Light pollution causes object collisions during local nocturnal manoeuvring flight by adult Manx Shearwaters *Puffinus puffinus*

Tim Guilford*, Oliver Padget, Sarah Bond and Martyna M. Syposz

** Correspondence author. Email: tim.guilford@zoo.ox.ac.uk*
Department of Zoology, University of Oxford, Oxford, Oxfordshire, OX1 3SZ, UK.

Abstract
Understanding the detrimental effects of anthropogenic light on nocturnally mobile animals is a long-standing problem in conservation biology. Seabirds such as shearwaters and petrels can be especially affected, perhaps because of their propensity to fly close to the surface, making them vulnerable to encountering anthropogenic light sources. We investigated the influence of light pollution on adult Manx Shearwaters *Puffinus puffinus* at close range in foggy conditions. We recorded collisions with a building at a breeding colony for six consecutive pairs of intervals in which the house lights were left on as normal for 135 seconds, then turned off for 135 seconds. The relationship between lighting condition and collision frequency was highly significant, with a collision rate in the presence of lighting around 25 times that in its absence. Our results show that birds were clearly affected by the lights, by being either directly attracted, or disorientated during flight close to the structure. This could have been due to the light source itself, or an indirect effect of the all-round reflective glow in the fog perhaps interfering with visual or magnetic control inputs on both sides of the bird simultaneously. Our results suggest a mechanism by which the screening of artificial lights close to shearwater breeding areas, at least during foggy nights, could lead to improved welfare and survival at breeding colonies.

Introduction
Understanding the detrimental effects of anthropogenic light on nocturnally mobile animals is a long-standing problem in conservation biology (Montevecchi 2006; Gaston *et al*. 2013; Gaston *et al*. 2014). Artificial light at night can draw individuals from long distances, whilst repelling others, affecting many activities including foraging (e.g. Garber 1978; Frank 2009; Pereszlényi *et al*. 2017), reproductive behaviour (e.g. Miller 2006; Kempenaers 2010; de Jong *et al*. 2015; Russ *et al*. 2017), and daily, monthly or annual movements (e.g. Salmon 2003; Mathews *et al*. 2015; Rodríguez *et al*. 2017).

Amongst the most endangered groups of birds (Croxall *et al*. 2012), shearwaters and petrels (Procellariiformes) are especially badly affected by anthropogenic light sources and the grounding of their fledglings, in particular, has been studied in many parts of the world (Rodríguez *et al*. 2017). Manx Shearwaters *Puffinus*

puffinus, which breed at island colonies predominantly around the British Isles, are classified as of Least Concern by the International Union for the Conservation of Nature (IUCN), but still they are often reported grounding in artificially lit urban areas or at other light sources particularly during the fledging period (Brooke 1990; Le Corre *et al*. 2002; Rodríguez *et al*. 2008; Miles *et al*. 2010; Archer *et al*. 2015). There are fewer studies on the grounding of adults on land, in this or other species, since adults usually constitute a small percentage of the individuals affected in any fallout (Telfer *et al*. 1987; Le Corre *et al*. 2002; Rodríguez & Rodríguez 2009).

Here we report a short experiment designed to test the instantaneous effect of anthropogenic house light on collisions with a man-made object, and outside of the fledging period when only adults are present at breeding colonies. Electric lighting is used to provide night service to the seasonal residents (a nightly summer maximum of 42 staff and tourists, of which up to 10 might stay in the Island Office) of the several buildings on Skomer Island National Nature Reserve (NNR), an internationally important Manx Shearwater breeding colony. Manx Shearwaters returning to the colony sometimes collide with the buildings and higher numbers of crashing seabirds are expected on cloudy and rainy nights (Jones 1980; Telfer *et al*. 1987). It may be that more birds visit breeding colonies in such conditions anyway, when there is less ambient light from the moon (Riou & Hamer 2008), but it is also possible that visual guidance in local manoeuvring flight is less effective and this contributes to collision risk. To determine whether there is a local effect of artificial light on collisions with the structure from which it is emanating, we conducted a very short experiment.

Methods

Study area: Skomer Island (51°44'N, 5°19'W) hosts the biggest colony of Manx Shearwaters in the world, an estimated 316,000 breeding pairs, making up around 36% of the global breeding population when combined with the neighbouring islands of Skokholm and Middleholm (Perrins *et al*. 2012). The other species active at night on the island include European Storm Petrels *Hydrobates pelagicus*, rarely seen close to the Island Office and not on the night of our experiment, and extremely unusually, vagrant shearwater species. There are no migratory passerines at this time of year. By contrast, thousands of Manx Shearwaters fly low over the colony each night at this time of year as they return to their burrow nests (if breeding), or in display flights whilst calling to prospective partners. Typically, when a shearwater collides with the building it will make a loud thud (too loud for a smaller bird), and will fall to the ground where it will remain for a few seconds or minutes, appearing stunned, before walking into the undergrowth. It is therefore overwhelmingly likely that every single impact we heard was of a different individual Manx Shearwater. We do not know the fate of crashed birds in general, but very occasionally we find a bird killed by the impact or bleeding from the head (TG pers. obs.), suggesting that whilst the vast majority escape to cover in the minutes following collision, there is the potential for serious injury which might affect future survival. We did not attempt to recover or assess birds for the effects of impact during this experiment.

Figure 1. Photograph of the Island Office showing its position on the shearwater nesting slopes at North Haven on Skomer Island. The windows through which light emanated during the lights-on treatment are the two furthest right of the line of five in the lower section of the building, and a small circular window in the door immediately right of these.

Experimental manipulation: On 27 May 2015, whilst undertaking fieldwork, we noticed that for several hours there were many shearwater collisions with the building. We therefore opportunistically conducted an experiment, exploiting the occasion of an unusually foggy night. The number of significant shearwater collisions with a prominent man-made structure, the Island Office (Figure 1), on Skomer Island NNR, was recorded by tallying in a notebook each audible crash with roof, walls or windows that could be heard from inside the researchers' quarters located centrally on the seaward (north) side of the structure. The predominantly wooden building is of a two-part design with a lower one-storey section measuring 17.5 m x 7.7 m x 5.5 m high at the top of the pitched roof leading to a taller two-storey section measuring 7.6 m x 12.0 m x 8.5 m at the highest point. The design of the study was decided as soon as we started observing the phenomenon and data on collision incidents were then recorded for six consecutive pairs of intervals in which (A) the house lights were left on as normal for 135 seconds, then (B) the lights were turned off for 135 seconds. This interval (2.25 minutes) was decided arbitrarily but to provide a short period (half an hour) that would allow six replicates during the middle of the night whilst the weather conditions persisted and before the colony became empty as the nights in May are short at this latitude. No other artificial lighting, except the very dim emergency exit panels and LEDs from electronic equipment indoors, was visible in the building. Luminance from two white fluorescent twin tube compact lights (Pro-light 11 W 2700 k) was visible externally via two rectangular glass windows (each 0.8 m x 1.0 m tall), and one small (0.37 m diameter) round window in the external door, and it is these sources that were extinguished during the lights-off treatment. The experiment started at 23:30 hours and lasted 27 minutes.

Results

The relationship between lighting condition and collision frequency was highly significant (Wilcoxon Test W = 0, N = 6, P = 0.0044; Table 1), with a collision rate in the presence of lighting (5.9 collisions per minute) around 25 times that in its absence (0.2 collisions per minute).

Table 1. Results from study showing the collision count data (rates per minute in brackets) across the six sequential treatment interval pairs.

Interval	I	II	III	IV	V	VI	Mean	Median
Lights on	13(5.8)	14(6.2)	10(4.4)	11(4.9)	18(8.0)	14(6.2)	13.3(5.9)	13.5(6.0)
Lights off	1(0.4)	0(0)	0(0)	1(0.4)	0(0)	1(0.4)	0.5(0.2)	0.5(0.2)

Discussion

The extinguishing of artificial building lights caused a dramatic (25-fold) and almost instantaneous reduction in Manx Shearwater collisions with the man-made structure from which the light was emanating. It is possible that the sound of one bird may be masked by another, so our numbers may even be, to some extent, underestimates. In addition, the recorders informally observed that collisions during the lights-off treatment always occurred shortly after the switch in treatment, suggesting that collisions during the lights-off period were mainly influenced by the effect of the light that had just been turned off. Because the treatment intervals were short (135 seconds) our experiment suggests a predominantly local effect of lighting, with collisions by birds already at the colony and in the vicinity of the buildings. In an earlier GPS tracking study, we estimated the mean speed of Manx Shearwaters in flight to be around 11 $m.s^{-1}$ (Guilford *et al*. 2008), allowing for the maximum attraction distance during an illuminated period to be about 1.5 km on this relatively calm night. Of course, it is possible that birds may have been attracted in to the area by illumination prior to the experiment, or during a previous lights-on interval during the experiment itself, but restricted penetration of light in foggy conditions is likely to mean that in fact our building lights were only visible from much shorter distances. Furthermore, the often immediate effect of turning on the lights and the striking disparity in collision rates between the on and off treatments, strongly suggests that a local effect of the light is responsible for inducing collision. A different design would be required to determine whether, as has been suggested for urban groundings (e.g. Reed *et al*. 1985; Miles *et al*. 2010), artificial lights can also attract birds from longer distances under some conditions. A study using GPS on Cory's Shearwaters *Calonectris borealis* showed that locations where birds were rescued had greater light pollution levels than at colonies, and found that areas with high intensity light attracted birds from further away than areas with low intensity light (Rodríguez *et al*. 2015). In our study, birds already at or close to the colony are either being attracted by the light source locally, or are being disoriented during visually guided flight close to the structure either directly by the light source or indirectly by the reflected glow in the fog. These two effects could operate in combination (Day *et al*. 2003). Although it might have been interesting to replicate this experiment under different conditions this has not been possible because curtains have been fitted to the building windows (in response to our observations) so that very restricted light now emanates from the structure under normal operation. Paradoxically, manipulation of light levels would now involve knowingly inducing potentially fatal collisions with the structure, whereas in the current experiment it opportunistically involved reducing them, thereby changing the ethical and legal basis of the research under UK law.

The mechanism by which light interferes with normal behaviour in flying birds is unknown. Hypotheses range from direct interference with stellar, lunar, or magnetic compass orientation mechanisms, to a normal attraction to light sources having its origin in mechanisms for hunting bioluminescent prey (for reviews see Montevecci 2006; Gaston *et al*. 2013). In our experiment birds would have been engaging in control flights above the colony rather than directional flights of any distance. This makes it unlikely that the mechanism interfered with was part of either long-distance guidance (the role normally assumed for compass orientation in migratory birds for example), or hunting. Direct attraction to the light is a possibility (Reed 1986), but it is interesting that most of the collisions witnessed in our experiment were not with the windows themselves, from which the light emanated, but with the surrounding structure. Furthermore, in fog, as here, light is scattered to produce a locally bright glow but with little distance penetration, so birds should if anything be attracted from less distance than on clear nights. Although we did not explicitly compare fog with clear conditions in this experiment, it is certainly the informal experience of researchers (see also Black 2005) that collisions are much rarer on clear nights which is the opposite of what would be expected if direct attraction was responsible. In the absence of the light, birds are apparently normally able to avoid collision with this structure despite the poor visibility. One hypothesis, therefore, is that sudden proximity to relatively bright light may disrupt the ability of birds to use their normal dark-adapted visual guidance effectively. This could be more pronounced on dark nights when birds are more dependent on dark-adaptation. Perhaps the scattering of light in fog also contributes by interfering with dark-adaptation in multiple directions, simultaneously disabling low-light visual guidance input from both eyes. A second hypothesis, however, is that birds manoeuvring in low light conditions might make use of a magnetic compass as a 'heading indicator' (Guilford & Taylor 2014) to monitor and control local changes in orientation relative to the ground. The suggestion that birds moving in a fluid medium might use compasses as heading indicators in flight control has been made before for a sun-compass during diurnal flight (Guilford & Taylor 2014), and we now know that Manx Shearwaters have a time-compensated sun compass (Padget *et al*. 2018), but in nocturnal flight when solar cues are unavailable a magnetic compass might operate in a similar way. It is possible, therefore, that a light-dependent magneto-receptor (Hore & Mauritsen 2016) becomes temporarily disrupted by saturation in the presence of bright light, and that this disrupts the bird's ability to gauge its heading changes during local flight manoeuvres, causing collision. Again, it is possible that in fog input from both eyes (eyes are thought to be the organs responsible for sensing magnetic direction) become affected simultaneously because of local light scattering.

Whether the effect of light witnessed in our experiment is an effect on visual or magnetic guidance in flight control remains to be determined. However, our results do suggest that light pollution may cause interference effects at several scales, with disruption of local flight control in addition to one or more attraction or compass disorientation effects operating at longer distances.

Measurements made during a rescue program for Manx Shearwaters suggested that around 7% of fledglings die as a result of grounding (Syposz *et al*. 2018), but such estimates are biased and the likely death rate may generally be much higher (about 40% in a study of Short-tailed Shearwaters *Ardenna tenuirostris*) where humans do not intervene (Le Corre *et al*. 2002; Rodríguez & Rodríguez 2009; Fontaine *et al*. 2011; Rodríguez *et al*. 2017). In particular the seriousness of the effect on flying shearwaters of collision with a man-made structure is not well understood. Manx Shearwaters rarely alight on a terrestrial surface with great control unless the wind strength and direction is very favourable (TG pers. obs.), so it is common to see or hear them crash into the undergrowth during normal attempts to land and they may be at least partially adapted to rough landings. However, after collision with buildings birds can usually be found sitting still for some time before making their way to cover, but on occasion may be found bleeding from the beak or killed by the impact. The longer-term effect of collisions on birds that survive immediate impact is not known, however. Birds that perish on the surface during the night, or fail to reach their nests, are likely to be removed and eaten by aerial predators and scavengers (mainly Great Black-backed Gulls *Laurus marinus* on Skomer Island, where there are no mammalian predators; Raymond *et al*. 1993).

Our results suggest that the normal controlled flight behaviour of adult shearwaters can be severely negatively affected by proximity to artificial lights on structures under some nocturnal conditions. They suggest a mechanism by which the screening of artificial lights close to shearwater breeding areas, at least during foggy nights, could lead to improved welfare and survival at breeding colonies. Off-shore, artificial light sources on structures or vessels are known to cause collisions in open water, particularly during foggy conditions, which can be reduced by light-screening or reduction (Black 2005; Glass & Ryan 2013). So, in addition it is possible that lights on vessels close to colonies, or close to the flight paths of returning birds, might interfere with collision avoidance behaviour in adult shearwaters, even if they do not attract birds from a distance. Large, highly lit tankers commonly anchor in the waters close to Skomer Island, and the neighbouring colonies of Skokholm, Middleholm, and Ramsey Islands, but their effect on the Manx Shearwaters remains unknown.

Acknowledgements
We would like to thank the Skomer and Skokholm Islands Conservation Advisory Committee, the Wildlife Trust for South and West Wales, and Natural Resources Wales.

References

Archer, M., Jones, P. H., & Stansfield, S. D. 2015. Departure of Manx Shearwater *Puffinus puffinus* fledglings from Bardsey, Gwynedd, Wales, 1998 to 2013. *Seabird* 28: 43–47.

Black, A. 2005. Light induced seabird mortality on vessels operating in the Southern Ocean: incidents and mitigation measures. *Antarctic Science* 17: 67–68.

Brooke, M. 1990. *The Manx Shearwater*. T. & A.D. Poyser, London.

Croxall, J. P., Butchart, S. H. M., Lascelles, B., Stattersfield, A. J., Sullivan, B., Symes, A., & Taylor, P. 2012. Seabird conservation status, threats and priority actions: a global assessment. *Bird Conservation International* 22: 1–34.

Day, R. H., Cooper, B. A., Telfer, T. C. & Powell, A. 2003. Decline of Townsend's (Newell's) Shearwaters (*Puffinus auricularis newelli*) on Kauai, Hawaii. *Auk* 120: 669–679.

de Jong, M., Ouyang, J. Q., Da Silva, A., van Grunsven, R. H., Kempenaers, B., Visser, M. E. & Spoelstra, K. 2015. Effects of nocturnal illumination on life-history decisions and fitness in two wild songbird species. *Philosophical Transactions of the Royal Society of London B* 370: 20140128.

Fontaine, R., Gimenez, O. & Bried, J. 2011. The impact of introduced predators, light-induced mortality of fledglings and poaching on the dynamics of the Cory's Shearwater (*Calonectris diomedea*) population from the Azores, northeastern subtropical Atlantic. *Biological Conservation* 144: 1998–2011.

Frank, K. 2009. Exploitation of artificial light at night by a diurnal jumping spider. *Peckhamia* 78: 1–3.

Garber, S. D. 1978. Opportunistic feeding behavior of *Anolis cristatellus* (Iguanidae: Reptilia) in Puerto Rico. *Transactions of the Kansas Academy of Science* 81: 79–80.

Gaston, K. J., Bennie, J., Davies, T. W. & Hopkins, J. 2013. The ecological impacts of nighttime light pollution: a mechanistic appraisal. *Biological Reviews* 88: 912–927.

Gaston, K. J. & Bennie, J. 2014. Demographic effects of artificial nighttime lighting on animal populations. *Environmental Reviews* 22: 323–330.

Glass, J., & Ryan, P. 2013. Reduced seabird night strikes and mortality in the Tristan rock lobster fishery. *African Journal of Marine Science* 35: 589–592.

Guilford, T., Meade, J., Freeman, R., Biro, D., Evans, T., Bonadonna, F., Boyle, D., Roberts, S. & Perrins C. M. 2008. GPS tracking of the foraging movements of Manx Shearwaters *Puffinus puffinus* breeding on Skomer Island, Wales. *Ibis* 150: 462–473.

Guilford, T. & Taylor, G. K. 2014. The sun compass revisited. *Animal Behaviour* 97: 135–143.

Hore, P. & Mouritsen, H. 2016. The radical-pair mechanism of magnetoreception. *Annual Review of Biophysics* 45: 299–344.

Jones, P. H. 1980. The effect on birds of a North Sea gas flare. *British Birds* 73: 547–555.

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. *Current Biology* 20: 1735–1739.

Le Corre, M., Ollivier, A., Ribes, S. & Jouventin, P. 2002. Light-induced mortality of petrels: a 4-year study from Réunion Island (Indian Ocean). *Biological Conservation* 105: 93–102.

Mathews, F., Roche, N., Aughney, T., Jones, N., Day, J., Baker, J. & Langton, S. 2015. Barriers and benefits: implications of artificial night-lighting for the distribution of common bats in Britain and Ireland. *Philosophical Transactions of the Royal Society of London B* 370: 20140124.

Miles, W., Money, S., Luxmoore, R. & Furness, R.W. 2010. Effects of artificial lights and moonlight on petrels at St Kilda. *Bird Study* 57: 244–251.

Miller, M. W. 2006. Apparent effects of light pollution on singing behavior of American Robins. *Condor* 108: 130–139.

Montevecchi, W. A. 2006. Influences of artificial light on marine birds. In: Rich, C. & Longcore, T. (eds.) *Ecological Consequences of Artificial Night Lighting*: 94–113. Island Press, Washington.

Padget, O., Bond, S., Kavelaars, M. M., van Loon, E. E., Bolton, M., Fayet, A., Syposz, M., Roberts, S. & Guilford, T. 2018. *In situ* clock shift reveals that the sun compass contributes to orientation in a pelagic seabird. *Current Biology* 28: 275–279.

Pereszlényi, Á., Horváth, G. & Kriska, G. 2017. Atypical feeding of woodpeckers, crows and redstarts on mass-swarming *Hydropsyche pellucidula* caddisflies attracted to glass panes. *Urban Ecosystems* 20: 1203–1207.

Perrins, C. M., Wood, M. J., Garroway, C. J., Boyle, D., Oakes, N., Revera, R., Collins, P. & Taylor, C. 2012. A whole-island census of the Manx Shearwaters *Puffinus puffinus* breeding on Skomer Island in 2011. *Seabird* 25: 1–13.

Reed, J. R., Sincock, J. L. & Hailman, J. P. 1985. Light attraction in endangered procellariiform birds: reduction by shielding upward radiation. *Auk* 102: 377–383.

Reed, J. R. 1986. *Seabird vision: spectral sensitivity and light-attraction behaviour.* PhD Thesis, University of Wisconsin-Madison.

Riou, S. & Hamer, K. C. 2008. Predation risk and reproductive effort: impacts of moonlight on food provisioning and chick growth in Manx Shearwaters. *Animal Behaviour* 76: 1743–1748.

Rodríguez, A., Burgan, G., Dann, P., Jessop, R., Negro, J. J., & Chiaradia, A. 2014. Fatal Attraction of Short-Tailed Shearwaters to Artificial Lights. *PLoS ONE* 9: e110114.

Rodríguez, A., Holmes, N. D., Ryan, P. G., Wilson, K-J., Faulquier, L., Murillo, Y., Raine, A. F., Penniman, J., Neves, V. & Rodríguez, B., Negro, J. J., Chiaradia, A., Dann, P., Anderson, T., Metzger, B., Shirai, M., Deppe, L., Wheeler, J., Hodum, P., Gouveia, C., Carmo, V., Carreira, G. P., Delgado-Alburqueque, L., Guerra-Correa, C., Couzi, F-X., Travers, M. & Le Corre, M. 2017. Seabird mortality induced by land-based artificial lights. *Conservation Biology* 31: 986–1001.

Rodríguez, A. & Rodríguez, B. 2009. Attraction of petrels to artificial lights in the Canary Islands: effects of the moon phase and age class. *Ibis* 151: 299–310.

Rodríguez, A., Rodríguez, B., Barone, R., Pérez, B., & Hernández, A. 2008. Status and conservation requirements of Manx shearwaters *Puffinus puffinus* on Tenerife (Canary Islands). *Alauda* 76: 72–74.

Rodríguez, A., Rodríguez, B. & Negro, J. J. 2015. GPS tracking for mapping seabird mortality induced by light pollution. *Scientific Reports* 5: 10670.

Russ, A., Lučeničová, T. & Klenke, R. 2017. Altered breeding biology of the European Blackbird under artificial light at night. *Journal of Avian Biology* 48: 1114–1125.

Salmon, M. 2003. Artificial night lighting and sea turtles. *Biologist* 50: 163–168.

Syposz, M., Gonçalves, F., Carty M, Hoppitt, W. & Manco, F. 2018. Factors influencing location and number of Manx Shearwater grounding in west Scotland. *Ibis* 160: 846–854.

Telfer, T. C., Sincock, J. L., Byrd, G. V. & Reed, J. R. 1987. Attraction of Hawaiian seabirds to lights: conservation efforts and effects of moon phase. *Wildlife Society Bulletin* 15: 406–413.