Chapter 4

Effects of Artificial Night Lighting on Migrating Birds

Sidney A. Gauthreaux Jr. and Carroll G. Belser

Many hundreds of species of birds typically migrate at night, and it is well known that fires and artificial lights attract birds during migration, particularly when the sky is cloudy and the ceiling is low. Romanes (1883) was first to discuss the similarities of the attraction of insects to a flame at night, birds to lighthouses, and fish to lanterns. In some instances, humans have exploited the attraction of migrating and local birds to lighted buildings, floodlights, and spotlights. In one early example, hunters used a simple reflecting lamp to attract shorebirds at night. "[T]he birds came all around and about them—like chickens when called to feed," reported the St. Augustine *Press* (quoted in Hallock 1874:150). In Jatinga, a small village on a ridge in the North Cachar Hills district of Assam in northeastern India, from August to October on moonless, foggy nights with south winds and drizzle, villagers use searchlights and lanterns to attract, capture, and kill hundreds of local birds for food (Dubey 1990). Up to fifty species have been collected, with herons and egrets being some of the largest victims and pittas and kingfishers representing some of the smaller species. In Africa the attraction of nocturnal

migrants to artificial lights at lodges and to automobile headlights has been used to enhance ecotourism (Backhurst and Pearson 1977, Nikolaus 1980, Nikolaus and Pearson 1983).

As human populations expand geographically, artificial lighting also expands, and it is now almost impossible to find areas that are free from its influence. Verheijen (1981b) was first to apply the term *photopollution* to situations in which artificial light has adverse effects on wildlife. His 1985 review elaborates on the concept of photopollution and highlights incidents involving birds and sea turtles, natural and artificial light fields, orientation issues, and remedies (Verheijen 1985). All evidence indicates that the increasing use of artificial light at night is having an adverse effect on populations of birds, particularly those that typically migrate at night.

In this chapter we provide a review of the literature on the attraction of birds to light at night. We first examine how and why birds are attracted to light and the mechanisms of avian vision. We then review examples of this attraction, organized by the type of lighting: lighthouses and lightships, floodlights and ceilometers, city lights and horizon glows, fires and flares, and broadcast and communication towers. We then report our observations of the response of migratory birds to lights on communication towers. We conclude with some specific recommendations to minimize light attraction of migrating birds and reduce the associated mortality.

Mechanisms of Bird Attraction to Artificial Light

Little is known about how birds are attracted to light at night (Verheijen 1985). It has been suggested that when a bird flies into lights at night it loses its visual cues to the horizon, and the bird uses the lights as a visual reference, resulting in spatial disorientation (Herbert 1970). According to Herbert (1970), birds using a light on a tower as a horizon cue would circle the tower, which may be a factor in bird attraction to lights on tall communication towers. Exposure to a light field at night causes alteration of a straight flight path (e.g., hovering, slowing down, shifting direction, or circling), and the change in flight path would keep the bird near the light source longer than if the flight path remained straight (Gauthreaux and Belser 1999, unpublished data). Under such circumstances *attraction* may not be as appropriate a term for the behavioral response as *capture* (Verheijen 1958). It is also likely in some cases that the intensity of the light bleaches visual pigments so that the birds are in effect blinded and can no longer see visual details that they could detect when dark adapted (Verheijen 1985).

There is also evidence that horizon glows from cities may influence the orientation behavior of caged migratory birds. It is well established that caged migratory birds often orient toward horizon glows produced by the lights of cities (Kramer 1949, 1951). Immature migratory birds may be more susceptible to the disruptive influences of artificial night lighting than adults (Gauthreaux 1982). In two different experiments that examined the age-dependent orientation of caged migratory birds, it was found that birds of the year responded to the sky glow of a city, whereas adults did not (Gauthreaux 1982). In the first experiment performed by Williams (1978) during the spring of 1978, 8 immature and 14 adult white-crowned sparrows (*Zonotrichia leucophrys leucophrys*) were tested in six circular, automatic orientation cages once the birds exhibited migratory restlessness (*Zugunruhe*). All field tests were conducted under relatively clear, starry skies with no more than a thin crescent moon and essentially calm winds. Each bird was tested for a total of four nights, except for one immature that was tested for an additional night. Both age classes were tested each night, starting just before sunset and ending about 7 A.M. local time.

Figure 4.1 shows the distribution of the summed activity in minutes for each treadle in the orientation cage for adults and immatures and the distribution of horizon glow around the test cages. The orientation of the adult and immature groups is significantly different ($p = 0.05$) from a uniform distribution (Rayleigh test), and the mean direction of the adult group is significantly different ($p = 0.05$) from that of the immature group (F test of Watson and Williams). The circular distribution of horizon glow as measured with a sensitive photometer also is shown in Figure 4.1. The two longest radii at azimuths 90° and 105° have the maximum horizon glow intensity of 0.0096 lux. The vector resultant of the horizon glow is 80° ($r = 0.455$).

The mean direction of the activity of the adult sparrows was largely seasonally appropriate, but most of the activity of the immatures was oriented toward the direction of maximum horizon glow. The results show that age is a factor in the influence of horizon glows on the orientation of caged migratory birds, and although this is a study of caged birds it suggests that free-flying birds could respond similarly.

In a related study by Beacham (1982), 12 immature and 12 adult indigo buntings (*Passerina cyanea*) were tested in six circular, automatic orientation cages once the birds exhibited migratory restlessness in the spring of 1981 (Gauthreaux 1982). Each bird was tested for a minimum of four nights and a maximum of seven nights. Six birds from each age group (12 total) were tested in Emlen funnels (newsprint funnels with an

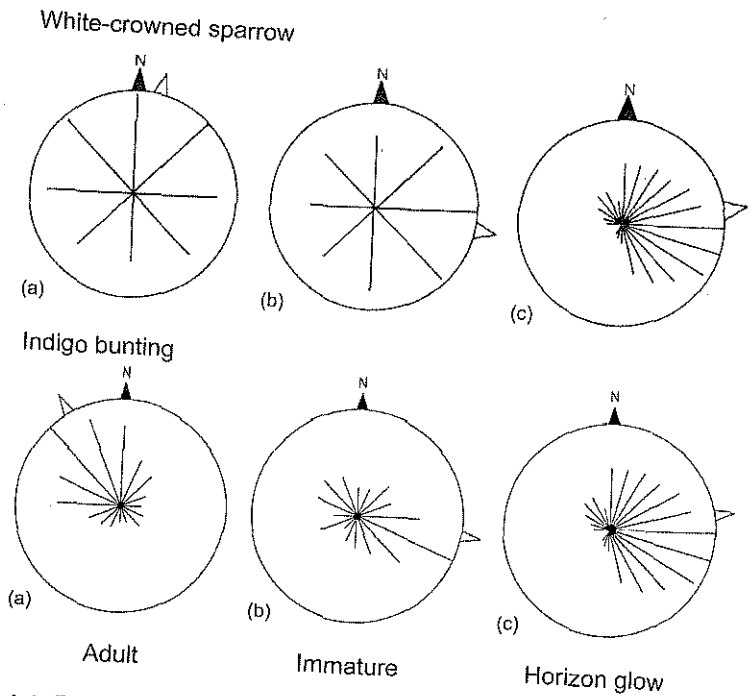


Figure 4.1. Distribution of migratory restlessness of *(a)* adult and *(b)* immature white-crowned sparrows and indigo buntings and *(c)* pattern of horizon glow around orientation cages. For white-crowned sparrows the longest radius is 17,015 minutes of activity toward 45° for adults and 8,265 minutes toward 90° for immatures. The resultant vector (mean direction) of all activity is 12° (r = 0.097) in *(a)* and 100° (r = 0.138) in *(b)*. For indigo buntings the longest radius is 5,221 hops toward 315° for adults and 4,402 hops toward 112.5° for immatures. The resultant vector (mean direction) of all hops is 327.6° (r = 0.392) in *(a)* and 98.5° (r = 0.181) in *(b)*.

ink-soaked sponge at the base). The funnel was divided into 16 sectors for analysis, and the number of hops in a sector was computed by comparing the density of hops with a scale of density patterns containing known numbers of hops. Figure 4.1 shows the distribution of the activity for adults and immatures as well as the pattern of horizon glow around the test funnels. The resultant vectors are significantly different (p = 0.05, Watson and Williams test) for the two age groups. As with the white-crowned sparrow, the greatest number of hops in the immature group is directed toward the greatest intensity of horizon glow, whereas the activity of the adults is oriented in a seasonally appropriate direction. Experimental studies of the migratory orientation of caged European robins (*Erithacus rubecula*) also found that the birds oriented toward the vector resultant of the distribution of illumination in the night sky (Katz and Vilks 1981).

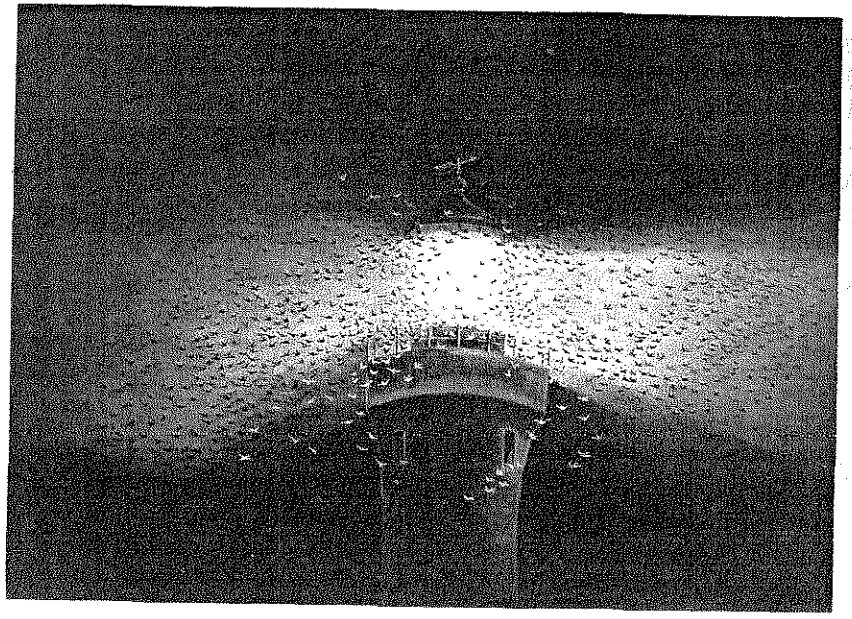
Birds have five different types of visual pigment and seven different types of photoreceptor: rods, double (uneven twin) cones, and four types of single cones (Hart 2001). Birds have a four-cone system and therefore broader spectral sensitivity than humans with a three-cone system (Wessels 1974, Graf and Norren 1974, Norren 1975). The extra cone type of birds is responsive to wavelengths in the ultraviolet range of the spectrum. In addition, bird eyes have oil droplets of different colors that narrow receptor sensitivities (Partridge 1989, Vorobyev et al. 1998). Because of these differences birds likely see their environment differently than do humans, which makes it difficult to speculate about the mechanism of how light pollution affects migrating birds at night. Another possible influence of artificial lighting on the behavior of night-migrating birds relates to the magnetic compass that several species use for direction finding during migration, as discussed in greater detail later in this chapter.

Sources of Light That Attract Birds

The tendency of birds to move toward lights at night when migrating and their reluctance to leave the sphere of light influence once encountered has been well documented. We review the various contexts in which birds have been attracted to lights and illustrate those that cause bird mortality. Although death or injury from collisions with structures is the most obvious adverse effect for migrating birds, attraction to lights may have other adverse consequences such as reducing energy stores necessary for migration because of delays and altered migration routes, mortality from collisions with glass during the daytime, and delayed arrival at breeding or wintering grounds.

Lighthouses and Lightships

Lighthouses and lightships (Figure 4.2) have attracted migrating birds since they were first operated (Dutcher 1884, Miller 1897, Hansen 1954), and this attraction was the basis of early, detailed studies of bird migration (e.g., Barrington 1900, Clarke 1912). In the 1800s lighthouse keepers noted that birds struck the lanterns most often on dark, cloudy nights with haze, fog, or rain, and that bird strikes on clear nights were extremely rare (Brewster 1886, Dixon 1897:268–274). Early studies supported the



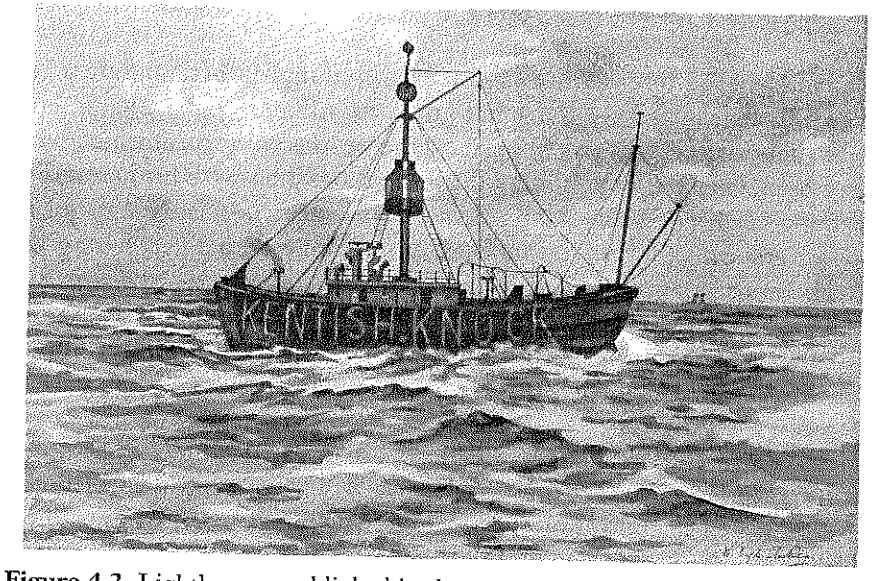


Figure 4.2. Lighthouses and lightships have attracted migrating birds at night since they were first operated. Above, an illustration of the Eddystone Lighthouse southwest of Plymouth, England, with nocturnal migrants milling around the lantern. Below, the Kentish Knock Lightship in the North Sea northeast of the coast of Kent, England. Illustrations are by M. E. Clarke and appear as frontispieces in volumes 1 and 2, respectively, of Clarke (1912).

notion that lightships attracted more birds than lighthouses on headlands and islands (Dixon 1897), and in more recent times lights on ships continue to attract nocturnal migrants crossing expanses of water (e.g., lighted ship in Gulf of Mexico, Bullis 1954; Cross Rip lightship in Nantucket Sound, Massachusetts, Bagg and Emery 1960; ore transport steamer on Lake Superior, Green and Perkins 1964).

An early survey of 24 lighthouses in North America showed that destruction of migrant birds was greatest at lighthouses in the Carolinas, Florida, and Louisiana, lower in the Northeast, and not present at two lighthouses in San Francisco Bay (Allen 1880). In a study of the destruction of migrating birds at lighthouses along the California coast, Squires and Hanson (1918) found relatively little collision mortality and attributed this to fewer migration waves in the western United States and less migration along the coastline. In contrast, a survey of 45 lighthouses on the coast of British Columbia by Munro (1924) found that nine reported high mortality rates, and overall annual mortality was more than 6,000 birds. Tufts (1928) surveyed lighthouses in the Canadian maritime provinces and Newfoundland and found that 45 of 197 experienced bird mortalities. Another survey of lighthouse keepers along the North American coasts and 225 lighthouse keepers in Central and South America and in the West Indies indicated that bird collisions were annual occurrences on the coasts of North America and along both coasts of South America and in the West Indies, especially along the northern coast of Cuba (Merriam 1885).

The literature on how migrant birds react to different types of lights at lighthouses and lightships is confusing. An analysis of birds that were killed (collided or shot) or caught at 58 light stations from 1881 through 1897 indicated that fixed lights were more attractive to migrants than rotating or blinking lights and that white lights were more attractive than red lights (Barrington 1900). Dixon (1897:269) also noted that "fixed white lights were more deadly than revolving or coloured lights." Thomson (1926:333–334) commented that it was known that "coloured lights do not attract the birds as white ones so fatally do." He added, "It therefore seems not unreasonable to ask that serious consideration should be given to the question of the gradual substitution of coloured for white lights at stations where great destruction commonly occurs and when the change may not be found to be impracticable for navigation reasons." Similarly, Cooke (1915) noted that a fixed white light beam attracted birds, a flashing light frightened them away, and red light was avoided. When the light beam of the lighthouse at Long Point, Lake Erie, Ontario, Canada was made narrower and dimmer in 1989, a dramatic reduction in avian mortality occurred (Jones and Francis 2003). From 1960 through 1989 mean annual

kills were 200 birds in spring and 393 in autumn, and from 1990–2002 mean annual kills dropped to 18.5 birds in spring and 9.6 in autumn.

The above findings, however, are not consistent with those reported by other authors. Munro (1924) reported that flashing and rotating lights caused more mortality than fixed lights, and the results of a survey of 135 lighthouse keepers showed that the responses of birds to different types of lighting at lighthouses varied widely (Lewis 1927), with flashing white lights causing the greatest mortality and fixed beacons and red lights attracting fewer birds. In a survey of bird mortality at lighthouses in the maritime provinces of Canada and Newfoundland, 152 lighthouses recorded no losses, of which 131 had fixed lights and 21 had flashing or rotating lights (Tufts 1928). Approximately half of the 45 lighthouses reporting some mortality had fixed lights, and half had flashing lights (Tufts 1928). The confusing results about the responses of birds to different types of lighting at lighthouses and lightships probably are related to the characteristics of the individual lamps, such as the wavelength or intensity, because the responses of the birds changed when the type of lamp was changed at a station.

In the early 1900s, when gas and kerosene lanterns at lighthouses were replaced with electric lamps, collision mortality decreased (Hansen 1954). When the original revolving white beacon at the Dungeness Light in Great Britain was replaced with a xenon-filled lamp that produced a bluish beam that flashed for one second in ten, attraction and mortality of migrants were eliminated (Baldwin 1965). When foghorns were placed near lighted structures, the number of birds striking the lights decreased dramatically (Dixon 1897).

Floodlights and Ceilometers

In an attempt to further reduce collision mortality at lighthouses, some were floodlit, and this practice produced mixed results. Illuminating a lighthouse in Denmark with a floodlight increased mortality (Hansen 1954). A similar increase in mortality followed illumination of the rotating beam Long Point lighthouse in Ontario (Baldwin 1965). In contrast, when five lighthouses in England were floodlit the number of collisions declined (Baldwin 1965). There is now considerable evidence to indicate that illuminating chimneys, buildings, bridges, and monuments with floodlights attracts and kills migrating birds, particularly on nights during the fall and spring that are misty with a low cloud layer (e.g., the 169-m [555-ft] Washington Monument in the District of Columbia [Overing 1938]; Bluff's lodge on the Blue Ridge Parkway, Wilkes County, North Carolina [Lord 1951]; the Long Point lighthouse [Baldwin 1965]; buildings on Holston Mountain, Tennessee [Herndon 1973]; and the 108-m [354-ft] Perry International Peace Monument and nuclear power plant cooling towers [Jackson et al. 1974]). Searchlights can also influence the flight behavior of migrating birds at night. Bruderer et al. (1999) switched on and off a strong searchlight mounted parallel to a radar antenna while tracking single migrants at night. The light beam caused a wide variation in shifts of flight direction (an average of 8° in the first 10 seconds and an average of 15° in the third 10-second interval). The mean velocity of the birds was reduced by 2–3 m (7–10 ft) per second (15–30% of normal airspeed), and climbing rate showed a slight increase, a possible response to escape the light beam. These effects declined with distance from the light source, and Bruderer et al. (1999) calculated that no reactions to the light should occur beyond 1 km (0.6 mi).

In the late 1940s meteorologists began using very bright (more than 1,000,000 candela), fixed-beam, vertically pointing spotlights, called ceilometers, to measure the height of the cloud ceiling at airports and weather stations. A rotating sensor measured the angle of the light spot on the cloud layer from a fixed distance from the base of the vertically pointing light beam, and the instrument computed the ceiling height using a simple trigonometric function. From 1948 through 1964, on overcast, misty nights these instruments were responsible for great losses of migrating birds. One of the earliest reports of mortality at a ceilometer was recorded at Nashville, Tennessee on the night of September 9–10, 1948 (Spofford 1949). On this night low clouds and misty conditions were present, and migrating birds congregated where the intense beam illuminated the cloud layer. Some circled, some collided, and some even dived into the ground. The largest kill of migrating birds ever recorded at a ceilometer, approximately 50,000, occurred October 6–8, 1954 at Warner Robins Air Force Base near Macon, Georgia, when a cold front moved over the Southeast (Chamberlain 1955, Johnston 1955). Howell et al. (1954) summarized the weather conditions that caused the buildup of migrants at ceilometers, the behavior of birds in and around the light beam, and the causes of injuries and mortality. In many instances the mortality of migrants at light beams would have been greater had it not been for meteorologists turning off ceilometers when birds began to accumulate in and around the beam (Ferren 1959, Fobes 1956, Green 1963, 1965).

Two changes to ceilometers greatly reduced and eventually eliminated the attraction and mortality of migrants. The first change involved filtering the wavelength of the light. When the longer wavelengths of ceilometer lamps were filtered so that mainly ultraviolet light remained, the

attraction was greatly reduced and mortalities were essentially eliminated (Laskey 1960, Terres 1956). The second change made in the early 1960s by the National Weather Service was the replacement of fixed-beam ceilometers with rotating beam units (Velie 1963). In the new units the ultraviolet beam rotated and the detector was stationary, and the rotating beam did not attract birds (Avery et al. 1980:5).

City Lights and Horizon Glows

In 1886, Gastman reported that nearly 1,000 migratory birds were killed around electric light towers in Decatur, Illinois on the evening of September 28 (Gastman 1886). Kumlien (1888) provided detailed accounts of migrating birds striking a Milwaukee building a year later, from September 22 to 29, 1887. The building had a tower 61 m (200 ft) above street level and was illuminated by four floodlights. Since these early reports we have seen steady increases in the number of streetlights, the number and sizes of cities, the heights of office buildings, and the number of offices with lights on after dark. In 1951 after a single stormy spring night, 2,421 dead migrants of 39 species (mostly warblers) were gathered beneath light poles on Padre Island, Texas (James 1956). The mortality of birds attracted to the lights of tall buildings has also increased. The hazards of lighted structures and windows to migrating birds are well documented in a report published by World Wildlife Fund Canada and the Fatal Light Awareness Program (Evans Ogden 1996). The executive summary concludes, "The collision of migrating birds with human-built structures and windows is a world-wide problem that results in the mortality of millions of birds each year in North America alone" (Evans Ogden 1996:2). This publication contains valuable references on the subject of light attractions. Two additional publications contain annotated bibliographies of avian mortality at human-made structures. A bibliography of bird kills as a result of attraction to lighted structures and possible solutions to the problem can be found in Weir (1976), and a bibliography of 1,042 references on this subject has been compiled by Avery et al. (1980). The latter effort has a very useful subject index, taxonomic index, geographic index, and author index.

Fires and Flares

Fires on the ground can attract birds during nocturnal migration. In March 1906 migrating birds were attracted to a large lumberyard fire in Philadelphia (Stone 1906). Stone noted that the birds did not change their flight direction as they flew over, but they appeared to lower their flight altitude. Some 30 birds were burned to death when they came too close to the flames. Gas flares on offshore oil and gas platforms and at oil refineries also pose a threat to migrating birds at night (see Chapter 5, this volume). Numerous reports of mass mortality of migrating songbirds at gas flares on oil platforms in the North Sea have been reported (Sage 1979), and Tornielli (1951) has reported an incident in Italy. Birds congregate around the flares on misty and foggy nights, and as they fly near and through the flames they are burned to death. Newman (1960) reports on an event after midnight on April 30, 1960 at an oil refinery in Baton Rouge, Louisiana. More than 1,000 migrants of 17 species were killed when they were attracted to a 76.2-m (250-ft) gas flame illuminating a low overcast sky. A similar incident occurred in late May 1980 in northwest Alberta (Bjorge 1987). On this evening approximately 3,000 birds of 26 species were found dead within 75 m (246 ft) of a 104-m (341-ft) flare stack.

Broadcast and Communication Towers

Television and FM radio station towers have steadily increased in height above ground level since they were first constructed in the late 1940s (Aldrich et al. 1966, Malakoff 2001, Manville 2001, in press). In the mid-1960s it was estimated that television towers in the United States killed more than a million birds per year (Aldrich et al. 1966). By the mid-1970s, 26 towers were between 580 m and 630 m (1,902–2,067 ft) above ground level in the United States, heights that penetrate the altitudinal layer where songbirds typically migrate. Taller towers need more stabilizing guylines and warning lights for aircraft, and it is documented that aircraft warning lights (Cochran and Graber 1958, Avery et al. 1976) and guylines (Brewer and Ellis 1958) on such towers are responsible for the deaths of hundreds of thousands of birds during nocturnal migration. Over the years many individuals have collected dead and injured birds at the base of broadcast towers and documented their findings in local and regional ornithological journals and newsletters. Some of the more extensive studies of tower kills have emerged as classics (e.g., Brewer and Ellis 1958, Stoddard 1962, Stoddard and Norris 1967, Crawford 1974). Only a few studies have continued into the 1990s (e.g., Kemper 1996, Nehring 1998, Morris et al. 2003), and these studies indicate a significant decline in the number of tower fatalities over the last 20 years (Figure 4.3). More work is needed to distinguish between the roles of evolutionary adaptation, behavioral habituation, declining populations of migratory birds, changing weather conditions, and changes in tower lighting systems as possible explanations for such declines (Morris et al. 2003, Clark et al. 2005).

Bird kills at tall lighted structures in the United States and at Dutch lighthouses show similar lunar periodicity (Verheijen 1980, 1981a,

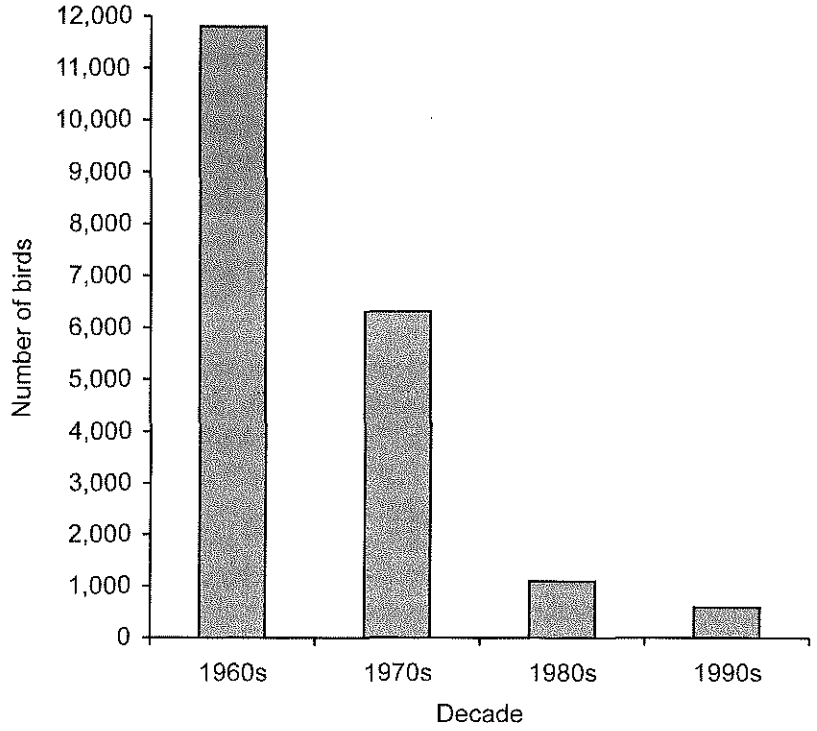


Figure 4.3. Long-term (38-year) trend in casualties of migratory birds at the WSMV-TV tower in Nashville, Tennessee. Redrawn from Nehring (1998).

1981b). None of the 229 events compiled by Verheijen occurred near a full moon, and most were clustered around the new moon period. When Crawford (1981) examined data from 1956–1980 from the WCTV tower in Leon County, Florida, however, he identified 683 nights on which ten or more birds were killed. Of these nights 40% occurred when the moon was 0–30% illuminated, while 28% occurred when the moon was 71–100% illuminated. If one examines the numbers of birds killed, the largest kill (2,127 birds) occurred on a night when the moon was 97% illuminated. The inverse relationship between lunar illumination and tower mortality is not as universal as Verheijen (1980, 1981a, 1981b) would suggest, but Crawford's (1981) analysis also suggests that more mortality events occur on nights when the moon is new or only slightly illuminated (notwithstanding the largest kill occurring during the full moon).

The flight behavior of migrant birds near tall towers with aircraft warning lights has been described on several occasions (e.g., Cochran and Graber 1958). We (SAG) observed the flight paths with an infrared scope near the WBRZ television tower in Baton Rouge, Louisiana on two occasions when winds were blowing from the same direction but at different wind speeds (Figure 4.4). When wind velocity was low to moderate, 3–8 m (10–26 ft) per second, some birds circled the tower, hovered, and accumulated on the leeward side of the tower (Figure 4.4a). When wind velocity increased, few birds hovered on the leeward side of the tower, and most passed the tower with only minor deflections in their flight path (Figure 4.4b).

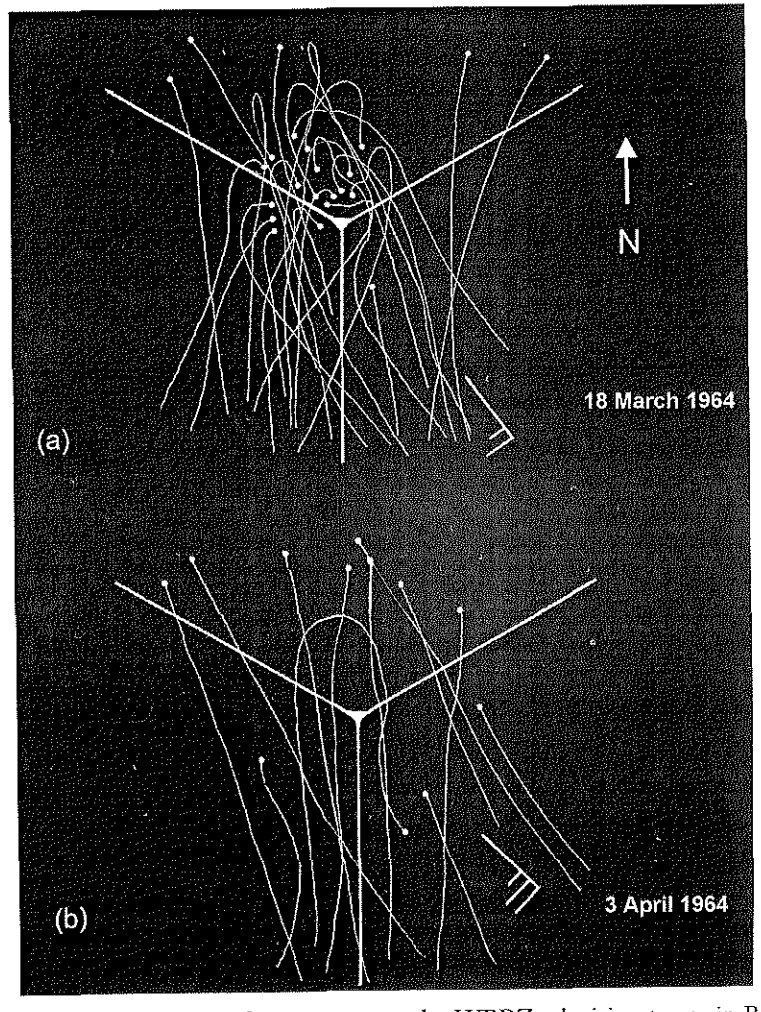


Figure 4.4. Flight paths of migrants near the WBRZ television tower in Baton Rouge, Louisiana in the spring of 1964. *(a)* March 18: winds are from the southeast at 7.5 m per second (15 knots). *(b)* April 3: winds are 12.5 m per second (25 knots). The tower is supported by three sets of guylines.

Portable tracking radar has been used to record the circular paths of birds flying near a broadcast tower in a sparsely populated area of the Upper Peninsula of Michigan on the night of September 9–10, 1983, when low clouds surrounded the tower (Larkin and Frase 1988). Figure 4.5 shows

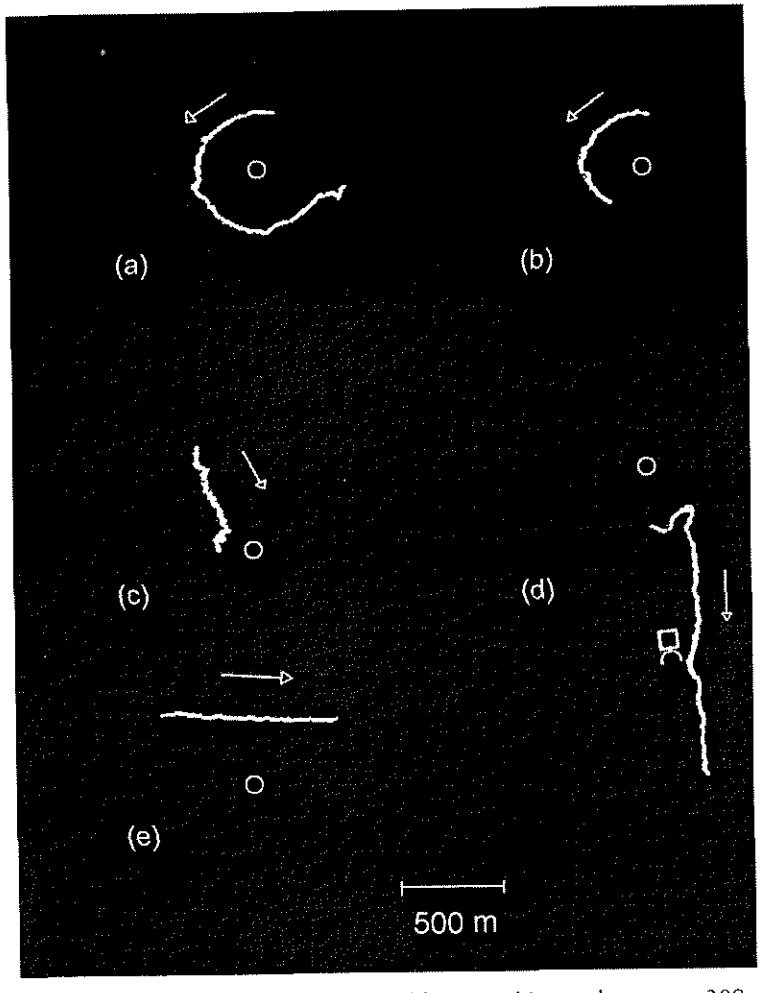


Figure 4.5. Flight paths of birds recorded by a tracking radar near a 308-m (1,010-ft) broadcast tower in the Upper Peninsula of Michigan on the night of September 9–10, 1983, when clouds surrounded the tower. The open circle shows the location of the tower, and the position of the radar is shown in *(d)*. Arrows indicate the direction of flight. *(a)* Time start 06:37 Universal Time Coordinate (UTC), duration 164 seconds. *(b)* 08:57 UTC, 94 seconds. *(c)* 09:04 UTC, 124 seconds. *(d)* 08:42 UTC, 186 seconds. *(e)* 05:31 UTC, 41 seconds. Redrawn from Larkin and Frase (1988).

the flight paths of nocturnal migrants as they were migrating near the tower. Arcs and circular paths were centered on the tower and had radii greater than 100 m (328 ft). Birds closer to the tower could not be tracked because the tracking radar would lock on the tower, the stronger target. When skies were clear or high overcast was present, the circling and curving behavior was not observed.

Influence of Lighting Type on Bird Behavior Near Tall Communication Towers

Tall communication towers historically have had arrays of incandescent red lighting as aircraft warning lights. This type of array includes continuously illuminated red lights alternating with slowly blinking red lights at different intervals along the length of the tower. Since the 1970s arrays of white strobe lights have been used increasingly as aircraft warning lights on tall communication towers. On towers with white strobe lights, the lights at different heights on the tower pulse (i.e., strobe) in unison or in sequence. Currently both types of lighting arrays are widely used. In an effort to understand why birds are attracted to lights and to assess the influences of different types of arrays of aircraft warning lights on towers, we examined the behavior of nocturnal migrants flying near tall towers with different types of lighting (Gauthreaux and Belser 1999, unpublished data).

During spring migration of 1986 from April 27 through May 15 we monitored flight behavior of migrating birds near the WNGC FM radio tower with strobe lights in northeast Georgia near the settlement of Neese and over a control area to the northeast (no tower present) for ten evenings (only nine with migration). We also collected data at this tower on the evenings of October 6 and 7, 1986. The FM radio tower was 366 m (1,200 ft) tall, with three sets of ten guylines and strobe lights located every 91.4 m (300 ft). The strobe lights pulsed at a rate of 40–46 pulses per minute. We used a vertically pointing image intensifier (AN/TVS 5, Varo Inc., Midland, Texas, 7× magnification) to monitor birds flying overhead near the tower (Figure 4.6) and coded the flight paths of migrants into the following categories: linear flight (straight) and nonlinear flight (pause or hover, curved, or circling). For statistical analysis the response variables were RATE (total paths per 20 minutes), PLIN (linear flight paths per 20 minutes), and PNON (nonlinear flight paths per 20 minutes). The explanatory variables were DATE and LOCATION (strobe tower or control site). We used a SAS general linear models procedure (SAS Institute 1999) for statistical analysis.

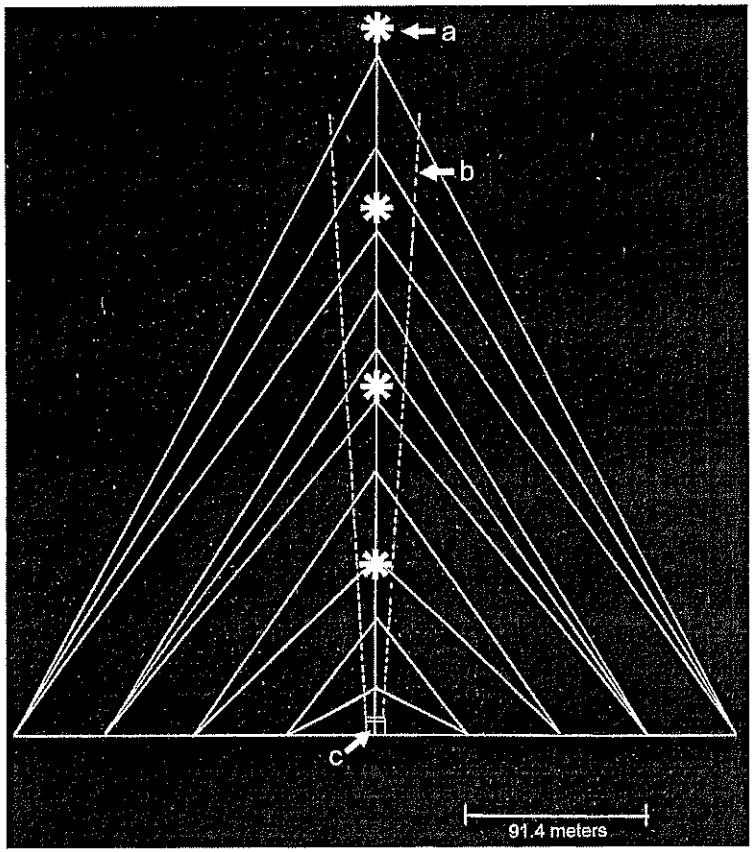


Figure 4.6. Communication tower and cone of observation. *(a)* Strobe aircraft warning lights and *(b)* cone of observation through the *(c)* image intensifier (AN/TVS 5). Only two of the three sets of ten guylines are shown in this illustration.

During the spring study in Georgia, the number of birds showing nonlinear flight near the tower with white strobe lights was significantly greater than at the control site, but the number of birds recorded at each site was not significantly different. For the response variables PLIN and PNON the explanatory variable DATE was not significant ($F_{8,8} = 1.43, p < 0.3116$), but the explanatory variable LOCATION was significant ($F_{1,8} = 5.78, p < 0.0429$). The rate of straight line flight paths was significantly greater at the control site, and the rate of flight paths that curved or showed hovering was significantly greater at the strobe light tower (Table 4.1). For the response variable RATE we found that the explanatory variables DATE and LOCATION were not significant ($F_{8,8} = 1.23, p < 0.3882$ and $F_{1,8} = 2.33, p < 0.1657$, respectively), indicating that the date when the samples were taken and the location (near or away from the strobe tower) had no effect on the number of flight paths per 20 minutes (Table 4.1).

Table 4.1. Results of *t*-tests (least significant difference) for response variables RATE, LRATE, PLIN, and PNON for Neese, Georgia and Garris (Moore's) Landing, South Carolina studies.

T Grouping	*Mean*	*N*	*Light*
	NEESE, GEORGIA		
	RATE (flight paths per 20 min)		
A*	8.593	9	Control
A	5.521	9	Strobe
	PLIN (linear flight paths per 20 min)		
A	0.974	9	Control
B	0.856	9	Strobe
	PNON (nonlinear flight paths per 20 min)		
A	0.026	9	Control
B	0.144	9	Strobe
	GARRIS (MOORE'S) LANDING, SOUTH CAROLINA		
	LRATE (log transformed flight paths per 20 min)		
A	2.674	14	Red
B	1.976	14	Control
B	1.390	13	Strobe
	PLIN (linear flight paths per 20 min)		
A	0.701	14	Red
B	0.979	14	Control
C	0.861	13	Strobe
	PNON (nonlinear flight paths per 20 min)		
A	0.299	14	Red
B	0.021	14	Control
C	0.139	13	Strobe

*Means with the same letter are not significantly different.

During the fall migration of 1986 we monitored the flight behavior of migrating birds near a television tower with red lights, near a television tower with white strobe lights, and over a control area that had no tower, all in the vicinity of Garris (Moore's) Landing, South Carolina (Figure

4.7). The two towers were 1.3 km (0.8 mile) apart, and both were 9 km (5.6 miles) southwest of the control site. One tower, operated by television station WTAT (Channel 24), was 508.1 m (1,667 ft) tall, with six continuously burning sets of red lights at 49, 146, 245, 340, 437, and 487 m (161, 479, 804, 1,115, 1,433, and 1,598 ft) that alternated with five slowly blinking red lights at 98, 195, 294, 392, and 508 m (322, 640, 965, 1,286, and 1,667 ft). The second tower, operated jointly by television stations WCSC and WCIV (Channels 4 and 5), was 614 m (2,016 ft) tall with nine sets of white strobe lights positioned approximately every 60 m (197 ft) starting at 76 m (249 ft). All strobes flashed synchronously. We used the same observation and data recording procedures as in the spring study. We recorded data on 14 evenings from October 2 to November 8, when conditions were favorable for bird migration. The rate data were log transformed (LRATE) to meet the requirements of normality, and we used the same SAS statistical procedures to analyze the fall data as we had used to analyze the spring data. The response variables were the same as in the spring study (LRATE, PLIN, and PNON), and the explanatory variables included RED (red light tower), STROBE (strobe light tower), and CONTROL.

During the fall study the log transformed flight paths per 20 minutes (LRATE) differed significantly by DATE ($F_{13,25} = 6.42$, $p < 0.0001$)

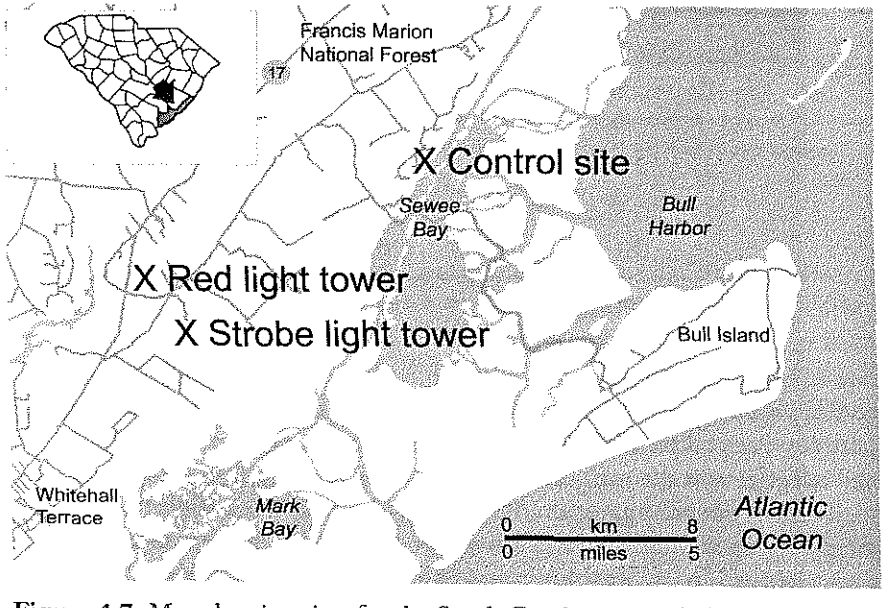


Figure 4.7. Map showing sites for the South Carolina tower lighting study.

and by light type ($F_{2,25} = 8.02$, $p < 0.0020$). The rate of linear flight paths did not change as a function of date ($F_{13,25} = 1.70$, $p < 0.1237$) but was significantly related to the type of lighting ($F_{2,25} = 14.29$, $p < 0.0001$). Nonlinear flight behavior was significantly greater near the tower with red lighting than near the tower with white strobes, and nonlinear flight behavior was significantly greater near the tower with white strobes than over the control site (Table 4.1). When the number of flight paths per 20 minutes recorded at each site is considered, significantly more birds were recorded flying near the tower with red lights than were recorded flying near the tower with white strobes and over the control site (Table 4.1). The number of birds detected flying near the tower with white strobes did not differ significantly from the number recorded over the control site, a result similar to that found in the Georgia spring migration study.

The type of lighting system on broadcast and communication towers influences the flight behavior of migrating birds at night. At both study sites the flight behavior of migrants differed significantly between the strobe light towers and the control sites, but the rate of flight paths per 20 minutes did not differ between the sites. In contrast, in the South Carolina fall migration study the number of flight paths per 20 minutes was greater at the tower with the red light array than at the tower with strobe lights and at the control site. Migrating birds at the red light tower showed significantly more nonlinear and hovering flight than birds passing the strobe tower and flying over the control site, and it is likely that nonlinear flight behavior over time contributed to the concentration of migrants at the tower with red lights. The greater number of birds near the tower with red lights probably is the result of attraction to the constantly illuminated lights on towers with red light arrays and the proportion of the time the birds showed nonlinear flight behavior. Whereas birds in linear flight spend only a brief instant near the tower and leave the area, birds showing curved, circling, or hovering behavior spend more time near the tower and thus build concentrations of migrants in the vicinity of the tower. Once concentrations build, the birds themselves may become collision hazards to other birds.

Our results showing greater disorientation from red lights are consistent with recent studies of the spectral sensitivity of birds. It has been demonstrated in the last decade that certain wavelengths of light appear to influence the magnetoreception of compass information by migratory birds (Wiltschko et al. 1993, Deutschlander et al. 1999, Wiltschko and Wiltschko 1999). Three passerine bird species have shown normal orientation of migratory restlessness under dim monochromatic light from the

blue-green range of the spectrum, whereas they were disoriented under yellow and red light (Wiltschko and Wiltschko 2002). If red light disrupts the magnetic compass used by birds during migration, then this could be an additional factor contributing to the aberrant flight behavior of migrating birds near towers with red warning light arrays. The absence of compass information could be the reason birds alter a straight flight path by hovering, slowing down, changing direction, or circling. We do not know how quickly red light affects the compass or whether birds are actually using the magnetic compass once a direction has been selected at the beginning of a migratory flight. Much more research is needed to answer these questions and those related to the mechanisms of how migratory birds are influenced by artificial lighting. If bird conservation is a goal, we must in the meantime develop and follow policies that minimize the types of lighting with which bird mortality and behavioral disruption have been observed.

Conclusion

Efforts are needed to avoid the adverse effects of lighting on birds, and if circumstances prevent such action, then appropriate mitigation measures should be developed. It would be impossible to detail all design and mitigation measures here; each project will require its own unique considerations. Our current understanding of bird behavior suggests the following general guidelines.

The intense glow of city lights can be reduced by making certain that all light is directed toward the ground whenever possible. Streetlights should be shielded so that the pattern of illumination is below the horizontal plane of the light fixture. Floodlights on the ground that point upward to illuminate buildings, bridges, and monuments are harmful and should be avoided. Such architectural lighting often is hazardous to migrating birds, particularly on nights that are misty with a low overcast ceiling. If such lighting designs must be used, then they should be turned off during migration seasons when weather conditions could contribute to attraction and mortality.

The Fatal Light Awareness Program has developed a Bird-Friendly Building Program that is aimed at building managers, building owners, office tenants, and employees of skyscrapers in Toronto. Their program has been effective in reducing bird mortality at participating buildings (Table 4.2). A similar program should be instituted in cities throughout the world.

Billboards often are lighted by floodlights that point upward, illumi-

Program (from www.flap.org).

Education

Implement the following educational strategies that carry the message about reducing bird collisions with your building:

- Elevator news.
- Lobby signage.
- E-mail migration alerts to tenants and staff in spring and fall.
- Educational displays.

Lighting Control Strategies

Program building's lighting system to achieve a measurable reduction in night lighting from 11 P.M. to 7 A.M. or, ideally, ensure that all lights are extinguished during that period.

Extinguish all exterior vanity lighting (e.g., rooftop floods, perimeter spots) during the migration periods.

When lights must be left on at night, examine and adopt alternatives to bright, all-night, floorwide lighting.

Options include the following:

- Installing motion-sensitive lighting.
- Using desk lamps and task lighting.
- Reprogramming timers.
- Adopting lower-intensity lighting.

Tenant Relations

Work with reluctant tenants to ensure that they comply with BFB guidelines. Coordinate meetings between FLAP and tenants, establish guidelines for tenants, and offer incentives to reward positive action.

Participate in the Bird Action Group Stations (BAGS) program by setting up stations where concerned tenants and staff can pick up bags, nets, gloves, and literature that enable them to rescue birds.

Building a Safer Environment

Implement measures (window film, netting, or other) to prevent birds from hitting windows at ground level in high-collision areas.

Eliminate use of chemical fertilizers and pesticides on grounds in favor of natural methods of pest control.

Staying on Course

Report to FLAP on your progress every spring and fall using the e-mailed questionnaire sent out early in the season. (This includes providing copies of all educational tools used and supplying FLAP with light energy consumption data.)

Strive for a built environment safe for birds and people by implementing these measures and developing partnerships with neighboring towers to ensure safe passage for night-migrating birds.

nating not only the billboard but also the sky above. A better design would be to mount floodlights on the top of the billboard pointing down. Alternatively, billboards could be illuminated from within, using less energy. Flashing lights do not attract migrating birds as much as constant lights (Avery et al. 1976). When floodlighting was replaced by strobe lighting at utility plants in Ontario, Canada, injury and mortality of birds at stacks and towers was nearly eliminated (Evans Ogden 1996:29).

Our studies and other evidence indicate that changing red warning lights to white strobes on broadcast towers may reduce the mortality of migrating birds (Gauthreaux and Belser 1999, unpublished data, M. Avery, personal communication, 2003). This solution, however, poses an additional problem. People living in the vicinity of strobe light towers complain about the flashing lights, particularly on overcast, misty nights. They report that it is like living in a thunderstorm with constant lightning and no thunder. Perhaps red strobe lights would be better, but no work has been completed on red strobes to see whether they are less likely than solid lights to attract migrating birds and less likely than white strobe lights to draw the attention of residents living near towers.

Populations of migratory birds are declining throughout the world, and the decline can be attributed to several different factors, including migration mortality, habitat change, and habitat destruction. By eliminating or controlling light pollution we can reduce one of the factors responsible for mortality during migration.

Acknowledgments

The work on the influence of different lighting arrays on the flight behavior of migrating birds near tall communication towers was supported by a grant from the Air Force Engineering and Services Center of the Air Force Systems Command to examine the behavioral responses of migrating birds to aircraft strobe lights.

We thank the personnel of Channel 24 in Charleston, South Carolina for access to the tower with the red light array and Channels 4 and 5 in Charleston, South Carolina for permission to work at the tower with the strobe light array. We thank Marianne B. Willey, Stuart R. Reitz, and David S. Mizrahi for their assistance during and after the tower lighting study. We also appreciate the detailed review by A. M. Manville II of an earlier draft of this manuscript.

Literature Cited

Aldrich, J. W., R. R. Graber, D. A. Munro, G. J. Wallace, G. C. West, and V. H. Cahalane. 1966. Report of the Committee on Bird Protection, 1965. *Auk* 83:457–467.

Allen, J. A. 1880. Destruction of birds by light-houses. *Bulletin of the Nuttall Ornithological Club* 5:131–138.

Avery, M., P. F. Springer, and J. F. Cassel. 1976. The effects of a tall tower on nocturnal bird migration: a portable ceilometer study. *Auk* 93:281–291.

Avery, M. L., P. F. Springer, and N. S. Dailey. 1980. *Avian mortality at man-made structures: an annotated bibliography* (revised). U.S. Fish and Wildlife Service, Biological Services Program, FWS/OBS-80/54.

Backhurst, G. C., and D. J. Pearson. 1977. Ethiopian region birds attracted to the lights of Ngulia Safari Lodge, Kenya. *Scopus* 1:98–103.

Bagg, A. M., and R. P. Emery. 1960. Fall migration: northeastern maritime region. *Audubon Field Notes* 14:10–17.

Baldwin, D. H. 1965. Enquiry into the mass mortality of nocturnal migrants in Ontario: final report. *Ontario Naturalist* 3:3–11.

Barrington, R. M. 1900. *The migration of birds as observed at Irish lighthouses and lightships*. R. H. Porter, London and Edward Ponsonby, Dublin.

Beacham, J. L. 1982. *Phototaxis and age dependent migratory orientation in the indigo bunting*, Passerina cyanea. M.S. thesis, Clemson University, Clemson, South Carolina.

Bjorge, R. R. 1987. Bird kill at an oil industry flare stack in northwest Alberta. *Canadian Field-Naturalist* 101:346–350.

Brewer, R., and J. A. Ellis. 1958. An analysis of migrating birds killed at a television tower in east-central Illinois, September 1955–May 1957. *Auk* 75:400–414.

Brewster, W. 1886. Bird migration. Part 1. Observations on nocturnal bird flights at the light-house at Point Lepreaux, Bay of Fundy, New Brunswick. *Memoirs of the Nuttall Ornithological Club* 1:5–10.

Bruderer, B., D. Peter, and T. Steuri. 1999. Behaviour of migrating birds exposed to X-band radar and a bright light beam. *Journal of Experimental Biology* 202:1015–1022.

Bullis, H. R. Jr. 1954. Trans-Gulf migration, spring 1952. *Auk* 71:298–305.

Chamberlain, B. R. 1955. Fall migration: southern Atlantic coast region. *Audubon Field Notes* 9:17–18.

Clark, A. R., C. E. Bell, and S. R. Morris. 2005. Comparison of daily avian mortality characteristics at two television towers in western New York, 1970–1999. *Wilson Bulletin* 117:35–43.

Clarke, W. E. 1912. *Studies in bird migration*. Volumes I and II. Gurney & Jackson, London.

Cochran, W. W., and R. R. Graber. 1958. Attraction of nocturnal migrants by lights on a television tower. *Wilson Bulletin* 70:378–380.

Cooke, W. W. 1915. Bird migration. *United States Department of Agriculture Bulletin* 185:1–48.

Crawford, R. L. 1974. Bird casualties at a Leon County, Florida, TV tower: October 1966–September 1973. *Bulletin of the Tall Timbers Research Station* 18:1–27.

Crawford, R. L. 1981. Bird kills at a lighted man-made structure: often on nights close to a full moon. *American Birds* 35:913–914.

Deutschlander, M. E., J. B. Phillips, and S. C. Borland. 1999. The case for light-dependent magnetic orientation in animals. *Journal of Experimental Biology* 202:891–908.

Dixon, C. 1897. *The migration of birds: an attempt to reduce avine season-flight to law.* Windsor House, London.

Dubey, R. M. 1990. Some studies on Jatinga bird mystery. *Tiger Paper* (Bangkok) 17(4):20–25.

Dutcher, W. 1884. Bird notes from Long Island, N.Y. *Auk* 1:174–179.

Evans Ogden, L. J. 1996. *Collision course: the hazards of lighted structures and windows to migrating birds.* World Wildlife Fund Canada and the Fatal Light Awareness Program, Toronto, Canada.

Ferren, R. L. 1959. Mortality at the Dow Air Base ceilometer. *Maine Field Naturalist* 15:113–114.

Fobes, C. B. 1956. Bird destruction at ceilometer light beam. *Maine Field Naturalist* 12:93–95.

Gastman, E. A. 1886. Birds killed by electric light towers at Decatur, Ill. *American Naturalist* 20:981.

Gauthreaux, S. A. Jr. 1982. Age-dependent orientation in migratory birds. Pages 68–74 in F. Papi and H. G. Wallraff (eds.), *Avian navigation.* Springer-Verlag, Berlin.

Gauthreaux, S. A. Jr., and C. G. Belser. 1999. The behavioral responses of migrating birds to different lighting systems on tall towers [abstract]. In W. R. Evans and A. M. Manville II (eds.), *Avian mortality at communication towers.* Transcripts of proceedings of the Workshop on Avian Mortality at Communication Towers, August 11, Cornell University, Ithaca, New York. Online: http://migratorybirds.fws.gov/issues/towers/agenda.html.

Graf, V. A., and D. V. Norren. 1974. A blue sensitive mechanism in the pigeon retina: λ_{max} 400 nm. *Vision Research* 14:1203–1209.

Green, J. C. 1963. Destruction of birdlife in Minnesota: September 1963. III. Notes on kills at Duluth on September 18/19. *Flicker* 35:112–113.

Green, J. C. 1965. Fall migration: western Great Lakes region. *Audubon Field Notes* 19:37–41, 44.

Green, J. C., and J. P. Perkins. 1964. Some notes on the fall 1964 migration of vireos and warblers. *Loon* 36:127–129.

Hallock, C. (ed.). 1874. Shot gun and rifle: game in season for October. *Forest and Stream* 3:149–150.

Hansen, L. 1954. Birds killed at lights in Denmark 1886–1939. *Videnskabelige Meddelelser fra Dansk Naturhistorisk Forening* 116:269–368.

Hart, N. S. 2001. The visual ecology of avian photoreceptors. *Progress in Retinal and Eye Research* 20:675–703.

Herbert, A. D. 1970. Spatial disorientation in birds. *Wilson Bulletin* 82:400–419.

Herndon, L. R. 1973. Bird kill on Holston Mountain. *Migrant* 44:1–4.

Howell, J. C., A. R. Laskey, and J. T. Tanner. 1954. Bird mortality at airport ceilometers. *Wilson Bulletin* 66:207–215.

Jackson, W. B., E. J. Rybak, and S. H. Vessey. 1974. Vertical barriers to bird migration. Pages 279–287 in S. A. Gauthreaux Jr. (ed.), *A conference on the biological aspects of the bird/aircraft collision problem.* Clemson University, Clemson, South Carolina.

James, P. 1956. Destruction of warblers on Padre Island, Texas, in May 1951. *Wilson Bulletin* 68:224–227.

Johnston, D. 1955. Mass bird mortality in Georgia, October, 1954. *Oriole* 20:17–26.

Jones, J., and C. M. Francis. 2003. The effects of light characteristics on avian mortality at lighthouses. *Journal of Avian Biology* 34:328–333.

Katz, Y. B., and I. K. Vilks. 1981. The role of distribution of illumination in the stellar picture in a planetarium for the orientation of redbreasts robins (*Erithacus rubecula*) in round cages [Russian with English abstract]. *Zoologicheskii Zhurnal* 60:1222–1230.

Kemper, C. 1996. A study of bird mortality at a west central Wisconsin TV tower from 1957–1995. *Passenger Pigeon* 58:219–235.

Kramer, G. 1949. Über Richtungstendenzen bei der nächtlichen Zugunruhe gekäfigter Vögel [On the directional tendencies of nocturnal *Zugunruhe* of caged birds]. Pages 269–283 in E. Mayr and E. Schüz (eds.), *Ornithologie als biologische Wissenschaft.* Carl Winter, Heidelberg.

Kramer, G. 1951. Eine neue Methode zur Erforschung der Zugorientierung und die bisher damit erzielten Ergebnisse [A new method to study migratory orientation and the results thereby obtained thus far]. Pages 269–280 in S. Hörstadius (ed.), *Proceedings of the Xth International Ornithological Congress, Uppsala June 1950.* Almqvist & Wiksell, Uppsala.

Kumlien, L. 1888. Observations on bird migration at Milwaukee. *Auk* 5:325–328.

Larkin, R. P., and B. A. Frase. 1988. Circular paths of birds flying near a broadcasting tower in cloud. *Journal of Comparative Psychology* 102:90–93.

Laskey, A. R. 1960. Bird migration casualties and weather conditions, autumns 1958–1959–1960. *Migrant* 31:61–65.

Lewis, H. F. 1927. Destruction of birds by lighthouses in the provinces of Ontario and Quebec. *Canadian Field-Naturalist* 41:55–58, 75–77.

Lord, W. G. 1951. Bird fatalities at Bluff's Lodge on the Blue Ridge Parkway, Wilkes County, N.C. *Chat* 15:15–16.

Malakoff, D. 2001. Faulty towers. *Audubon* 103(5):78–83.

Manville, A. M. II. 2001. The ABCs of avoiding bird collisions at communication towers: next steps. Pages 85–103 in R. L. Carlton (ed.), *Avian interactions with utility and communication structures.* Proceedings of a workshop held in Charleston, SC, USA. December 2–3, 1999. Electric Power Research Institute Technical Report 1005180.

Manville, A. M. II. In press. Bird strikes and electrocutions at power lines, communication towers, and wind turbines: state of the art and state of the science —next steps toward mitigation. In C. J. Ralph and T. D. Rich (eds.), *Bird conservation implementation and integration in the Americas: proceedings of the third*

international Partners in Flight conference 2002. GTR-PSW-191. USDA Forest Service, Albany, California.

Merriam, C. H. 1885. Preliminary report of the committee on bird migration. *Auk* 2:53–65.

Miller, G. S. Jr. 1897. Winge on birds at the Danish lighthouses. *Auk* 14:415–417.

Morris, S. R., A. R. Clark, L. H. Bhatti, and J. L. Glasgow. 2003. Television tower mortality of migrant birds in western New York and Youngstown, Ohio. *Northeastern Naturalist* 10:67–76.

Munro, J. A. 1924. A preliminary report on the destruction of birds at lighthouses on the coast of British Columbia. *Canadian Field-Naturalist* 38:141–145, 171–175.

Nehring, J. D. 1998. *Assessment of avian population change using migration casualty data from a television tower in Nashville, Tennessee*. M.S. thesis, Middle Tennessee State University, Murfreesboro, Tennessee.

Newman, R. J. 1960. Spring migration: central southern region. *Audubon Field Notes* 14:392–397.

Nikolaus, G. 1980. An experiment to attract migrating birds with car headlights in the Chyulu Hills, Kenya. *Scopus* 4:45–46.

Nikolaus, G., and D. J. Pearson. 1983. Attraction of nocturnal migrants to car headlights in the Sudan Red Sea Hills. *Scopus* 7:19–20.

Norren, D. V. 1975. Two short wavelength sensitive cone systems in pigeon, chicken and daw. *Vision Research* 15:1164–1166.

Overing, R. 1938. High mortality at the Washington Monument. *Auk* 55:679.

Partridge, J. C. 1989. The visual ecology of avian cone oil droplets. *Journal of Comparative Physiology A* 165:415–426.

Romanes, G. J. 1883. *Mental evolution in animals*. Kegan, Paul, Trench & Co., London.

Sage, B. 1979. Flare up over North Sea birds. *New Scientist* 81:464–466.

SAS Institute, Inc. 1999. *The SAS system for Windows*. SAS Institute, Inc., Cary, North Carolina.

Spofford, W. R. 1949. Mortality of birds at the ceilometer of the Nashville airport. *Wilson Bulletin* 61:86–90.

Squires, W. A., and H. E. Hanson. 1918. The destruction of birds at the lighthouses on the coast of California. *Condor* 20:6–10.

Stoddard, H. L. Sr. 1962. Bird casualties at a Leon County, Florida TV tower, 1955–1961. *Bulletin of Tall Timbers Research Station* 1:1–94.

Stoddard, H. L. Sr., and R. A. Norris. 1967. Bird casualties at a Leon County, Florida TV tower: an eleven-year study. *Bulletin of Tall Timbers Research Station* 8:1–104.

Stone, W. 1906. Some light on night migration. *Auk* 23:249–252.

Terres, J. K. 1956. Death in the night. *Audubon Magazine* 58:18–20.

Thomson, A. L. 1926. *Problems of bird-migration*. H. F. & G. Witherby, London.

Tornielli, A. 1951. Comportamento di migratori nei riguardi di un pozzo metanifero in fiamme [Behavior of migratory birds under the influence of a burning natural gas well]. *Rivista Italiana di Ornitologia* II 21:151–162.

Tufts, R. W. 1928. A report concerning destruction of bird life at lighthouses on the Atlantic coast. *Canadian Field-Naturalist* 42:167–172.

Velie, E. D. 1963. Report of a survey of bird casualties at television towers, ceilometers, and other obstructions. *Flicker* 35:79–84.

Verheijen, F. J. 1958. The mechanisms of the trapping effect of artificial light sources upon animals. *Archives Néerlandaises de Zoologie* 13:1–107.

Verheijen, F. J. 1980. The moon: a neglected factor in studies on collisions of nocturnal migrant birds with tall lighted structures and with aircraft. *Die Vogelwarte* 30:305–320.

Verheijen, F. J. 1981a. Bird kills at lighted man-made structures: not on nights close to a full moon. *American Birds* 35:251–254.

Verheijen, F. J. 1981b. Bird kills at tall lighted structures in the USA in the period 1935–1973 and kills at a Dutch lighthouse in the period 1924–1928 show similar lunar periodicity. *Ardea* 69:199–203.

Verheijen, F. J. 1985. Photopollution: artificial light optic spatial control systems fail to cope with. Incidents, causations, remedies. *Experimental Biology* 44:1–18.

Vorobyev, M., D. Osorio, A. T. D. Bennett, N. J. Marshall, and I. C. Cuthill. 1998. Tetrachromacy, oil droplets and bird plumage colours. *Journal of Comparative Physiology A* 183:621–633.

Weir, R. D. 1976. *Annotated bibliography of bird kills at man-made obstacles: a review of the state of the art and solutions*. Department of Fisheries and the Environment, Environmental Management Service, Canadian Wildlife Service, Ontario Region, Ottawa.

Wessels, R. H. A. 1974. *Tetrachromatic vision in the daw* (Corvus monedula *L.*). Ph.D. dissertation, State University of Utrecht, The Netherlands.

Williams, J. N. 1978. *Age dependent factors in the migratory behavior of the white-crowned sparrow*, Zonotrichia leucophrys leucophrys. M.S. thesis, Clemson University, Clemson, South Carolina.

Wiltschko, W., U. Munro, H. Ford, and R. Wiltschko. 1993. Red light disrupts magnetic orientation of migratory birds. *Nature* 364:525–527.

Wiltschko, W., and R. Wiltschko. 1999. The effect of yellow and blue light on magnetic compass orientation in European robins, *Erithacus rubecula*. *Journal of Comparative Physiology A* 184:295–299.

Wiltschko, W., and R. Wiltschko. 2002. Magnetic compass orientation in birds and its physiological basis. *Naturwissenschaften* 89:445–452.