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Global change biology

Light at night, clocks and health: from humans to wild organisms

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The increasing use of electric lights has modified the natural light environment dramatically, posing novel challenges to both humans and wildlife. Indeed, several biomedical studies have linked artificial light at night to the disruption of circadian rhythms, with important consequences for human health, such as the increasing occurrence of metabolic syndromes, cancer and reduced immunity. In wild animals, light pollution is associated with changes in circadian behaviour, reproduction and predator–prey interactions, but we know little about the underlying physiological mechanisms and whether wild species suffer the same health problems as humans. In order to fill this gap, we advocate the need for integrating ecological studies in the field, with chronobiological approaches to identify and characterize pathways that may link temporal disruption caused by light at night and potential health and fitness consequences.

1. Introduction

Within the past century, there has been a rapid and unprecedented increase in artificial light at night (ALAN) that has modified both the indoor and outdoor light environment. Given the ubiquitous role that light plays in daily and seasonal organization of behaviour and physiology, it is reasonable to expect that any perturbation of the light environment could have far-reaching effects. Indeed, biological rhythms are fundamental life processes: organisms possess cell autonomous clocks that are directly or indirectly responsive to light. Biomedical research is rapidly providing evidence that exposure to ALAN in humans and model species can be harmful, and that circadian disruption might be the underlying mechanism [1]. Several laboratory studies demonstrate that aberrant light exposure can influence the circadian system, with downstream alterations in immune, reproductive, cognitive and metabolic function [2–4]. All of these systems are critical to fitness. In the wild, animals can be subjected to several other ecological effects of ALAN that are not linked to physiological changes but can still impact survival [5–7]. However, advancements in the understanding of the mechanisms underlying the health effects of ALAN in humans and model species have not been paralleled by equal evidence from ecological research: discovering whether wild populations suffer from the same health consequences of ALAN remains a significant research objective. Here, we first review the biomedical implications of ALAN, focusing on circadian disruption as a main underlying mechanism. We then highlight how the integration of chronobiology and ecology can provide substantial help to understand the ultimate effects of ALAN.

2. The health effects of artificial light at night

Exposure to ALAN can have direct or indirect physiological effects. Direct physiological effects often involve the disruption of circadian rhythms, and in

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particular the release of the hormone melatonin, which orchestrates changes in many physiological processes as a function of day length, including body mass, metabolic rate, hormone synthesis and immunity [1]. Well-studied biomedical implications of ALAN are obesity and metabolic disruption. Obesity can result from changes in caloric intake and energy expenditure, but time of feeding can also play a significant role. Mice exposed to ALAN shift their normal nocturnal time of food intake to their inactive part of the day, and despite equivalent daily caloric intake to mice exposed to dark nights, they gain more weight and have impaired glucose tolerance [4]. This has direct implications for human health: a recent cross-sectional study on more than 100 000 British women reported a positive association between obesity and exposure to ALAN [8]. Mistimed feeding may also have subsequent fitness consequences, as it reduces reproductive health in flies [9]. Another postulated consequence of ALAN is cancer. Indeed, ALAN seems to promote ageing and tumour growth in rats and to slow breast cancer therapy [10,11], and epidemiological data show that ALAN correlates with breast cancer in women [12]. Although the mechanisms are unclear, suppression of melatonin is likely involved. ALAN can also have indirect effects on other physiological processes. For instance, as many core components of the immune system possess circadian clocks [13], they are likely vulnerable to the effects of ALAN. Indeed, ALAN suppresses T-cell-mediated immunity in hamsters [2]. Other indirect circadian effects of ALAN are associated with sleep deprivation, such as cardiovascular disease and endocrine disruption [1].

Despite this evidence, potential long-term health consequences of ALAN are difficult to demonstrate experimentally in humans, and model species have little or no genetic variation that does not represent the complexity of the natural world, where associated health costs of ALAN might be offset by other potential benefits. Indeed, male songbirds breeding close to street lamps sang earlier in the morning and were thereby able to increase extra-pair paternity gain [6], and shorebirds obtained more night-time foraging opportunities on light-polluted mudflats [7]. Thus, besides clear effects of ALAN on immediate mortality [5], it remains unclear whether wild animals might suffer from similar, ALAN-induced health problems that might compromise reproduction and survival and eventually reduce fitness.

3. How chronobiology can help ecologists

Classic circadian theory can help ecologists to assess long-term effects of ALAN on important circadian parameters. A recent study has found that songbirds living in light-polluted territories in urban areas had a shorter circadian period length than conspecifics in dark, rural areas [14]. It is unclear whether this change is a consequence of masking from light, after-effects of light exposure on the speed of the circadian clock, and/or selection for shorter period lengths in urban areas. In addition, what are the consequences of faster circadian rhythms in the wild? A recent study showed that *tau* mutant mice with shorter circadian period length had reduced survival and fecundity than heterozygous mice [15], but evidence of links between naturally occurring variation in circadian periodicity and fitness is scarce. In this context, an exciting avenue of research would be to assess whether prolonged exposure to ALAN can produce evolution of circadian traits in wild populations [16].

A great advantage of captive chronobiology studies is the possibility to record activity patterns continuously and to obtain repeated physiological samples to assess other circadian traits such as body temperature and melatonin secretion. Although this might be complicated to do in the field, ecologists are starting to use such approaches. For instance, while biotelemetry tools have been mostly used to assess animal movement and migration strategies, these can also be used to record circadian activity. Indeed, automatic radio-telemetry that allows continuous recording of activity has revealed links between exposure to ALAN and changes in activity patterns of wild songbirds [17]. However, the physiological implications of such changes are mostly unknown. Given that a substantial portion of the genome is under circadian regulation [18], to obtain a single physiological sample from one wild animal will only provide limited information, especially if the time of sampling is not controlled for in the subsequent analyses. Tools usually deployed by ecologists or chronobiologists, such as radio-telemetry or next-generation sequencing, could help to resolve this issue: for instance, radio-telemetry can be used to record body temperature at a fine scale and for multiple days. While such application has been mostly applied thus far to study the circadian physiology of arctic mammals [19], light pollution studies might also benefit from it. Next-generation sequencing has been widely used by chronobiologists to assess the effect of circadian disruption, with excellent results [18,20]. If applied in mechanistic studies of light pollution, next-generation sequencing will allow ecologists to characterize specific pathways affected by ALAN, and thus identify potential physiological markers. For instance, recent studies revealed that sleep deprivation can have profound effects on the circadian expression of the transcriptome, and in particular of genes involved in immune and stress responses [18], and that oxalate is a robust marker of sleep debt [20]. In the wild, ALAN can disrupt sleep [21], but the potential consequences are unknown. The integration of experiments in the wild with metabolic profiling and targeted analysis of specific markers such as oxalate could provide evidence linking ALAN-induced sleep deprivation to health-related changes in physiology.

4. How ecology can help chronobiologists

Given the widespread presence of circadian rhythms in virtually all organisms, chronobiologists have often assumed that possessing functional circadian clocks must be adaptive. However, the few experiments performed in semi-natural settings using transgenic mice have shown contrasting effects with often surprising results. Indeed, while *tau* mutant mice showed reduced survival and reproductive success [15], *Per2-null* mice did not have lower survival than heterozygous individuals, and in the latter study, mice did not show the predominantly nocturnal behaviour they display in the laboratory [22]. This suggests that unexpected features and consequences of circadian behaviour may be widespread in natural populations. This should be of interest of chronobiologists whose aim is to understand the adaptive nature of circadian rhythms. Therefore, we advocate the need for experimental study systems in the wild where longitudinal physiological samples can be obtained, circadian activity of individual animals monitored and fitness measured. Examples of these systems are already being used to study the ecological effects of ALAN, and thus could offer important insights into the fitness consequences of circadian disruption [23].

Just as ecologists can use biotelemetry tools to gain insights into the circadian behaviour of wild species, chronobiologists can also benefit from using these techniques to bring their research into the wild [24]. In particular, the integration of accelerometers with GPS loggers is the most promising technique currently available [25]. The greatest advance allowed by this technology is the possibility to identify specific behavioural states of tagged animals while simultaneously recording their exact position in space, which would be crucial to understanding how activity may vary between dark- or light-polluted areas. Important circadian behaviours such as foraging and resting could be easily quantified and, if integrated with measurements of reproductive success and survival, will offer unique insights into the adaptive function of circadian rhythms. Some chronoecologists have already started to follow this path [6,24], but more studies are needed. Moreover, collaboration between ecologists and chronobiologists will ensure that state-of-the-art tools are deployed to analyse biotelemetry data with respect to biological rhythms [15,24].

5. Conclusion

It is essential that we learn about the effects of modern lighting on health, so that we might appropriately manage them. Many different non-visual responses, including circadian responses, have different spectral sensitivity, peaking at short wavelengths between 450 and 490 nm [1]. The recent shift from sodium lamps (approx. 589 nm) to fluorescent and LED lights of considerably shorter wavelengths has highlighted the need to trade-off economic and health benefits, as the latter types are increasingly used both indoors and outdoors. Thus, it may be of interest to compare wild populations in areas where sodium lamps or LED street lighting are present.

Besides a few sparse examples, research on the effects of ALAN has been marked by a lack of connection between biomedical studies on the circadian effects of ALAN in the laboratory and ecological studies in the field. We envision merging the mechanistic approach of chronobiologists with the possibility of sampling animals in the wild, including measuring their health and longevity, as the way forward for scientists interested in the proximate mechanisms as well as in the ultimate consequences of ALAN. We believe that researchers in both fields have much to offer to each other; ecologists will understand *how* light pollution can affect wild species, whereas circadian biologists will appreciate *why* circadian disruption matters in the real world.

Ethics. No animals were used in this study.

Data accessibility. This study contains no data.

Authors' contributions. D.M.D. and R.J.N. conceived the paper. D.M.D., J.C.B. and R.J.N. wrote the paper. All authors agree to be held accountable for the content therein and approve the final version of the manuscript.

Competing interests. We declare we have no competing interests.

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References

1. Foster RG, Kreitzmann L. 2004 *Rhythms of life: the biological clocks that control the daily lives of every living thing*. New Haven, CT: Yale University Press.
2. Bedrosian TA, Fonken LK, Walton JC, Nelson RJ. 2011 Chronic exposure to dim light at night suppresses immune responses in Siberian hamsters. *Biol. Lett*. **7**, 468–471. (doi:10.1098/rsbl.2010.1108)
3. LeGates TA *et al.* 2013 Aberrant light directly impairs mood and learning through melanopsin-expressing neurons. *Nature* **491**, 594–598. (doi:10.1038/nature11673)
4. Fonken LK, Workman JL, Walton JC, Weil ZM, Morris JS, Haim A, Nelson RJ. 2010 Light at night increases body mass by shifting the time of food intake. *Proc. Natl Acad. Sci. USA* **107**, 18 664–18 669. (doi:10.1073/pnas.1008734107)
5. Rich C, Longcore T. 2006 *Artificial night lighting*. Washington, DC: Island Press.
6. Kempenaers B, Borgström P, Loës P, Schlicht E, Valcu M. 2010 Artificial night lighting affects dawn song, extra-pair siring success, and lay date in songbirds. *Curr. Biol*. **20**, 1735–1739. (doi:10.1016/j.cub.2010.08.028)
7. Dwyer RG, Bearhop S, Campbell HA, Bryant DM. 2012 Shedding light on light: benefits of anthropogenic illumination to a nocturnally foraging shorebird. *J. Anim. Ecol*. **82**, 478–485. (doi:10.1111/1365-2656.12012)
8. McFadden E, Jones ME, Schoemaker MJ, Ashworth A, Swerdlow AJ. 2014 The relationship between obesity and exposure to light at night: cross-sectional analyses of over 100,000 women in the breakthrough generations study. *Am. J. Epidemiol*. **180**, 245–250. (doi:10.1093/aje/kwu117)
9. Xu K, DiAngelo JR, Hughes ME, Hogenesch JB, Sehgal A. 2011 The circadian clock interacts with metabolic physiology to influence reproductive fitness. *Cell Metab*. **13**, 639–654. (doi:10.1016/j.cmet.2011.05.001)
10. Dauchy RT *et al.* 2014 Circadian and melatonin disruption by exposure to light at night drives intrinsic resistance to tamoxifen therapy in breast cancer. *Cancer Res*. **74**, 4099–4110. (doi:10.1158/0008-5472.CAN-13-3156)
11. Vinogradova IA *et al.* 2009 Circadian disruption induced by light-at-night accelerates aging and promotes tumorigenesis in rats. *Aging* **1**, 855–865.
12. Stevens RG. 2009 Light-at-night, circadian disruption and breast cancer: assessment of existing evidence. *Int. J. Epidemiol*. **38**, 963–970. (doi:10.1093/ije/dyp178)
13. Arjona A, Silver AC, Walker WE, Fikrig E. 2012 Immunity's fourth dimension: approaching the circadian–immune connection. *Trends Immunol*. **33**, 607–612. (doi:10.1016/j.it.2012.08.007)
14. Dominoni DM, Helm B, Lehmann M, Dowse HB, Partecke J. 2013 Clocks for the city: circadian differences between forest and city songbirds. *Proc. R. Soc. B* **280**, 20130593. (doi:10.1098/rspb.2013.0593)
15. Spoelstra K *et al.* 2015 Natural selection against a circadian clock gene mutation in mice. *Proc. Natl*

Acad. Sci. USA **113**, 686 – 691. (doi:10.1073/pnas.1516442113)

16. Swaddle JP *et al.* 2015 A framework to assess evolutionary responses to anthropogenic light and sound. *Trends Ecol. Evol*. **30**, 550 – 560. (doi:10.1016/j.tree.2015.06.009)
17. Dominoni DM, Partecke J. 2015 Does light pollution alter daylength? A test using light loggers on free-ranging European blackbirds (*Turdus merula*). *Phil. Trans. R. Soc. B* **370**, 20140118. (doi:10.1098/rstb.2014.0118)
18. Moller-Levet CS *et al*. 2013 Effects of insufficient sleep on circadian rhythmicity and expression amplitude of the human blood transcriptome. *Proc. Natl Acad. Sci. USA* **110**, E1132 – E1141. (doi:10.1073/pnas.1217154110)
19. Williams CT, Barnes BM, Buck CL. 2012 Daily body temperature rhythms persist under the midnight sun but are absent during hibernation in free-living arctic ground squirrels. *Biol. Lett*. **8**, 31 – 34. (doi:10.1098/rsbl.2011.0435)
20. Weljie AM, Meerlo P, Goel N, Sengupta A, Kayser MS, Abel T, Birnbaum MJ, Dinges DF, Sehgal A. 2015 Oxalic acid and diacylglycerol 36:3 are cross-species markers of sleep debt. *Proc. Natl Acad Sci USA* **112**, 2569 – 2574. (doi:10.1073/pnas.1417432112)
21. Raap T, Pinxten R, Eens M. 2015 Light pollution disrupts sleep in free-living animals. *Sci. Rep*. **5**, 13557. (doi:10.1038/srep13557)
22. Daan S *et al.* 2011 Lab mice in the field: unorthodox daily activity and effects of a dysfunctional circadian clock allele. *J. Biol. Rhythms* **26**, 118 – 129. (doi:10.1177/0748730410397645)
23. Spoelstra K, van Grunsven RHA, Donners M, Gienapp P, Huigens ME, Slaterus R, Berendse F, Visser ME, Veenendaal E. 2015 Experimental illumination of natural habitat—direct and indirect ecological consequences of artificial light of different spectral composition. *Phil. Trans. R. Soc. B* **370**, 20140129. (doi:10.1098/rstb.2014.0129)
24. Greives TJ *et al.* 2015 Costs of sleeping in: circadian rhythms influence cuckoldry risk in a songbird. *Funct. Ecol*. **29**, 1300 – 1307. (doi:10.1111/1365-2435.12440)
25. Nams VO. 2014 Combining animal movements and behavioural data to detect behavioural states. *Ecol. Lett*. **17**, 1228 – 1237. (doi:10.1111/ele.12328)