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ORIGINAL ARTICLE

Birds and the 'Post Tower' in Bonn: a case study of light pollution

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Abstract

During six consecutive autumn seasons we registered birds that were attracted to an illuminated 41-storey building in Bonn, Germany, the so-called 'Post Tower'. Casualties on the ground were disoriented by the light and in most cases collided with the building. All-night observations with numbers of casualties, effective light sources, moon, and weather parameters registered hourly allowed for analyses of the role of these factors for the attraction and disorientation of numerous migratory birds. As expected, the conspicuous façade illumination was responsible for many casualties (fatal or non-fatal). Additionally, the illuminated roof logos and even faint light sources like the emergency lights were attractive and led to casualties. Moon and rain were negatively correlated with casualties, but there was no clear correlation with other weather parameters. Turning off lights was key, but effects of other ex post mitigation measures were limited: shutters were not originally intended for the attenuation of light emissions, control technology was insufficient, and there was a lack of willingness of the building owner to reduce light emissions consistently, even during core bird migration periods. Conservation recommendations are derived from this case study.

Keywords Light pollution · Artificial light at night (ALAN) · Illuminated skyscraper · Bird-building collisions with glass · Migration · Disorientation

Zusammenfassung

Vögel und der „Postturm" in Bonn: Eine Fallstudie zur Lichtverschmutzung

In sechs aufeinanderfolgenden Herbstsaisons erfassten wir die Vögel, die an ein beleuchtetes, 41stöckiges Hochhaus in Bonn (Deutschland), den sog. „Postturm " angelockt wurden. Die Opfer am Boden waren aufgrund der Beleuchtung desorientiert und in den meisten Fällen mit dem Gebäude kollidiert. Basierend auf Beobachtungen während des gesamten Nachtverlaufes wurden die registrierten Opfer, die in Betrieb befindlichen Lichtquellen, Mond und Wettervariablen stundenweise dargestellt, um die Bedeutung dieser Faktoren für die Anlockung und Desorientierung zahlreicher Zugvögel zu analysieren. Die auffällige Fassadenbeleuchtung war erwartungsgemäß für die meisten der Todesfälle und Verletzungen verantwortlich. Zusätzlich führten die beleuchteten Firmenlogos auf dem Dach und sogar schwache Lichtquellen wie die Notbeleuchtung zu Opfern durch Anlockung, auch bei ausgeschalteter Fassadenbeleuchtung. Mond und Regen korrelierten negativ mit den Opferzahlen, aber mit anderen Wettervariablen fehlten klare Korrelationen. Das Abschalten der Beleuchtung war ausschlaggebend, während andere nachträgliche Abhilfemaßnahmen wenig wirksam waren: Sonnenschutzlamellen waren ursprünglich beim Einbau nicht dafür konzipiert, Lichtabstrahlung zu reduzieren, die Steuerungstechnik war fehleranfällig und die Bereitschaft der Gebäudeeigentümerin, Lichtemissionen selbst während der Kernzeiten des Vogelzugs konsequent zu reduzieren, war begrenzt. Aus dieser Fallstudie werden Empfehlungen für Schutzmaßnahmen abgeleitet.

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Introduction

Light-induced bird-building collisions are known to science for more than 150 years (e.g. Fox 1862; Cordeaux 1870). The attraction of lights had been used much longer to make use of migratory birds as food for humans (Hennicke 1910; Weigold 1925; Booth and Griffith 1927; Alcasid 1968) or to use attractive light to capture birds as a means of pest control (Meanley 1971). Even though the detrimental effects of artificial light at night on different organisms including humans has been subject to research and communication more intensively during the last decades (Longcore and Rich 2004; Hölker et al. 2010; American Medical Association 2012; Gaston et al. 2015), numerous detrimental and avoidable light emissions have been and are still being tolerated or even adopted by the relevant authorities. The "Post Tower" building in Bonn (Germany) has been recognized as a case study in this regard. The 41-storey skyscraper with its lights disorients and kills numerous migratory birds every year.

The temporal distribution of bird collisions with modern buildings with glass and light is often unknown but may allow to make better inference regarding potential driving factors. To quantify the bird collisions at the Post Tower and to try to identify responsible light sources and critical conditions, the occurrence of bird casualties, alive or dead, on the ground next to the Post Tower was investigated voluntarily in the context of different light regimes.

Bird collisions with glass windows and façades during daytime occur year-round when glass is not recognizable for birds due to see-through situations or specular reflections (Klem 1989). The number of collisions can be dramatically higher when building light sources attract and disorient migratory birds during darkness. The dimensions of bird collisions with glass have been estimated without discriminating daytime collisions and light-induced collisions by night (see Machtans et al. 2013; Loss et al. 2014). Observations at lighthouses and lightships (Allen 1880; Gätke 1895; Barrington 1900) or at television towers with air safety lights (e.g. Kemper 1958; Able 1963; Feehan 1963; Kemper et al. 1964; Stoddard and Norris 1967; Laskey 1969; Avery et al. 1973) have shown long ago that collisions can take place during all hours of the night. In 2020, bird-glass collision censuses in Hamburg and Berlin showed that night-time collisions can play a considerable role (Jödicke and Mitschke 2021; Steiof pers. comm.). Sometimes it is assumed that collisions, especially with high-rise buildings, mainly occur in the early morning hours of birds attracted to the vicinity of the building during the night (Sloan 2007; Parkins et al. 2015; Aymi et al. 2017). Such a conclusion may seem reasonable when bird victims are collected only during early morning hours and when, at these hours, collisions are witnessed live. Other observers report contradictory results with collisions during the entire night (Fink and French 1971; Evans Ogden 1996), with victims being collected long before dawn (McAdams 2003; City Wildlife 2020). However, this has rarely been documented by systematic nightly observations so far.

At the Post Tower, various lighting installations were operating in different manners during the nights and over the years. Disoriented, injured and dead birds were observed in considerable numbers at the base of the façades and led to nightly searches by HH since 2006 (for first results see Haupt 2009) and more systematically afterwards, in 2008 mainly by IvM (von Maravic 2009). Here, we present results from identical time windows per year of these searches and examine connections between the number of casualties, light sources, and weather and moon data.

Methods

The building

The Post Tower is a 163 m tall office building in Bonn, Germany (50° 42′ 56″ N, 7° 07′ 48″ E; Fig. 1 and pictures in the electronic supplement (S1–S4) and in Haupt 2009). The construction was finished in 2002. The ground plan of the tower corresponds roughly to a simple leaf (82 m long and, in the middle, 41 m wide; see Fig. 3), hence there are two main façades, one orientated towards north-northwest, one towards south-southeast, on both sides connected by two slender façade areas. All façades are glass-covered, and the glass extends about 3.5 m beyond both edges as well as about 12 m beyond the roof top. On the north side of the tower, the "Conference centre building" (25 m high) is separated from the tower by only a narrow gap.

Light systems and regime

Both façades of the tower are illuminated in the evening using different light colours and patterns (Fig. 1, left). The façade illumination is the first of three sources of light we consider in our analyses. The second source of light are the emergency lights in the corridors inside the building, which are permanently on. Façade and emergency lights can be attenuated by shutters lowered behind the main façades. However, these shutters are sunshades and not designed to maximally reduce light emission from the building: they are translucent, there is a gap between adjacent shutters, and shutters are lacking at the slender façade areas (Fig. 1, right, and especially S3 and S4 in the electronic supplement). The third source of light are strong spotlights installed on the roof and directed vertically into the sky (similar to searchlights), backlighting two large, mainly yellow logos on the top edge of the building (logo lights; Fig. 1, left; size of logo

Fig. 1 The Post Tower with full façade illumination (in blue [see digital article]) and logo lights and emergency lights on (left), and with façade illumination and logo lights off, and emergency lights maximally attenuated (right; maximal attenuation of emergency lights only incompletely shields off light emissions)

on the south side is about 100 m^2 and on the north side about 250 m^2). We analysed the effects of these three light sources (façade lights, emergency lights, logo lights), but there are additional lights in the lower parts, e.g. in the entrance area and the ground floor.

The façade illumination has been operating since completion of the tower in 2002. In the years before our investigation period the façade was illuminated for 3 h in the evening (21:00–00:00 CEST) in changing colours blue, yellow, and red, using 2000 lights with neon tubes (1000 at each main façade, used at about 60% of their maximal power of 28 W each) and 114 spotlights (used at about 60% of their maximal power of 575 W each). In addition, all spotlights on the roof (28 lights, 150 W each) were on all night. From 2008 on, the light regime was adjusted during core bird migration time. The 114 façade spotlights were switched off. Since 2009, façade illumination was on for 2 h only (beginning 22:00 CEST, but 21:00 CEST in 2012; Fig. 2, column "Façade" and y-axis labels "on1" to "on3"; for details, see Table 2) and the shutters were often lowered to reduce façade and emergency light emissions (Fig. 2, column "Emergency"). Since 2010, façade light has been reduced by creating blue bird shapes moving over the façade, illuminating no more than about 10% of the tubes at any given time (Fig. 2, grey part of the rectangles for "Façade"). From the roof lights, only the logo lights have been operating since 2008: continuously during all nights in 2008, and with several hours off between 00:00 or 01:00 to 05:00 or 06:00 CEST in most or all nights from 2009 to 2013 (Fig. 2, column "Logo").

Correlations between light regime, time, and year

A major challenge for the inferential analyses was the strong correlation among the light situations at the tower, the hour of the night, and the year, as described above. Since façade illumination was on only in the first part of the night, it was not possible to separate this effect from a general pattern of casualty numbers across the night (reflecting changing migration activity across the night). Therefore, we categorized each night into one of two levels: "full" vs. "reduced" façade illumination, and describe the course of casualties across the night separately for each (using an interaction between façade illumination and the night hour relative to switching off this illumination, i.e. the hours "on1" to "off6" as shown in Fig. 2).

The shutters attenuated the emission of emergency light and of the façade illumination. However, façade light was still well visible even with shutters lowered. Due to limited sample size (especially of nights with reduced façade illumination and with shutters not lowered), it was not possible to include the interaction between façade illumination and shutters in the model described below. Hence, nights with full façade illumination may have had shutters applied or not (during on1–on3).

Searches of bird casualties

In our analysis, we focus on the autumn period including the nights 12–13 September to 31 October-1 November of the years 2008–2013 when searches for bird casualties at the Post Tower were most systematic, including 2220 search hours from 283 nights (301–475 search hours from 44–50 nights per year). For the analyses, we only used the hours between 22:00 and 06:00 CEST (= 21:00 and 05:00 CET) per night and excluded hours with unknown light status (hours later in the night also had to be excluded if the type of façade illumination at the beginning of that night was unknown; Fig. 2 is based on these data selection including 241 nights). In addition, we excluded nights with less than 6 h with data (dropping 32 nights), nights with only 1 h of façade illumination (3 nights), and nights without any façade illumination due to the small number of such nights (16 nights). This yielded 1444 search hours from 190 nights for the model, including 981 bird casualties (dead or alive and using only fresh casualties). Sunset was between 18:28 and 16:37 CET, hence, the data used for the analyses were collected during astronomical twilight or full night.

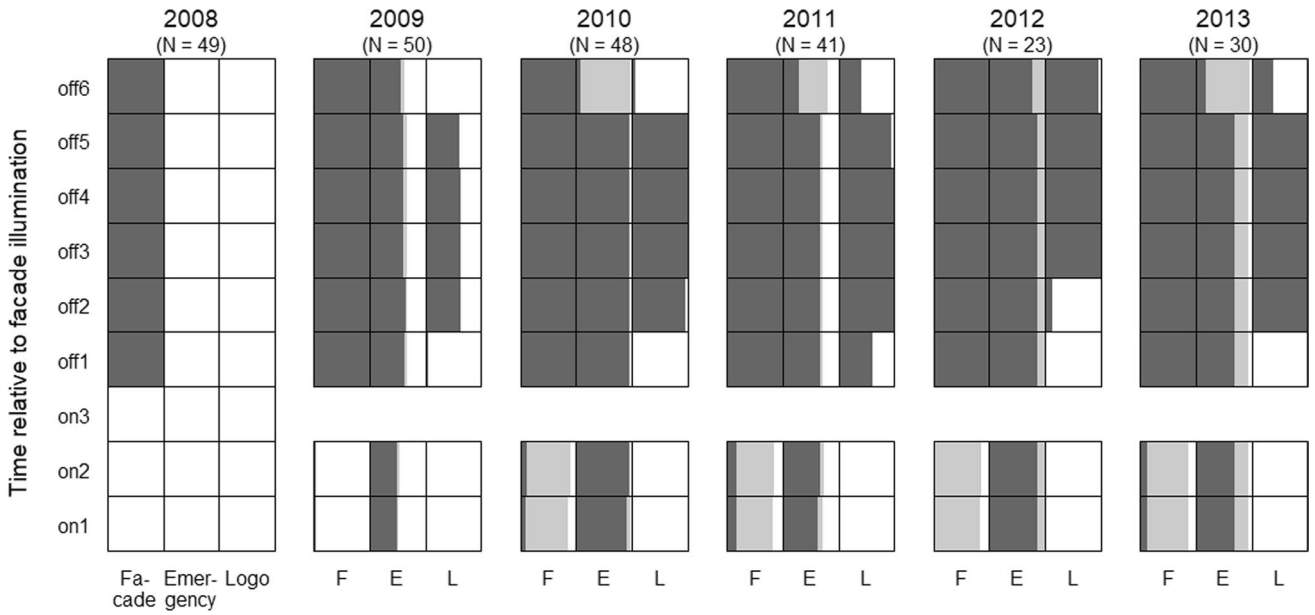

Fig. 2 Overview over the light sources for the years 2008 to 2013 and the 8–9 night hours (from bottom to top: 2–3 h "on", before façade illumination was switched off, then 6 h "off"). The three columns per year are the three light sources "façade illumination", "emergency lights" (which were always on but sometimes attenuated by shutters) and "logo light" on the roof of the tower. White portion of rectangles = full light (or, for emergency lights, no attenuation), grey = reduced façade illumination or partial attenuation of emergency lights, dark grey = lights switched off (or maximal attenuation of emergency lights by shutters). Depending on the year, the hour "on1" started at 21:00 or 22:00 CEST, "off1" at 23:00, 00:00 or 01:00 (see Table 2 for details). *N* = nights with known illumination situation

The entire surroundings of the building were searched slowly by foot at least once per hour during all night. During the first hours and when birds were found, the surroundings were inspected continuously. Live birds were marked with quick-drying nail polish (individual combinations of claws were marked to prevent double counting) and released in 200–300 m distance from the building. Dead birds were transferred to the Zoological Research Museum Alexander Koenig in Bonn. The light regime at the tower (façade lights, shutter position, logo lights), and several weather parameters were noted on-site continuously and aggregated per hour on rough scales: cloudiness (0/8 to 8/8), fog (0 to 3, corresponding to: no fog, hazy, visibility > 100 m, and visibility < 100 m), and rain (0 to 3, corresponding to no rain, drizzle, light rain, and heavy rain). Wind speed and direction were taken from the nearest available weather station (Bonn-Roleber, 5.1 km to the ENE of the tower), because on-site measurements would be strongly influenced by very specific wind systems around the building. The percentage of the full moon visible was taken from http://malorny.net/moon (zero if the moon was below horizon, but not taking cloud cover into account).

Statistical analyses

We modelled the number of bird casualties found per hour using a negative binomial model, which allows to model count data analogously to a Poisson model but including a dispersion parameter (to model overdispersion, which was present in our data). As explained above, due to strong correlation between the light situation and the hour of the night (Fig. 2), we classified each night according to the façade illumination type (full vs. reduced; nights with no façade illumination were excluded from the model due to the small number of such nights, but these are discussed separately), and the hour of the night was characterized relative to the façade illumination ("relative hour"; *y*-axis in Fig. 2). By including the interaction between the façade illumination type and relative hour, we model the course of bird casualties over the night, separately for the two façade illumination types.

The effects of the logo lights and the shutters were added to the model as additional predictors. The former was coded as on vs. off (values 1 vs. 0, i.e. larger value = more light emission), the latter as none, partial or maximal (attenuation of the light; values 2, 1 and 0). The values were used as continuous predictors, so that they could be averaged across the current and the previous relative hour, since the birds collected at a certain time were considered a mix of the casualties of these 2 h. If 1 of the 2 h was missing (e.g. for the first hour of each

night), the single non-missing value was used. Similarly, the weather and moon parameters were averaged over the same two relative hours. The day of year was included as a linear and quadratic effect to account for the non-linear relationship with the number of bird casualties. The individual night was added as a random factor to account for non-independence among the hours of the same night. No model selection was conducted except that we also fitted a model including the interaction between the logo lights and the relative hour, a model including a cubic term for the date, and a model including year as random factor, but all did not improve the model, hence they were not retained.

The model was fit in a Bayesian framework using Hamiltonian Monte Carlo in Stan (Stan Development Core Team 2019) accessed by the R interface rstanarm (function stan_glmer.nb; Goodrich et al. 2018; R Core Team 2019). In a Bayesian analyses, we receive a large number of draws from the posterior distribution of the parameters estimated in the model; the distributions of the drawn parameter values represent the estimate and its uncertainty for each parameter. We used the default settings of the R function, i.e. using weakly informative priors (with minimal influence of priors on the result) and 4 chains each with 1000 retained samples after a warm-up phase of 1000. Continuous predictors (including, e.g. the mean roof light value for the current and previous relative hour) were centred and scaled to 1 SD which is favourable for the model fitting algorithm but has no effect on the conclusions. Model fit was checked graphically and using posterior predictive model checking. The model somewhat overestimated the number of zeros but overall distribution of the number of bird casualties matched well (Figure S5 left in the electronic supplement). Residual vs. predictor plots were used to check whether a non-linear relationship was suggested. Some temporal autocorrelation was present but judged acceptable (Figure S5 right in the electronic supplement); including a cubic effect of the day of year did not reduce this slight violation of the model assumptions. Parameter uncertainty is given as the 95%-interquantile range of the marginal posterior distribution of the model parameters (95% credible interval). For effect plots, the covariates not shown in the plot are set to their average value, wind direction to the level "South", relative hour to "on2" and illumination to "full façade illumination".

Results

In the periods analysed, 1478 bird casualties were found at the Post Tower, 107 of these were already dead when found. At least 25 species were affected (Table 1), with kinglets accounting for 63.6% of all casualties. Other common casualties were European Robin and the thrushes, while warblers, flycatchers, tits and others were less commonly found.

Table 1 Number of casualties found per species during the nights 12–13 September to 31 October—1 November of the years 2008—2013 at the Post Tower in Bonn (dead or alive). Dead casualties are given separately, too

Species	Total	Dead
Common Firecrest *Regulus ignicapilla*	661	30
European Robin *Erithacus rubecula*	229	31
Goldcrest *Regulus regulus*	154	6
unidentified kinglet *Regulus sp.*	125	0
unidentified small bird	118	0
Eurasian Wren *Troglodytes troglodytes*	63	3
Song Thrush *Turdus philomelos*	39	12
Common Blackbird *Turdus merula*	13	1
Feathers left from scavenger	8	8
Eurasian Nuthatch *Sitta europaea*	8	6
unidentified thrush *Turdus sp.*	7	1
European Pied Flycatcher *Ficedula hypoleuca*	6	2
Eurasian Blackcap *Sylvia atricapilla*	6	1
Common Redstart *Phoenicurus phoenicurus*	5	2
Common Wood Pigeon *Columba palumbus*	4	1
Redwing *Turdus iliacus*	4	1
Eurasian Reed-warbler *Acrocephalus scirpaceus*	4	1
unidentified treecreeper *Certhia* sp.	4	0
Common Chiffchaff *Phylloscopus collybita*	3	0
Coal Tit *Periparus ater*	2	1
Eurasian Skylark *Alauda arvensis*, Black Redstart *Phoenicurus ochruros*, Northern Wheatear *Oenanthe oenanthe*, Common Grasshopper Warbler *Locustella naevia*	2	0
Water Rail *Rallus aquaticus*, Feral Pigeon *Columba livia* f. *domestica*, Marsh Warbler *Acrocephalus palustris*, unidentified warbler *Phylloscopus* sp., Willow Warbler *Phylloscopus trochilus*, Short-toed Treecreeper *Certhia brachydactyla*, Yellowhammer *Emberiza citrinella*	1	0
Total	1478	107

The temporal appearance of each species across the study season is depicted in Fig. S6 in the electronic supplement.

717 of the 1371 bird casualties alive were so disoriented that they could be caught by hand. They were then released away from the building. The others were able to escape from the searching person or were sitting on a rim or fluttering against the building and, thereby, could not always be identified to species level. Many kinglets were entangled to some degree with spider web during fluttering (394 individuals = 42% of the kinglets, and 7 other individuals of small species), in many cases hampering or preventing flight.

Birds were found around the entire tower and the attached Conference centre building (Fig. 3; buildings to the NW hide the NW façade for migrating birds, hence few casualties were found). Generally, more birds were found on the northern side of the tower, with a strong concentration inside the

wing wall, which "collects" the birds coming from the north. The southern façade also showed a concentration inside the wing wall.

The number of casualties was clearly lower in the years with a reduced light regime (Table 2). A comparison with the numbers found during the same autumn period in 2007 is somewhat hampered by the different search protocol in 2007, when searches were less systematic and only in some cases covered most night. Nevertheless, our numbers suggest that switching from full façade illumination with changing colours (in 2007: blue—yellow—red) to full façade illumination with only blue light (2008 and often 2009) did not reduce the number of casualties. The numbers are somewhat lower in 2008 and 2009, but the roof lights were also switched off more often compared to 2007, and, if on, only the logo lights were on compared to all spotlights on the roof during 2007. Also, façade beamers (in addition to the façade illumination) were switched off after 2007.

The number of bird casualties increased over the first relative hours of the night ("on1" to "off2") during full façade illumination, while the increase was much weaker during reduced illumination. The largest difference between the two light regimes was found during the first hour after turning off the façade illumination (reflecting also or mainly bird casualties during the last hour with illumination; estimate for full façade illumination: 0.53 [credible interval: 0.31–0.94] casualties/hour, for reduced façade illumination: 0.16 [0.08–0.31]; Fig. 4, Table S1). Some effect may still be visible during the second hour after switching off the illumination ("off2" in Fig. 4), but generally less thereafter.

The effect of the Post Tower shutters was in the expected direction (less casualties when shutters were used) but it was weak and very uncertain (Fig. 5 left). The estimated reduction with maximal use of the shutters (i.e. shutters lowered for the current and the previous hour) was only by a factor of 1.27 [0.8–2.1]. Logo lights showed a decrease by a factor of 2.0 [1.3–3.1] resulting from 0.33 [0.18–0.60] casualties/h on average when logo lights were on during the current and previous hour, and 0.17 [0.08–0.34] casualties/h when they were off (Fig. 5 right). With reduced façade illumination in the hour "off1", just after 2–3 h of operation, there were about 3.3 [1.7–6.5] times less casualties compared to full façade illumination (Fig. 4).

We observed somewhat more bird casualties during the first week of October compared to the time before and after (effect plots for date and the weather parameters in the electronic supplement, Figure S7; for parameter estimates see Table S1). Overall, somewhat more casualties were found with more cloud cover (Table S1, Figure S8). However, most of the nights with especially high numbers of casualties, predominantly kinglets, were cloudless and clear. Fog showed

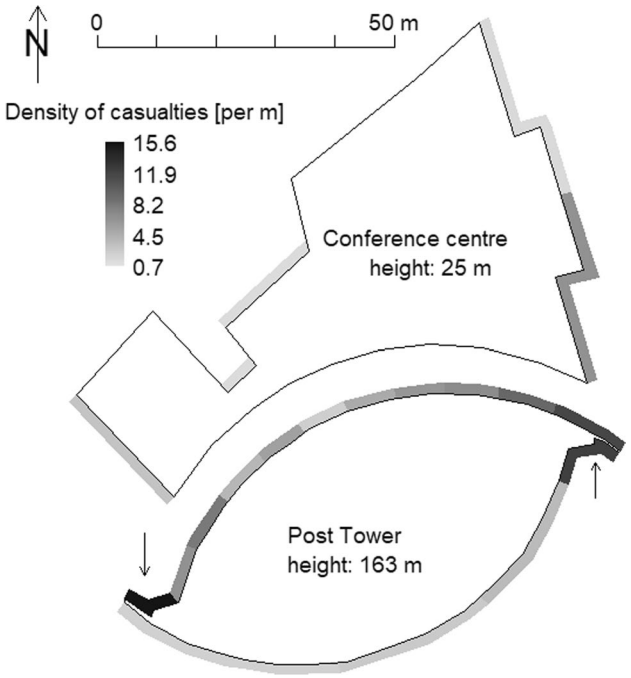

Fig. 3 Ground plan of the Post Tower and the Conference centre building (without projecting roofs of the conference centre), and the density of bird casualties found per location during the study period 12 September—1 November and 2008–2013. The strongest concentrations were observed inside the "wing wall" areas (glass walls extending 3.5 m beyond both edges of the tower; arrows). $N = 1478$ casualties in total

only an unclear signal (fewer casualties correlated with more fog, but uncertainty of this relationship was large). Rain, on the other hand, was strongly and negatively correlated with the number of birds found (Fig. 6 left). Stronger wind and wind from the south or south-west also led to fewer casualties. Finally, more moonlight reduced the estimated number of birds found (Fig. 6 right).

The night with the most casualties was just outside our focus period analysed here, namely from 1 to 2 November 2008, with 95 casualties. The next "worst nights" were nights with 64 casualties (4–5 October 2010), 53 (8–9 October 2010 and 21–22 October 2012), 44 (7–8 October 2008) and 43 (6–7 October 2008). We compared the 5% worst nights (15 nights with 64 to 21 casualties) with all nights (285 nights during our study period) regarding the distribution of the light and weather parameters and the date. The 5% worst nights almost all were during full façade illumination and mostly when there was no attenuation of light emissions by shutters and when the logo lights were on (Table 3). On the other hand, we found no strong indication that worst nights happened during very specific weather situations or only during a specific period in autumn (similar trends

Table 2 Characterization of the general light regime and the number of bird casualties per year

Year	General light regime			Casualties
	Façade (% per nights with known illumination)	Attenuation by shutters (% per observation hours)	Roof lights[2)](% per night)	(thereof found dead)
2007 (50 nights)	3 h (21:00–00:00) full (blue–yellow–red) 142 façade beamers	100% none	All night on all spotlights	533 (76)
2008 (49 nights)	3 h (22:00–01:00) 98% full (blue) 2% off	100% none	100% all night on Logo lights only	461 (42)
2009 (50 nights)	2 h (22:00–00:00) 96% full (29 blue, 19 special) 4% off	58% maximal 5% partial 37% none	62% off 01:00–05:00 38% all night on Logo lights only	368 (22)
2010 (48 nights)	2 h (22:00–00:00) 75% reduced 15% full (3 blue–yellow–red, 4 special) 10% off	84% maximal 14% partial 2% none	100% off 01:00–05:00 Logo lights only	322 (19)
2011 (41 nights + 3 with unknown illumination)	2 h (22:00–00:00[1)]) 66% reduced 17% full (special) 17% off	61% maximal 12% partial 28% none	100% off 00:00–05:00 Logo lights only	99 (10)
2012 (23 nights + 23 with unknown illumination)	2 h (21:00–23:00) 83% reduced 17% full (special)	86% maximal 14% partial	100% off 00:00–06:00 Logo lights only	173 (9)
2013 (30 nights + 16 with unknown illumination)	2 h (22:00–00:00) 73% reduced 13% full (2 blue–yellow–red, 2 special) 13% off	63% maximal 30% partial 7% none	100% off 00:00–05:00 Logo lights only	105 (10)

The number of nights with observations is given in parentheses, the number of casualties is scaled to 50 nights (12–13 September to 31 October—1 November) to make numbers comparable between years (based on $N = 1478$ casualties). In 2007, the search protocol was somewhat different; hence comparisons with other years must be done with care. "Special" full façade illumination was mainly illumination with different colours and duration; unknown: observations started after the illumination was switched off. See Fig. 2 for more details regarding the light regime. All times are CEST

[1)]10 of the "reduced" were 21:00–23:00

[2)]Off-times varied somewhat, we provide the typical situation

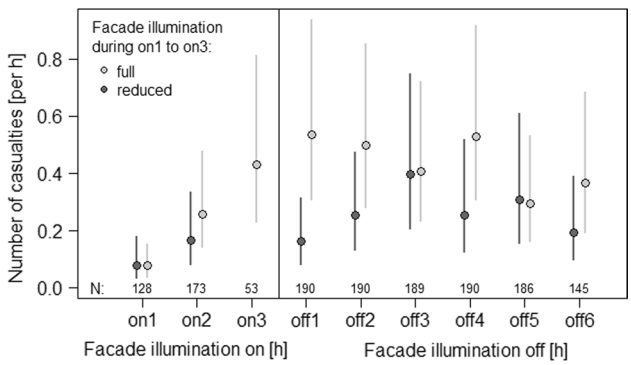

Fig. 4 Estimated average number of bird casualties (with 95% credible intervals) in the course of the night, i.e. during the first 2 or 3 h with façade illumination ("on1" to "on3") and the following hours without façade illumination ("off1" to "off6"), separately for nights with full vs. reduced façade illumination during "on1" to "on3" (no nights with 3 h reduced illumination). N = total number of nights with data for the corresponding hour

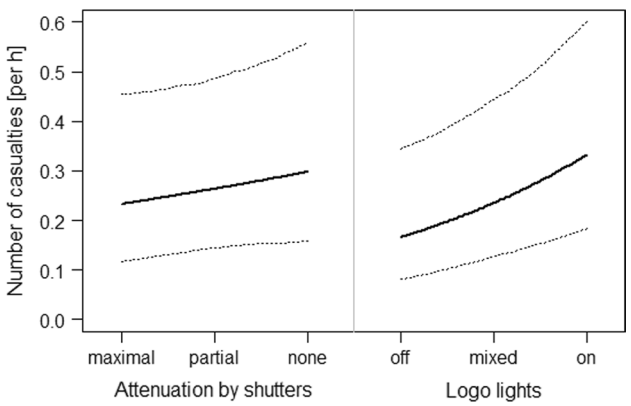

Fig. 5 Effects (with 95% credible interval) of the Post Tower shutters (that reduce but not eliminate light emission from the façade illumination and the emergency lights) and the logo lights (on the roof) on the number of bird casualties found

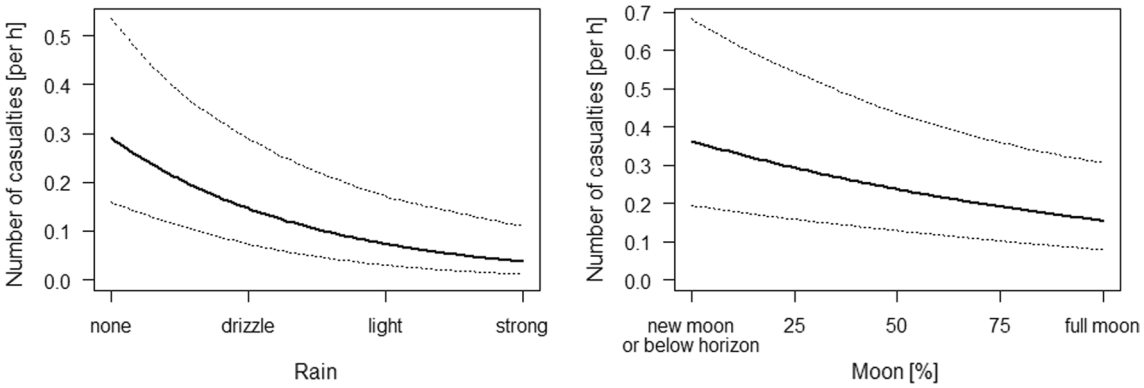

Fig. 6 Effect (with 95% credible interval) of rain and moon on the estimated number of casualties. Moon: percentage of visible moon disk; 0% includes hours with moon below horizon irrespective of moon phase

Table 3 Distribution of the observation hours for different light regimes (separately for façade illumination, attenuation of light emissions by shutters, and logo lights on the roof) for all nights (containing 2219 observation hours from 285 nights) and for the 5% nights with most bird casualties ("worst nights", 138 observation hours from 15 nights)

Light regime	Light	all night	worst nights
Façade illumination			
off	●	6.0%	0.0%
reduced	◐	42.8%	5.8%
full	○	51.3%	94.2%
Attenuation by shutters			
maximal	●	49.3%	21.9%
partial	◐	18.1%	8.0%
none	○	32.7%	70.1%
Logo lights			
off	●	38.1%	12.3%
on	○	61.9%	87.7%

as seen from the model above; Figure S8 in the electronic supplement).

It would have been desirable to also include a level "no façade illumination" in the model, but with only 16 such "off-nights", this was not feasible. Looking at the raw data, we find that these nights did not produce any of the 5% worst nights discussed above; 9 off-nights had maximally 3 casualties, one had 5, two 7, and one each had 8, 9, 11, and 18 casualties.

Discussion

The numbers of casualties found at the Post Tower illustrate the significant negative effect on birds that such buildings can have. Our search time was restricted to the core autumn migration period, hence not including bird casualties during the rest of the year including daytime collisions at the many glass structures. While many of the casualties found were not dead, many of them, if not being collected, would have died unnoticed, e.g. due to internal injuries, disorientation, subsequent collisions, predators or strong entanglement with spider web. Many of these victims would have been missed had we searched only in the morning, leading to a substantial underestimation of the adverse effect of the building. Surviving casualties lost energy and time on their migration towards the south. Along this route, many artificial light sources contribute to the cumulative and growing effect of light pollution, and the Post Tower is a particularly obvious example of what must be avoided.

Using our data, the temporal distribution of collisions allows for some inferences regarding factors that appear to be responsible, among others, for the bird casualties at the Post Tower. Before discussing these factors, we first focus on the search efficiency during our field work. During search nights, we judge that search efficiency was comparable over the years. We have no indication that carcass removal by predators around the buildings changed, rather such removal was obviously low in all years. Scavengers were noted only rarely close to the building (stone marten *Martes foina*, feral cat not in all years, red fox *Vulpes vulpes* only accidentally and only in greater distances; rats *Rattus norvegicus* were

never observed). Carcasses left untouched when found were never removed by scavengers during the night. Some casualties from non-lethal collisions and those disoriented by the beams of the roof lights, however, are not expected to be found in the vicinity of the buildings, therefore, leading to an underestimation of total numbers.

We have no indication that the number of birds passing the Post Tower or their altitudinal distribution would have changed significantly over the study years. The only reasonable main driver for the changing number of casualties is the light situation at the tower, modulated to some degree, e.g. by date, weather and moon parameters. Regarding causal effects especially of weather parameters, however, we need to be aware that we could not correct for the migration traffic rate, since it was not possible to collect data about this important covariate.

Façade illumination particularly detrimental

Our data suggest that the façade illumination is the building's light source with the most pronounced attraction effect. Reducing the façade illumination led to a significant reduction of casualties. The reduction of casualty numbers from 2008 to 2009 can be considered a result of limiting illumination time from 3–2 h. In 2010, the first year with the reduced façade illumination ("flying birds"), the number of casualties was still quite high. However, in 2010 there were still several nights with full façade illumination, and these had particularly high numbers of casualties: Six such nights showed 160 casualties (52% of all casualties of 2010; two nights alone produced 38% of the casualties). In the course of the night, a lingering effect of casualties after switching off the illumination (see Fig. 4) can be ascribed to birds falling down after clinging to the facade for any length of time (as frequently observed in the lower parts of the building) and to the attraction of the remaining light sources. Hence, in our view, the strong difference between full and reduced façade illumination during "off1" and "off2" (Fig. 4) are effects of the façade illumination that would have persisted across the night if façade illumination would not have been switched off.

Full facade illumination at selected nights during migration seasons has been continued to date although killing and injuring protected wild birds is prohibited in Germany according to § 44 of the Federal Nature Conservation Act, implementing the respective provision of the Wild Birds Directive of the European Union (Directive 2009/147/EG). Enforcement deficits in nature conservation have long been stated (Erz 1978, 1980), also for Bonn (Haupt et al. 2010).

Disorientation irrespective of light colour

In 2008, façade light emissions were restricted to blue colour, compared to alternating blue, yellow, and red light before. However, this did not markedly reduce casualties; the reduction from 533 to 461 casualties, in our opinion, was mainly due to the reduction of the spotlights on the roof. While we were not able to disentangle the effect of the blue vs. alternating-colour full façade illumination (due to correlations with changes of other light sources), our data strongly indicate that the often recommended short-wave light is not suitable as remediation measure. Recommendations for blue or green light (e.g. CityWildlife 2020) often refer to Poot et al. (2008), although their results had soon been relativized by Evans (2010). Rather contrary results were presented by Leuzinger (1965), Evans et al. (2007), and Goller et al. (2018). Consequently, Minatchy (2004) is sceptical about green and blue light and Dominoni and Nelson (2018) about short-waved light as remediation measure. In addition, an assessment of a potential alleviating effect of blue light would have to include effects on other organisms such as insects and bat species which often—not always—show strongest responses to short-waved light emissions (Spoelstra et al. 2017; Dominoni and Nelson 2018; Donners et al. 2018; Longcore et al. 2018; Voigt et al. 2018). Overall, there is no indication that particular spectra of artificial light were less critical for birds (Longcore 2018; see also Longcore et al. 2018; Mattfeld et al. 2012) and changes in light spectra may be less effective than expected also for other organisms (van Geffen et al. 2015a,b; van Langevelde et al. 2017) or may reveal heterogeneous effects (Dominoni and Nelson 2018; Longcore 2018).

Turning off lights is key

Instead of changing light colour, only reducing light emissions can significantly reduce negative effects, either by turning off lights (Van Doren et al. 2021) or, if not feasible, by effective attenuation. We need to be aware that completely preventing light emissions e.g. by shutters is often not possible and even strongly reduced light emissions may still cause too many casualties (Manville 2001a,b, 2009).

Full-façade illumination at the Post Tower generally began at 22:00 CEST and the first birds fell to the ground 20 min later. Hence, the Post Tower case study illustrates the urgency for turning off lights at buildings at 22:00 local time. However, our data do not provide judgement about the situation before this time with already many migrating birds aloft. Numerous observations at lighthouses and lightships (e.g. Harvie Brown et al. 1881, 1882; Clarke 1902; Tomison

1907; Baxter and Rintoul 1916; Rintoul and Baxter 1917) or buildings (Taylor and Kershner 1986) have shown that collisions also take place significantly earlier.

Reduced façade illumination with "flying bird" silhouettes—designed as a symbol for this bird conservation measure—seems to cause less problems. In this reduced mode the blue "flying birds" appear for some seconds, alternating with some seconds pause. During operation, every single light is activated for just about one second. Flashing and blinking lights have proven to be less problematic than steady-burning lights (Manville 2001a,b; USFWS 2021; Gehring 2007, Gehring et al. 2009), however, even flashing light cannot be regarded as unproblematic in all situations (Gauthreaux and Belser 2002).

Even faint lights attract birds

Even faint lights like the emergency lighting on the floors of the Post Tower attract migratory birds. In our data, this is suggested by still increasing numbers of casualties after turning off the façade illumination and by direct observations of birds fluttering against the façade with emergency lights only. For security reasons, these lights cannot be turned off but only attenuated by the shutters. Their alleviating effect is weak as their shielding effect is incomplete; they were not designed for this purpose (they actually are sunshades). Hence, the remaining numbers of casualties can be explained, also taking into account the slender sides of the building where shutters are lacking entirely (see the concentration of birds at both wing walls). The attracting and disorienting effect of weaker or even very faint light sources has been recognized early (Mullens 1908) and consistently confirmed (e.g. Griffin et al. 1974; Kaplan 1998; Evans Ogden 2002; Jones and Francis 2003).

The distance from which birds are lured to the Post Tower remains unclear. The number of casualties contradicts the assumption that only birds were affected that would anyway have passed the building (see Larkin 1988; Larkin and Frase 1988). A certain pull effect of exposed light sources over several kilometres can be assumed in accordance with Drost (1925), Bruinzeel and van Belle (2010), and Van Doren et al. (2017).

Logo light effect visible even on the ground

Roof logo lighting affected the number of casualties on the ground. Evidence of birds being attracted by and colliding with exposed but indirectly lit signs or billboards as observed by Müller (1981) is scarce. Bird casualties at tall advertising pylons, tower cranes etc. with darker areas below the lighted surface (e.g. advertising logos mounted on a tall mast) are mostly more difficult to be documented than at the Post Tower. The lighted tower retains the birds fluttering down phototactically in this area, whereas the darker areas below lighted pylons cause birds to drop or fly away in all directions.

Other birds flying over the roof of the building showed irregular flight behaviour like return or sideward flight, speed reduction, or non-directional back and forth flight (Haupt and Schillemeit 2011). Such birds may continue their disoriented flight and may collide with obstacles elsewhere as directional orientation does not resume immediately after leaving the light beam (Bruderer et al. 1999; Haupt and Schillemeit 2011). The duration of this disorientation effect is currently unclear as well as the energetic costs and resulting negative effects. Collisions with obstacles in greater distances are also possible, however, providing evidence is difficult and documentation is scarce: in immediate vicinity (Fink and French 1971; Van Doren et al. 2017), one kilometre apart (Haupt 2011) and possibly in greater distance (McArthur 1887).

Our results urge to abstain from exposed light sources for advertising purposes at least during migration periods. From the results presented here, a reduction of luminous density of such exposed light sources is not sufficient for bird conservation.

Moon effect

We observed a reduction of casualties with increasingly visible moon disk. The effect of moon on the attraction of migratory birds has so far primarily been considered with regard to the visible moon disc and to new moon and full moon, respectively, and even long-term observation data reveal ambiguous results. Although collision risk is generally rated lower in moonlit nights (e.g. Headley 1920; Lewis 1927; Drury and Nisbet 1964; Lindenthaler 1969; Mercer 1905; Verheijen 1981a,b; Pearson 1981; Pearson and Backhurst 1978; Telfer et al. 1987; Tomison 1907; Weigold 1925), other conclusions have been drawn (Stoddard 1962; Stoddard and Norris 1967; Crawford 1981) and even mass collisions in clear moonlit nights have been noticed (Culver 1915). Early observers have noticed nightly collisions just after moonset (e.g. Howell and Tanner 1951; Kaplan 1998; Nikolaus 1980; Overing 1936, 1938), before moonrise (Liebe 1885), or collisions were influenced by the visible moon (Stone 1885; Sloan 2007). At the Post Tower, too, mass collisions point at such a relationship (pers. obs.): Nights with more than 20 casualties are mainly characterized by early moonsets, late moonrises, or lacking visible moon at all.

Visible effect of date and rain, but less so of other weather parameters

The number of casualties was highest during early October, although this pattern showed rather large uncertainty. The

decline of casualties towards November obviously is due to the general reduction of the migration activity. The peak in early October correlates with the peak migration period of the species mainly found at the tower (kinglets, European Robin, thrushes, i.e. short-distance and partial migrants). Our extended search periods in 2007 (Haupt 2009), 2008 (from early August), 2010 and 2011 (from late August) suggest that long-distance migrants are less prone to collisions with the Post Tower. Notwithstanding that collision risk must be considered independent from population numbers (Longcore et al. 2013), this may be due to lower numbers crossing this area, but also to higher flight altitudes. Species-specific information on flight altitudes of nocturnally migrating birds is scarce but may be relevant as other short-distance migrants crossing the area during night-time are also rare or lacking at the tower during the observation periods, e.g. Eurasian Blackcap, Black Redstart, and Starling. Also other, still unknown reasons for species- or site-specific collision rates are likely. For example, Redwings and Eurasian Skylarks were reported to be common collision casualties elsewhere (for skylarks e.g. Booth 1878; Cordeaux 1870, 1879; Liebe 1885; Owen 1953; Riviere 1933; van Dobben and Mörzer Bruyns 1939), but seem less prone to collisions at the Post Tower, even though they are often seen flying above or even around the tower (for Redwings, and for the well-known fact that attraction does not necessarily correspond with immediate collision see Haupt 2009). On the other hand, kinglets and European Robins may preferably migrate at lower altitudes, explaining the peak of casualties in accordance with their local migration activity.

Rain strongly reduced the number of casualties in our data, but this seems trivial as rain strongly reduces migration. However, rainy nights have regularly been noticed as nights with higher numbers of light-induced casualties (Clarke 1902; Weigold 1924; Ballasus 2007; Blasius 1896; Evans Ogden 2002; Remy 1974) or even with mass collision events (Bjorge 1987; Blasius 1895; Goodpasture 1976; Kibbe and Boise 1985). Among others, Gauthreaux and LeGrand (1975) and Owen (1953) report cases with significant collisions in nights with continuous rainfall, suggesting that collisions during rain are not restricted to situations where migrating birds are confronted with incipient rain. Hence, the correlations between precipitation, migration and collision rates are complex, including effects of precipitation along the entire track the birds travel during a specific night.

Other weather parameters showed rather weak if any effects. Contrary to other observations, where casualties strongly increased in situations with fog combined with lights (Blasius 1896; Weigold 1924; Creutz 1956; Peterson 1963; Lindenthaler 1969; Baxter 1971; Hall 1974; Knight 1993, 1997; Ballasus 2007), we found no such association. The fog situation in Bonn is somewhat particular, with fogs around the tower often ascending from and being concentrated around the river Rhine, 300 m away from the building. Birds that get into these local fogs may simply land or may easily avoid flying through the fog.

Conservation recommendations

(1) Short-time surveys are not sufficient for investigations on the attraction of migratory birds by artificial light. Few nights with high migration activity, connected with numerous casualties, are accompanied by many nights with low activity. Consequently, at least one year's full migration seasons must be monitored for a first impression.
(2) Bird conservation, aiming at preventing collisions by day and disorientation from artificial light at night, must be taken into account by building owners, architects, and responsible authorities from the beginning of the planning stage. Otherwise, preparedness for solutions is scarce and effective bird conservation by retrofitting, if at all, can only be realized at high costs. Equipment not designed for bird conservation is often insufficient and fault prone.
(3) Exposed light sources, particularly for decorative or advertising purposes and not relevant for security, should generally be waived to prevent light pollution, but as a priority during migration seasons and the vegetation period (for the reason of insect conservation).
(4) Even faint but exposed light sources attract and disorient migratory birds. In our opinion, an intensity level low enough not to cause disorientation in the field cannot be defined at present.
(5) Even long-lasting interventions did not prevent unnecessary light emissions, despite the building owner's promise to reduce tower lights during migration periods, resulting in high numbers of casualties. Therefore, voluntariness does not seem to be sufficient. Mandatory provisions and arrangements and effective enforcing measures are needed to prevent avoidable casualties.

Data repository

The data are available at: https://doi.org/10.5281/zenodo.6444620 "Korner et al. 2022 – Data for Birds and the Post Tower in Bonn".

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