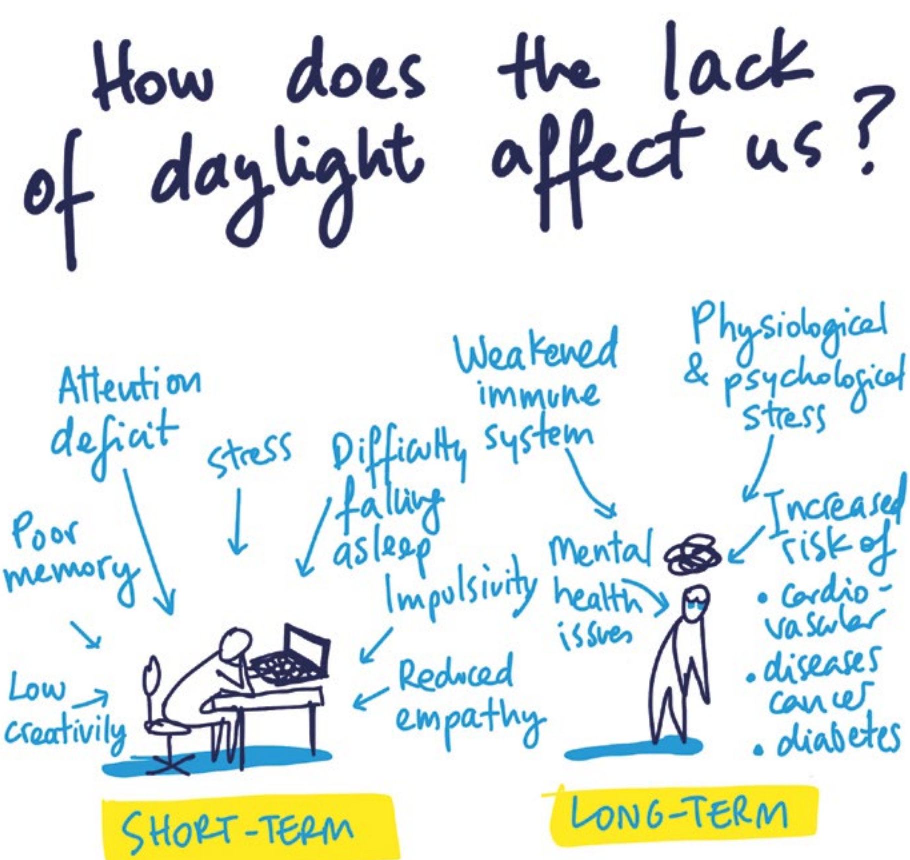
The last decades have seen a remarkable unravelling of the molecular secrets of the circadian clock in living organisms. In mammals, circadian rhythms in cells, tissues and organs are generated by self-sustained molecular core transcription-translation feedback loops [1]. We have learned a great deal about the synchronisation of the clock to the external day-night cycle, and the effect of different wavelengths, intensities, and timing of light on human physiology and behaviour. Dawn – dusk simulations have revealed the innate sensitivity of the clock to the gradually changing low light intensities found in nature [2], and clinicians have used artificial bright light to treat mood and sleep disorders [3,4].

The field of biological rhythms is thereby truly interdisciplinary (bench to bedside and back again), where psychiatrists understand the formal properties of the circadian system, and cell biologists may contribute with experimental knowledge to improve sleep/wake functions.

Light research has primarily been carried out under controlled laboratory conditions, using defined light–dark environments and timed application of artificial light. Given that the evolution of circadian clocks and entrainment to the 24-hour light–dark cycle occurred under naturalistic conditions long before the invention of electricity and use of light sources other than the sun, it seems appropriate that light research should now move towards understanding the impact of daylight on human physiology and psychology under field conditions, even though such research is much more difficult due to the unpredictable and less controllable variations of environmental light [5]. Recently, under the auspices of the Daylight Academy, we published two focus papers related to daylight research: "Daylight: What makes the difference?" [6] and "The role of daylight for humans: Gaps in current knowledge" [7]. Although we know the physical differences between daylight and electric light quite well, it is technically extremely difficult to mimic all the properties of natural light with electric light and combine it into one light source (i.e. spectra, dynamics, temporal variations, rate of change, spatial light distribution, flicker frequecies, polarisation [5,7]). Maybe it is this "uniqueness" which implies that natural light is superior to electric light. The specific benefits of daylight probably go beyond subjective preference or the positive symbolism of the sun, but we do not yet have the data to support this assumption.

In everyday life, exposure to daylight is diminished by buildings and defined by their apertures to the outside; daylighting design is complex, and a view is an additional, crucial factor. Temperature also plays an important role – extreme heat and cold keep people indoors and create new engineering tasks to adequately adjust temperature in the indoor environment. Lastly, geographical, cultural aspects as well as societal practice and standards determine individual in- and outdoor-related behaviour. Here we focus on new developments that may stimulate real-life field studies.

Daylight Awareness Week 2020



Illustrated by Marina Roa from SenseTribe

2. What is daylight?

Daylight is direct and indirect electromagnetic radiation from the sun, which is altered by different reflections and conveyed and filtered through the atmosphere. The duration and availability of daylight depends on geographical latitude, season and atmospheric conditions. Daylight has a broad continuous spectral power distribution, changing within and across days and with weather and sky conditions in absolute power (irradiance), colour, diffuseness, polarity and direction. Outdoors on a sunny day light intensity (illuminance) varies between 20,000 and 100,000 lx, is around 3,000 lx when it rains, and up to 1,000 lx during civil twilight. Indoors, daylight fluxes are usually much lower and decline exponentially with distance from windows. The highly dynamic pattern of daylight contrasts with the (almost everywhere) constant availability of electric light. Additionally, depending on the light source (incandescent, fluorescent, or LED), the spectral power distribution of the lights are quite different from each other and from daylight, even though they may all be perceived as "white" light [6].

3. Light input to the eye and brain

In mammals, light reaching the retina is crucial for vision (motion, spatial detail, colour), transduced into electrical signals in the rods and cones. Light is also important for non-visual input to the brain via a subset of intrinsically photosensitive retinal ganglion cells (ipRGCs) that express the short-wavelength-sensitive photopigment melanopsin. The ipRGCs project to the circadian clock in the suprachiasmatic nuclei (SCN), where they release glutamate and PACAP. GABA is the most prevalent neurotransmitter in the SCN, co-expressed in VIP, AVP and GRP- expressing neurones. SCN cellular oscillators can be synchronised to one another to produce a precise, coherent output signal, mediated by synaptic and humoral factors [8]. The ipRGCs thereby mediate entrainment of the circadian clock in the SCN to the 24-hour light–dark cycle, modify sleep, alertness, pupil size and many more physiological functions. They also interact with other retinal ganglion cells to convey visual and non-visual light input [9]. These two photic systems were long considered independent, however newer evidence indicates interactions in animals [10,11], and in human visual perception [12,13], e.g. melanopsin-mediated information via the primary visual cortex [14]. The complexity has expanded even more since the finding that visual responses at all levels from ipRGCs to the primary visual cortex and retinal activity are modulated by arousal state [15], and with the discovery of new GABA-ergic pathways in animals [16].

The range of central nervous system functions found to be affected by light continues to grow. The most important – now classical – zeitgeber role of light, is to synchronise and shift circadian rhythms. Daylength (and rate of change of daylength) triggers seasonal responses, and the day-night transitions at twilight are crucial. Not only does light directly increase alertness, but daytime exposure appears to modify night-time sleep [17]. The mood-enhancing effects of light (known from clinical applications) are mediated not only by circadian mechanisms but also by a SCN-independent pathway linking ipRGCs to the perihabenular nucleus (PHb), itself close to neurons modulating mood and stress [18].

Photic information to the PHb can also influence learning separately from the circadian role of the SCN [18]. The habenulae are small paired nuclei in the brain contributing to many cognitive and motivational functions and are additionally part of the circadian circuitry. In both animals and humans, habenular neurones respond to retinal illumination with a time of day dependency [19,20].

It is clear that further studies of such basic mechanisms relating to the eye and its signalling pathways to the brain and the neurotransmitters involved will remain laboratory based, using controlled and well-defined electric light sources. However, understanding these basic mechanisms will help define, direct and analyse daylight data from field research.

4. Lack of daylight

There are two major epidemiological developments related to daylight (or rather, lack of daylight). A widespread and growing occurrence of myopia in the young is a worrying trend, particularly in Asia [21]. It starts between 4 and 6 years of age or later, and even though wearing glasses can correct vision, it cannot stop the progression of myopia [22]. Exposure to natural light has been shown to be protective against the development of myopia in many species including young humans [22], such as being outdoors for 2–3 h daily and reducing the hours of near-work activities under low light levels combined with breaks [22,23]. A few hours of daylight exposure outdoors each day seem to be the simple "miracle" preventive prescription [22,23]. The biochemical pathways that lead to myopia-inducing eye growth are not fully understood. Mechanisms related to retinal dopamine, that is stimulated by light, control the growth of the eye [23]. Involvement of circadian regulation on refractive development in myopia has also been suggested [24].

Not only myopia, but more generally, children's health in the digital age appears to be at risk with increased screen time [25]. Well known is the delay of sleep timing found in young people using blue-emitting screens of mobile phones or tablets in the evening. The developing child's lack of natural daylight exposure, a major consequence of increased time spent indoors online, is correlated with multiple health risks ranging from physiological disorders (sleep, obesity), psychological problems (depression, anxiety), and cognitive impairment [25]. Key neurotransmitters widespread in brain neuronal networks are involved. For example, serotonin is a crucial neurotransmitter linked with mood and circadian regulation; dopamine regulates the brain's reward circuits (motivation, attention) and movement centres [26].

Vitamin D is essential for bone development and health. We know that without Vitamin D bones can become soft, thin and brittle (rickets, osteoporosis). New data suggest that Vitamin D, synthesised by ultraviolet-B in daylight reaching the skin, is additionally linked to the circadian system and the sleep-wake cycle, possibly through the immune system [27–29] or the newly discovered melanopsin-photosensitive system in human skin [30]. Immune responses are also regulated by central and peripheral circadian clocks [31]. Their proper coordination is crucial for adaptive immunity, such as for protective antibody production after vaccination (e.g. via T and B-cells). The responses also vary with time of day [32,33], season [34] and sleep [35]. Low Vitamin D levels are associated with a higher risk of COVID-19 infection [29]; a recent study of a Vitamin D metabolite administered to hospitalised COVID-19 patients showed significantly reduced intensive care unit admission [36]. These findings open up entirely new interactions of daylight with clocks, sleep, and immunological health, with emphasis on the current pandemic COVID-19 situation worldwide [37].

5. Light and mood disorders

The link between affective disorders and circadian rhythms has a long history (reviewed in [38,39]), in that altered sleep-wake cycles and periodic mood shifts have been documented since the early psychiatric literature. In our modern times it has been found that imposed circadian disruptions due to shift work, light at night, and transmeridian flight promote affective symptoms in vulnerable individuals [39,40]. Animal models suggest that even short-term exposure to nighttime light can trigger depressive-related symptoms [41]; irregular light schedules act directly via ipRGCs to increase depression-related behaviours and learning, reversible with antidepressant drugs [42]. On the other hand, bright light is an established antidepressant for seasonal and other depressions [38]. A daily walk outdoors can similarly improve mood in SAD [43]. Additionally, increased electric light [44] or mixed (day-) light exposure can ameliorate mood in neurodegenerative diseases [45].

Again, linking to today's COVID-19 pandemic, daylight might be helpful in limiting both the psychiatric sequelae of hospitalisation [46] and the probability of infection itself: through the antidepressant effect of bright light, and its disinfectant properties [47,48].

6. A future with daylight?

The climate change and the environmental debate [49] mandate serious consideration of sunlight not just for solar power but also for health. Even though the new generation of LEDs can approach the spectral distribution of daylight and are programmable in terms of intensity and Correlated Colour Temperature throughout the day to simulate daylight as well as the crucial dawn-dusk transitions, a new focus on natural daylight is required in architectural solutions to attain better energy efficiency. There remain key gaps of knowledge in daylight research related to uncertainty as to the 'daylight quantity and quality needed for 'optimal' physiological and psychological functioning and general health' [7]. We still do not have standardised tools to accurately and continuously measure individual daylight (and electric light) exposure across multiple time scales including spectral composition [5]. Not only is the daily exposure to a given light intensity, duration, wavelength and timing important, but the modification by prior light exposure, age, eye problems, medication etc. needs to be documented and integrated into optimisation of (day-)light exposure. We need consensus on methodologies to determine the effects of daylight on visual, psychological, and somatic functions, as well as a better integration and exchange of daylight knowledge bases from different disciplines (Fig. 1).

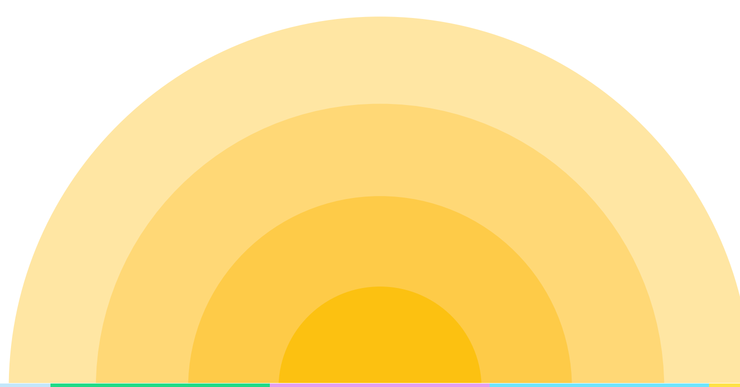
On a broader scale, this means translation into appropriate design for daylight-enhanced buildings and urban settings. The research problem is clear: daylight as a dynamic natural source is difficult to control, predict, or replicate. Can we develop a metric to measure the "naturalness" of light? And can we determine if and how the effects of daylight are different from the effects of electric light? It is clear that in everyday life we move between daylight and electric light, so that the consequences of exposure to a pure naturalistic photoperiod can only be measured in communities living isolated far from artificial light sources [50], or camping in the wild [51].

And lastly, daylight may also be efficiently used to strengthen circadian entrainment (e.g. in hospitals) in order to improve efficacy and reduce side effects of any therapeutic intervention. The timing of an individual's clock is relevant for the timing of drug administration, and the timing of treatment in turn modifies its effects [52–54].

A list of the gaps in knowledge about the impact of daylight on humans can be found in [7]. Given the growing recognition of the importance of *Circadian Rhythm and Sleep-wake Dependent Regulation of Behaviour and Brain Function* (a special issue of *Biochemical Pharmacology* [Vol 121, 2021]) in relation to health and well-being, our two "white papers" on daylight [6,7] provide a detailed blueprint for future research.

In summary, we need more evidence-based data to support the premise that access to natural daylight is necessary and advantageous for sustainable and healthy living. The circadian and sleep community is intellectually rich enough to meet this research challenge to define the necessary parameters, but will need to interact better across disciplines and develop an updated theoretical framework, in which it will be crucial to integrate the findings of daylight research, thus creating the groundwork for beneficial community applications.

Fig. 1. Short overview of the most important functions of daylight (first row), its realisation (second row) and the main content this article addresses (third row).



Functions of daylight	Reflection of the environment	Reduce risk of myopia	Bone health, Immune system	Major zeitgeber	Anti-depressant
Realised via	Visual system	Eye development	Skin	Circadian system	Multiple systems
Content	Vision	Myopia	Vitamin D synthesis	Circadian entrainment	Mood

Given that light has strong direct effects on mood, cognition, alertness, performance, and sleep, light can be considered a “drug” to treat many clinical conditions. Light therapy is already well established for winter and other depressions and circadian sleep disorders.

(Wirz-Justice et al., 2021, p. 1)

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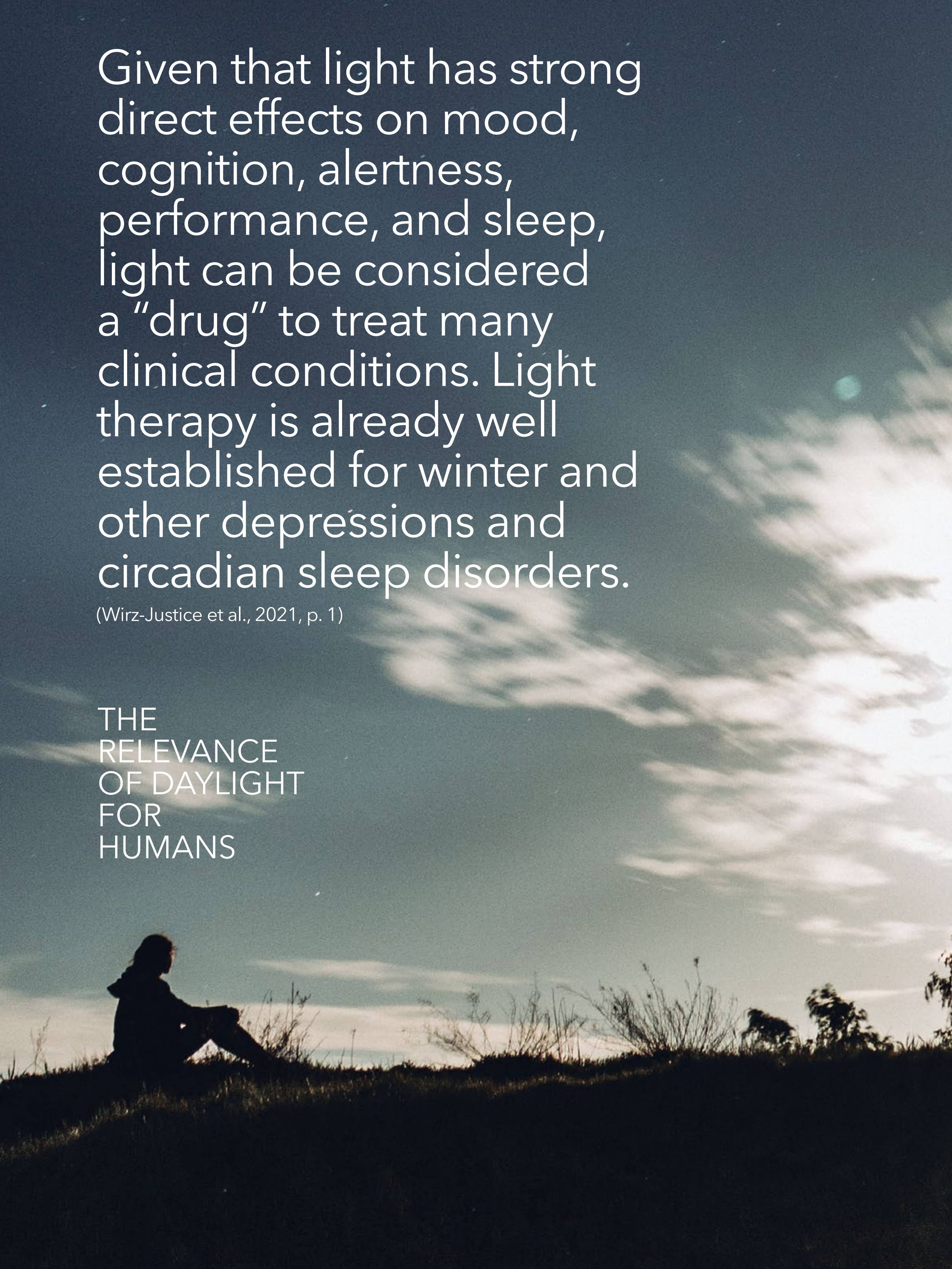

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VELUX STIFTUNG
Kirchgasse 42
8001 Zurich
Switzerland
office@daylight academy

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Daylight Academy
A VELUX STIFTUNG initiative
Kirchgasse 42
8001 Zürich
Switzerland

www.daylight.academy
office@daylight.academy