

## Effects of a Hazing-Light System on Migration and Collision Avoidance of Eiders at an Artificial Oil-Production Island, Arctic Alaska

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(Received 14 April 2016; accepted in revised form 22 August 2016)

**ABSTRACT.** During migration, Common and King Eiders (*Somateria mollissima* and *S. spectabilis*) cross the Beaufort and Chukchi Seas of Arctic Alaska. Because they may become attracted to lights, eiders are susceptible to collision with structures, including offshore oil facilities. We used ornithological radar in 2001–04 to characterize the behavior of eiders migrating past Northstar Island, an oil-production island near Prudhoe Bay, Alaska, and to assess the effects of a hazing-light system on migrating eiders. “Eider” radar targets exhibited pulsed, irregular periods of movement; movement rates were higher when sea ice was present, without precipitation, and during tailwinds and crosswinds but were not affected by lights. Velocities (ground speeds) were higher when ice was present and with strong tailwinds. They were lower at night when the lights were on, but higher during the day when the lights were on. Radar targets exhibited little variation in flight behavior as they passed the island; the proportion of non-directional behavior was larger when ice was present, with tailwinds, with weak winds, and near the full moon when it was not visible. Lights had no effect on flight behavior. Birds tended to exhibit more course changes as they approached the island, greater angular changes when they changed course, and larger net increases in passing distance as a result of those course changes when the lights were on; however, none of these differences were statistically significant. Overall, the hazing lights at Northstar did not disrupt the birds’ migratory movements but resulted in increased avoidance of the island.

**Key words:** Alaska; behavior; collision; eider; light attraction; migration; risk; *Somateria*

**RÉSUMÉ.** En période de migration, l’eider à duvet et l’eider à tête grise (*Somateria mollissima* et *S. spectabilis*) survolent la mer de Beaufort et la mer des Tchouktches dans l’Alaska de l’Arctique. Comme ils sont attirés par les lumières, les eiders risquent d’entrer en collision avec des structures, y compris les installations pétrolières au large. De 2001 à 2004, nous avons utilisé un radar ornithologique pour caractériser le comportement des eiders qui migrent au-delà de l’île Northstar, une île de production pétrolière près de Prudhoe Bay, en Alaska, et pour évaluer les effets d’un système d’éclairage de dispersion sur les eiders en migration. Les « eiders » ciblés par le radar présentaient des périodes de mouvement pulsées et irrégulières; les taux de mouvement étaient plus importants en présence de glace marine, en l’absence de précipitation et en présence de vent arrière et de vent latéral, mais n’étaient pas touchés par les lumières. Les vitesses (vitesses au sol) étaient plus élevées en présence de glace et de forts vents arrière. Elles étaient plus basses la nuit lorsque les lumières étaient allumées, mais plus élevées le jour lorsque les lumières étaient allumées. Nous avons observé peu de variation quant au comportement de vol des cibles atteintes par le radar pendant qu’elles survolaient l’île; la proportion de comportements de vol non directionnels était plus importante en présence de glace, de vent arrière, de vent faible et lorsque la pleine lune n’était pas visible. Les lumières n’ont pas eu d’impact sur le comportement de vol. Lorsque les lumières étaient allumées, les oiseaux avaient tendance à changer de direction plus souvent durant leur vol à l’approche de l’île et à effectuer de plus grandes variations angulaires lorsqu’ils changeaient de direction, puis présentaient une nette augmentation de la distance de passage à la suite de ces changements de direction. Toutefois, aucune de ces différences n’était statistiquement importante. En général, les lumières de dispersion de l’île Northstar n’ont pas nui aux mouvements migratoires des oiseaux, mais ces derniers ont davantage évité de voler près de l’île.

**Mots clés :** Alaska; comportement; collision; eider; attirance vers la lumière; migration; risque; *Somateria*

Traduit pour la revue *Arctic* par Nicole Giguère.

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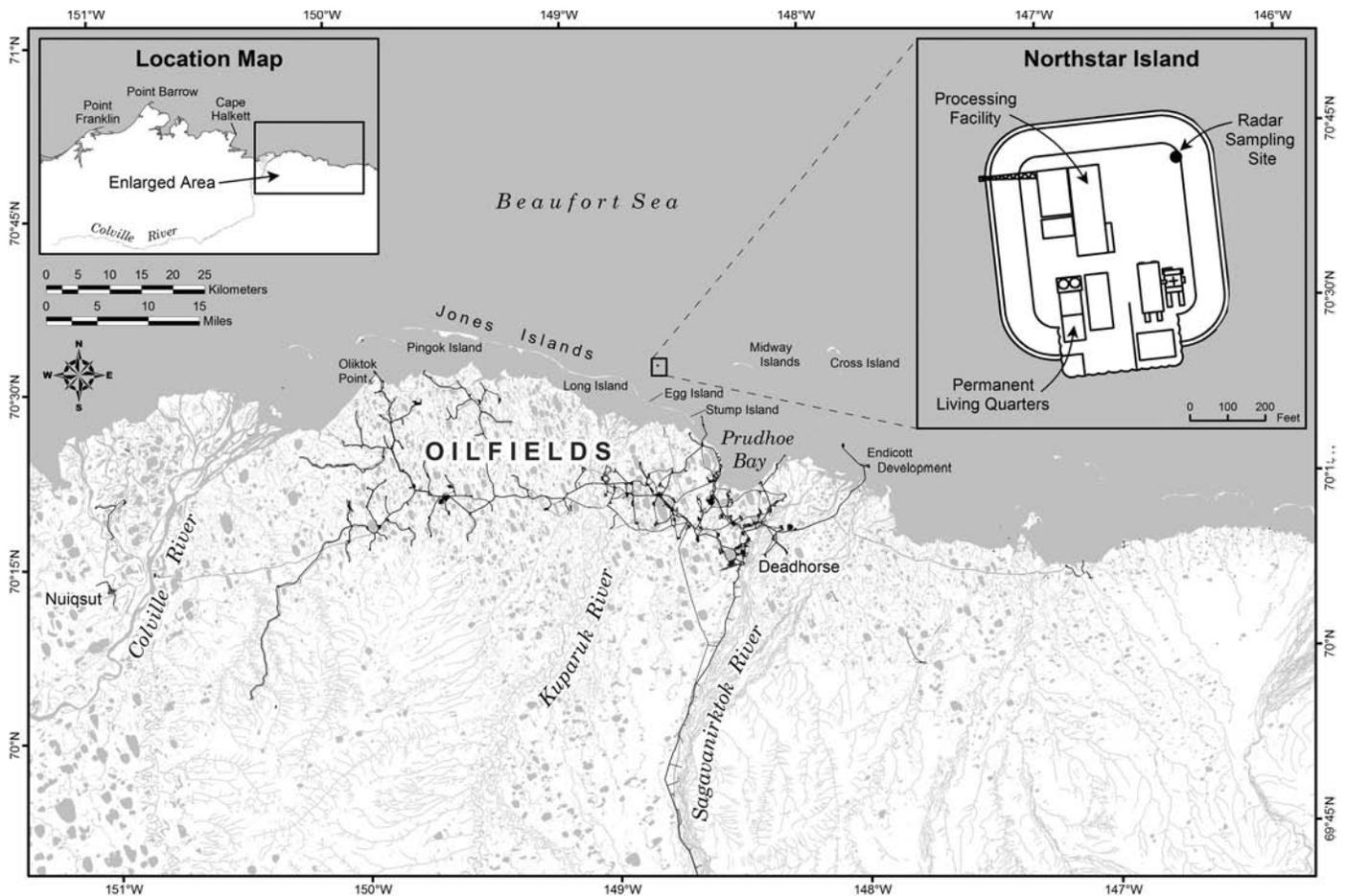


FIG. 1. Location of Northstar Island, northern Alaska, and radar-sampling site.

## INTRODUCTION

Large numbers of migrating Common and King Eiders (*Somateria mollissima* and *S. spectabilis*) cross the Beaufort and Chukchi Seas of Arctic Alaska (Thompson and Person, 1963; Johnson, 1971; Richardson and Johnson, 1981; Johnson and Richardson, 1982; Woodby and Divoky, 1982; Divoky, 1984a; Suydam et al., 1997, 2000b; Quakenbush and Suydam, 2004). Migrating eiders are susceptible to collision with human-made structures in the nearshore zone because they fly low over the water (Thompson and Person, 1963; Johnson and Richardson, 1982; Day et al., 2004), fly rapidly (Day et al., 2004), and may be attracted to bright lights (Dick and Donaldson, 1978; J.L. Sease, Victoria, British Columbia, pers. comm. 1985; J.J. Burns, Fairbanks, Alaska, pers. comm. 2001; L.T. Quakenbush, Fairbanks, Alaska, pers. comm. 2001). Eiders may also collide with land during periods of poor visibility (Mallory et al., 2001), which suggests a limited ability to avoid collision by changing course quickly. Common and King Eider populations in the Beaufort Sea have declined substantially (Suydam et al., 2000a), so any additional source of mortality is of concern.

BP's oil-production island, Northstar Island, is a potential hazard for migrating eiders off northern Alaska

(Fig. 1). (The assets of Northstar Island and its oilfield were purchased by Hilcorp in 2014.) When Northstar was built in 2001, knowledge of eider migration near the island was limited. To assess and mitigate potential impacts, BP, in consultation with the U.S. Fish and Wildlife Service, painted structures tan (not white) to increase the visibility of buildings over a natural background, reduced outdoor lighting as much as possible, shielded exterior lighting and directed it downward and inward to reduce light trespass into the night sky, installed an extremely bright strobe-light system that was intended to warn eiders of the island's presence and haze (drive) them away from the island, and monitored eider collisions. Hazing-light systems are used at night to elicit an avoidance response from birds; they are particularly useful in situations in which flammable materials may prevent the use of pyrotechnics as a hazing technique (Gorenzel and Salmon, 2008). In addition, the flashing nature of the lights does not cause birds to be attracted to the lights, as they might be to fixed, non-flashing lights (Gehring et al., 2009). However, no standard hazing-light system exists, so the system used here was developed as a joint effort of BP engineers and U.S. Fish and Wildlife Service personnel.

Concerns about eider mortality have not been unfounded: collisions with Northstar in fall 2001–04 killed

at least 17 Common Eiders, four King Eiders, and two unidentified eiders, plus 14 Long-tailed Ducks (*Clangula hyemalis*) and two unidentified waterfowl, although none of them were killed during periods when we actually were sampling. Fall migration extended over several months each year, whereas we sampled for only a few weeks each year (Day et al., 2005).

We monitored the behavior of migrating eiders near Northstar during fall 2001–04 to assess the effects of the hazing-light system and determine whether the system disrupted migratory behavior in birds. Results may be relevant to other high-latitude offshore developments, including proposed offshore oil and gas facilities and wind farms in coastal and nearshore areas.

## METHODS

### Study Area

Northstar Island (70°13.5' N, 146°20.6' W) is an artificial oil-production island (3.6 ha in area) that lies about 6 mi (10 km) northwest of Prudhoe Bay, Alaska (Fig. 1; Day et al., 2015). The highest permanent structures on the island are 40 to 50 m above sea level. Numerous bird species, including eiders, nest nearby and migrate through the surrounding area (Thompson and Person, 1963; Schamel, 1977; Richardson and Johnson, 1981; Johnson and Richardson, 1982; Divoky, 1984a, b; Johnson and Herter, 1989; Suydam et al., 1997, 2000a, b; Day et al., 2004; Fischer and Larned, 2004).

The area has a permanent community for oilfield support to the southeast, at Deadhorse, and a permanent Inupiat community to the southwest, at Nuiqsut, on the Colville River. Other than activity on the island itself, there is little human activity and disturbance in this area, and oilfield workers on the island are not allowed to fish or hunt to minimize disturbance and reduce the attractiveness of the island to predators such as Arctic foxes (*Vulpes lagopus*) and polar bears (*Ursus maritimus*). Hence, the main sources of possible disturbance to wildlife in this area are the crew boats that supply the island during the open-water season and helicopters that supply it during periods of broken ice. After the sea ice freezes completely, the island is supplied by ice roads, but no eiders are present at that time, so the disturbance from ice-road traffic is negligible.

The island's hazing-light system consists of 14 white strobe lights mounted ~15 m above the ocean's surface along the island's perimeter wall. These lights are pointed out to sea and fire asynchronously at a rate of 40 flashes/min with a daytime intensity of 20 000 candela (ca) and a nighttime intensity of 2 000 ca. These are standard U.S. Federal Aviation Administration anti-collision lights used to mark towers so that planes do not collide with them. Their flashing rates and light intensities are not adjustable. During data collection, the hazing lights were operated every other hour (i.e., 60 min on, then 60 min off), whereas

the island's other permanent lights remained on at all times and represented controls for the experiment.

### Data Collection

We studied the movements, behavior, and flight altitudes of eiders during their fall migration each year on 20 nights between late August and mid-October in 2001–04. We sampled for 7 to 11 h per night with radar and visual equipment (binoculars and night-vision equipment), collecting 298 h of radar data and 525 h of visual data. A calendar day began at 0700 and ended at 0659 the following morning, so an entire night's sampling was classified as occurring on the same day. When possible, we collected radar and visual data concurrently, with the radar operator helping the visual observer locate birds and the observer identifying targets. The visual observer used 10× binoculars during daylight and crepuscular periods and a 5× night-vision scope during periods of darkness. At times, we could not collect data because of heavy precipitation, the presence of polar bears that drove us indoors for safety, or excessive sea-clutter echoes on the radar screen caused by high, wind-driven waves. These were rare occurrences, except in 2002–04, when sea ice was minimal and sea-clutter echoes occurred about 50% of the time.

At the beginning of each sampling session, we recorded environmental information on wind direction and speed, light condition (daylight, crepuscular, darkness; a few beginning and ending sessions in some years occurred during daylight periods), precipitation, minimal visibility (the nearest distance one could see something; poor: < 500 m; good: ≥ 500 m), lunar visibility (moon visible or not visible to an observer on the ground), and anti-collision light setting (off, on). We experimented with the lighting system by collecting data with the anti-collision lights off for one half-hour sampling session (25 min of sampling + 5 min break) and lights on for the next half-hour session, then reversing the sequence for the following two sessions. Although this experimental procedure provided similar sampling intensity in lighting categories, numbers of birds observed on radar varied among sessions and between categories.

We monitored eider movements with a Furuno™ FCR 1411 X-band surveillance radar transmitting at 9.410 GHz with a peak power output of 10 kW (Furuno Electric Co., Nishinomiya, Japan; Cooper et al., 1991). The radar's range was set at 1.5 NM (~2.77 km) in a north–south direction, although the range was 2.0 NM (~3.67 km) to the east because the screen was not circular in shape (Fig. 2). We used the radar to determine movement rates (radar targets/h), ground speeds (velocities), general flight behaviors (three categories: straight-line, erratic, and circling; Fig. 2), and flight paths of birds (i.e., where they occurred in relation to the island). The sampling unit was a radar target (echo), which indicated a flock of birds (regardless of flock size) on the display screen. For each target, we recorded time; target type (“eider-like,”

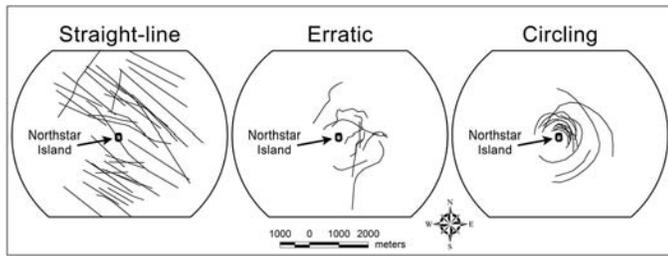


FIG. 2. Examples of straight-line, erratic, and circling tracklines on radar near Northstar Island, northern Alaska.

“non-eider-like”; see below); ground speed velocity (to nearest 5 mi/h [8 km/h]; we were unable to measure accurately on targets not flying in a straight line); and flight behavior (Fig. 2). When possible, we visually determined the species and number of birds in a target. Excluding one night of extensive gas-flaring that caused extensive attraction of birds other than eiders to the island, when the accuracy of target identification was lower because non-eiders were flying so quickly (Day et al., 2015), the accuracy of target identification was 62%. The main source of misidentification appeared to be Long-tailed Ducks, which sometimes fly with characteristics similar to those of eiders and which migrate across the Beaufort Sea at the same time as eiders do. We also traced target tracklines and digitized them later with GIS software.

An “eider-like” radar target had specific characteristics. Eider flocks usually have overall directional flight with small (fine-scale) lateral and vertical motion. On the radar screen, their echoes generally are large and fast-moving (95% of visually confirmed eider targets fly at 40–60 mph (64–96 km/h); Day et al., 2004) and generally (but not always) have directional (straight-line) flight, whereas “non-eider-like” targets range widely in size, speed, direction, and behavior. Although “eider-like” (hereafter, eider) targets exhibit erratic lateral motion at small scales, they generally are directional at larger scales (e.g., Richardson and Johnson, 1981).

#### Data Analysis

We examined the effects of both environmental factors and lights on movements of migrating eiders concurrently because bird migration is affected strongly by environmental factors (Richardson, 1990). Consequently, the birds’ responses to lights occurred within the context of their responses to the overall environmental conditions they faced while migrating. Migratory attributes that we examined were common ones examined in most migratory studies: movement (passage) rates, flight velocity, flight behavior, and spatial distribution. We also examined behaviors in high resolution by first digitizing tracklines of individual targets in a GIS system, then using the trackline information to examine aspects of behavior.

We compared competing models of factors affecting aspects of migration and movements with a

Kullback-Leibler information-theoretic approach (Burnham and Anderson, 2002). In building sets of candidate models, we included factors that potentially were important in explaining variation in eider movements and behavior. We examined the effects of (1) *ice conditions* by categorizing years as either “ice present” (2001; pack ice near the island) or “ice absent” (2002–04; pack ice far offshore); (2) *time of day* by categorizing samples from daytime and crepuscular periods as “daytime” and nocturnal samples as “nighttime” (see Day et al., 2015:370); (3) *precipitation level* by categorizing samples as “no precipitation” or “precipitation” (including fog); (4) *visibility* by categorizing session visibility as “good” ( $\geq 500$  m) or “poor” ( $< 500$  m); (5) *wind direction* by using theoretical or relative wind directions (see below); (6) *wind strength*, especially in the context of wind direction  $\times$  wind strength interactions (Day et al., 2004), by categorizing strength as “weak” ( $\leq 16$  km/h) or “strong” ( $> 16$  km/h); and (7) *hazing lights* by categorizing them as either “off” or “on.”

We used theoretical wind directions for all analyses except flight velocity, for which we used relative wind directions. Theoretical directions reflect the fact that most birds leave the Beaufort Sea by flying northwesterly toward Barrow. Hence, winds blowing from the west, northwest, or north represented a theoretical headwind for birds assumed to be leaving the Beaufort Sea by flying to the northwest; those from the east, southeast, or south represented a tailwind; those from the northeast and southwest represented a crosswind; and no winds or variable winds were called calm. Relative directions, in contrast, were based on the actual direction of the wind relative to the actual flight direction of bird targets (i.e., not all birds actually flew toward the northwest); they occurred only in analyses of flight velocity because that factor strongly affected velocity (ground speed) and hence had implications for collision avoidance.

We also examined the effects on bird behavior of lunar visibility from the ground and of moon phase, as indicated by the fraction of the lunar disk illuminated on each date (see <http://aa.usno.navy.mil/data/docs/MoonFraction.php>). We categorized the moon as “full” if the disk was 75% or more illuminated and as “not full” if it was less than 75% illuminated and recorded whether the moon was visible to an observer on the ground, assuming that a bird flying low over the ocean would be seeing what we saw.

All statistical tests were two-tailed, and the level of significance ( $\alpha$ ) for tests was 0.05. We calculated Akaike Information Criteria adjusted for small sample sizes ( $AIC_c$ ) with least-squares or log-likelihood models and used Akaike weights to estimate the probability that each model was the best model in the set (Anderson et al., 2000). We considered a potential “best model” to be one with a  $\Delta AIC_c \leq 2.0$  units from that model having the lowest  $AIC_c$ . For each variable, we calculated the sum of Akaike weights for all models containing that variable and calculated unconditional parameter estimates and SEs (Anderson et al., 2000; Burnham and Anderson, 2002). We calculated the

weight of evidence in favor of the top-ranked model ( $w_{\text{best}}/w_{\text{second-best}}$ ; Burnham and Anderson, 2002) and interpreted that weight as the strength of support.

We analyzed the effects of environmental factors and lights on movement rates by first tabulating numbers of targets recorded during each sampling session, then converting them to movement rates (targets/h) for each session. We then used the estimated movement rates for each session to calculate the mean movement rate by day, factor (ice conditions, time of day, precipitation, session visibility, wind direction, wind strength), and lighting setting (off, on). We examined the effects of the lights on movement rates by testing the above factors (except visibility, which was correlated with precipitation) with all combinations of multifactor ANOVA models containing the above main effects (factors) and related two-way interactions; interaction terms were used only in models that included both factors as main effects. Prior to analysis, we added 0.167 to each movement-rate estimate to avoid computing the logarithm of zero (Mosteller and Tukey, 1977), then normalized the movement-rate data with an ln-transformation. The large number of zeros that skewed the statistical distribution of the data was potentially problematic, but Monte Carlo simulations of untransformed data indicated that significance levels of t-tests did not differ greatly from those expected, reflecting the t-test's robustness to deviations from normality (Zar, 1984).

We conducted a similar analysis of flight velocity to determine whether the lights increased, decreased, or had no effect on the velocity of migrating birds. We examined the effects of environmental factors and lights on flight velocities by testing the above factors (except precipitation, which was correlated with visibility but was not as appropriate in this case) in ANOVA models, as described above.

We also analyzed differences in general patterns of flight behavior. After pooling erratic and circling behaviors as "non-directional" (following Day et al., 2015), we summarized frequencies of flight-behavior categories (directional and non-directional) by factor and lighting setting and then tested for differences between proportions of straight-line (i.e., directional) and non-directional behaviors with multifactor logistic-regression models containing the above factors (except precipitation), plus the factors moon phase (full, not full), moon visible (yes, no), and moon phase  $\times$  moon visibility. We compared models based on AIC<sub>c</sub> values (Burnham and Anderson, 2002).

To examine the effects of anti-collision lights on spatial distribution, we digitized radar tracklines of all eider targets and then used GIS software (Arcview; ESRI, Redlands, California) to examine the data by lighting setting. We used these digitized tracklines to examine the effects of various factors on fine-scale movements. First, we classified parts of tracklines into five categories of distance from the island (0–499 m, 500–999 m, 1000–1499 m, 1500–1999 m, > 1999 m). For each category, we then examined the effects of each factor on (a) the number of course changes ( $\geq 5^\circ$ )

per kilometer of trackline, (b) the mean angular change per course change, and (c) the net change in passing distance from the island resulting from a course change. (The net change is the difference between the original estimated passing distance and the actual passing distance after changing course.) For these analyses, we used only those targets for which we could see the entire trackline.

We analyzed the number of course changes by using Generalized Linear Models with a Poisson distribution for counts and using the length of the tracklines as the offset variable to account for variable lengths. We ran one model with light setting, distance zone, and an interaction between the two, then ran models to test for a difference with lights at each distance zone separately. We used two-factor ANOVAs to analyze how lighting category, distance zone, and interaction between lighting and distance affected angular change and net change in passing distance from the island. We tested for differences between lighting categories at each distance zone individually by using t-tests for independent samples. We used Bonferroni adjustments for multiple inference when comparing the effect of lights at different distance zones (Beal and Khamis, 1991); these models were run in IBM SPSS Statistics 18.0. We calculated 95% confidence intervals by conducting 5000 bootstrap simulations of the data.

## RESULTS

In 2001, sea ice surrounded the island, and there were few high winds and little precipitation other than fog. In 2002–04, in contrast, extensive retreat of the sea ice occurred, along with frequent precipitation and many high winds, which resulted in high seas. Ambient light conditions at this latitude also differed within and between years, with periods of complete darkness ranging between 4 h: 11 min (24 August) and 13 h: 51 min (22 October). Lunar phases and the visibility of the moon also differed within and between years.

### *Movement Rates*

During the study, we recorded 928 radar targets (470 with the lights off and 458 with the lights on) that we called eiders on the basis of flight characteristics or visual identification. Eider radar targets exhibited pulsed movements (Fig. 3). From 24 August to 4 September 2001, they exhibited little movement: no targets were recorded on six of the 12 nights and maximal rates were  $\sim 3$  targets/h on a few nights. However, from 5 to 13 September 2001, movement rates averaged 5–36 targets/h on nearly every night. In contrast, movement rates in 2002–04 were almost uniformly low (near or at 0 targets/h on nearly all nights). Rates as large as  $\sim 5$  targets/h occurred on only three nights in 2002 (13, 20, and 25 September) and on the final night in October 2004.

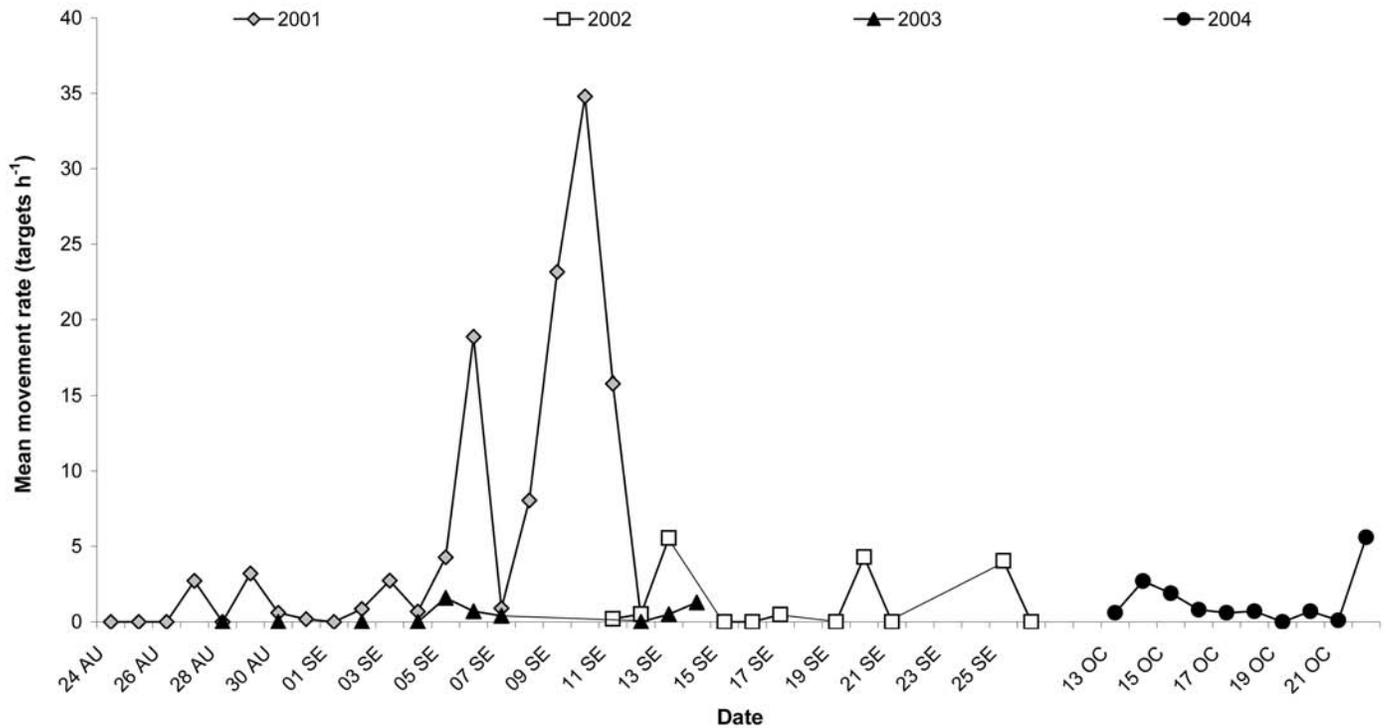


FIG. 3. Movement rates (targets/h) of “eider” radar targets near Northstar Island, northern Alaska, fall 2001–04, by date.

The best-approximating model included the parameters ice conditions ( $\Sigma w_i = 1.000$ ), precipitation level ( $\Sigma w_i = 1.000$ ), and wind direction ( $\Sigma w_i = 0.995$ ), all of which were included in all models in the best-model set (Tables 1 and 2). This model had an Akaike weight of 0.303 and a weight of evidence ( $w_{\text{best}}/w_{\text{second best}}$ ) 1.6 times that of the second-best model, which provided fairly strong support for the best model. Movement rates were higher when sea ice was present (2001) than when it was absent (2002–04; see Discussion), larger without precipitation than with it, and larger during tailwinds and crosswinds than during headwinds and calm winds. Movement rates did not differ by time of day, wind strength, lights, or any interaction term.

#### Flight Velocity

Flight velocities (ground speed) varied little with most factors, averaging 77.1 km/h (47.9 mi/h) overall (range 40–129 km/h). The best-approximating model included the parameters ice conditions ( $\Sigma w_i = 0.747$ ), relative wind direction ( $\Sigma w_i = 1.000$ ), wind direction  $\times$  wind strength ( $\Sigma w_i = 1.000$ ), and lights  $\times$  time of day ( $\Sigma w_i = 0.993$ ; Tables 1 and 2). This model had an Akaike weight of 0.373 and a weight of evidence 1.6 times that of the second-best model, providing fairly strong support for the best model. Velocities were larger when ice was present than absent, larger with tailwinds than other directions, and larger with strong tailwinds than weak ones. During the day, velocities were greater when the lights were on; at night, however, they were greater when the lights were off. Velocity did not differ by visibility.

#### Flight Behavior

Flight behavior of eider radar targets was overwhelmingly directional, in that 95% of all targets flew in a straight-line (directional) manner, whereas 4% flew erratically and 1% flew by circling. The best-approximating model included the parameters ice conditions ( $\Sigma w_i = 0.987$ ), wind direction ( $\Sigma w_i = 0.990$ ), wind strength ( $\Sigma w_i = 0.949$ ), and moon phase  $\times$  moon visibility (included in all candidate models; Fig. 4, Tables 1 and 2). This model had an Akaike weight of 0.210, which was 1.5 times that of the second-best model, providing fairly strong support for the best model. The proportion exhibiting non-directional behavior was larger when ice was present than when it was absent, larger with tailwinds than with headwinds, and larger with weak winds than with strong ones. The interaction moon phase  $\times$  moon visibility was also important: when the moon was full, the proportion of non-directional behavior was larger when the moon was not visible than when it was visible, but moon visibility had no effect when the moon was not full. Behavior did not vary by light setting.

#### Course Changes

Eider radar targets exhibited variable numbers of course changes at all distances from the island. The mean number of vertices/km of line generally increased as birds approached the island (Fig. 5, top), suggesting that eiders were seeing the island and responding to it naturally by turning more often as they approached it, presumably to avoid collision. The interaction between lights and distance zone was significant

TABLE 1. Significant factors affecting movement rates, velocity, and flight behavior of “eider” radar targets near Northstar Island, northern Alaska, fall 2001–04. All models examined the effects on the response variable of these factors: ice conditions (ice), time of day (time), precipitation level (precipitation) or session visibility (visibility), wind direction (direction; relative for velocity, theoretical for all others), wind strength (strength), and lights (off, on). A few other models included the factors moon visibility (moon) and moon phase (phase). For each response variable and species-group, these models have a change in Akaike Information Criterion ( $\Delta AIC_c$ ) of  $\leq 2$ .  $n$  = sample size;  $K$  = number of estimable parameters.

Response variable / Model	$n$	$K$	$AIC_c$	$\Delta AIC_c$	Akaike weight $w_i$
<b>Movement rate</b>					
Ice, precipitation, direction	721	7	662.90		0.303
Ice, precipitation, direction, lights	721	8	663.78	0.88	0.195
Ice, time, precipitation, direction	721	8	664.76	1.86	0.119
<b>Velocity</b>					
Ice, time, direction, strength, lights, direction $\times$ strength, lights $\times$ time	912	12	3495.76		0.373
Ice, time, visibility, direction, strength, lights, direction $\times$ strength, lights $\times$ time	912	13	3496.68	0.91	0.236
<b>Flight behavior</b>					
Ice, direction, strength, moon visibility, moon phase, moon $\times$ phase	928	9	327.58		0.210
Ice, time, direction, strength, lights, lights $\times$ time, moon, phase, moon $\times$ phase	928	12	328.46	0.88	0.136
Ice, visibility, direction, strength, moon, phase, moon $\times$ phase	928	10	328.98	1.40	0.104
Ice, time, direction, strength, moon, phase, moon $\times$ phase	928	10	329.04	1.46	0.101
Ice, time, visibility, direction, strength, lights, lights $\times$ time, moon, phase, moon $\times$ phase	928	13	329.33	1.75	0.088
Ice, direction, strength, lights, moon, phase, moon $\times$ phase	928	10	329.54	1.96	0.079

TABLE 2. Model-weighted parameter estimates for factors affecting movement rates, velocity, and flight behavior of “eider” radar targets near Northstar Island, northern Alaska, fall 2001–04. Estimates for movement rates are ln-transformed, and non-significant parameter estimates have been removed.

Response variable	Model parameter	Estimate	SE	$p$
Movement rate	Intercept	-1.764	0.155	< 0.001
	Ice conditions	1.280	0.131	< 0.001
	No precipitation	1.170	0.139	< 0.001
	Calm	-0.173	0.271	0.522
	Crosswind	-0.005	0.159	0.975
	Headwind	-0.572	0.153	< 0.001
Velocity	Intercept	46.765	0.949	< 0.001
	Ice conditions	1.075	0.526	0.041
	Lights off	0.971	0.653	0.137
	Daytime	0.466	0.785	0.553
	Visibility good	0.939	0.948	0.32
	Calm	-1.387	1.310	0.290
	Crosswind	-1.786	0.641	0.005
	Headwind	-2.352	0.808	0.004
	Wind strong	3.705	0.634	< 0.001
	Strong crosswind	-3.074	1.803	0.088
	Strong headwind	-5.125	1.563	0.001
	Lights off-daytime	-4.441	1.168	< 0.001
	Flight behavior	Intercept	-6.274	1.093
Ice conditions		1.643	0.579	0.005
Moon full		1.915	0.529	< 0.001
Moon visible		-0.283	0.560	0.613
Moon full-moon visible		-2.194	0.851	0.010
Lights off		0.513	0.588	0.383
Daytime		0.813	0.665	0.221
Visibility good		0.627	0.670	0.349
Calm wind		-1.788	0.808	0.027
Crosswind		-0.019	0.471	0.969
Headwind		-1.802	0.812	0.027
Wind weak		1.586	0.641	0.013

( $p = 0.014$ ). Mean numbers of course changes/km for the innermost two distance zones (0–499 m and 500–999 m) were significantly different from those for the outermost two zones (1500–1999 m and > 1999 m;  $p = 0.004$  for 0–499 vs. 1500–1999;  $p < 0.001$  for other comparisons).

Within the innermost zone, the mean number of course changes/km was 46% higher with the lights on than with lights off; however, the difference was not significant ( $p = 0.191$ ). The number of course changes/km increased by 59% from the 500–999 m zone to the 0–499 m zone with lights on, whereas the number of course changes/km decreased by 5% from the 500–999 m zone to the 0–499 m zone when the lights were off. After Bonferroni corrections for multiple comparisons, the only significant difference between lighting categories occurred in the 1000–1499 m zone; there, the number of course changes/km was significantly higher when the lights were off than when the lights were on ( $p = 0.050$ ).

#### Angular Changes

Targets also exhibited variably sized angular changes when course changes did occur, with the mean angular change increasing as they approached the island, but only in the innermost zone (Fig. 5, bottom). The mean angular change in the innermost zone was 13% higher with the lights on than with them off, and the mean angular change increased by 34% from the 500–999 m zone to the 0–499 m zone with the lights on but increased by only 15% with the lights off; however, these differences were not statistically significant.

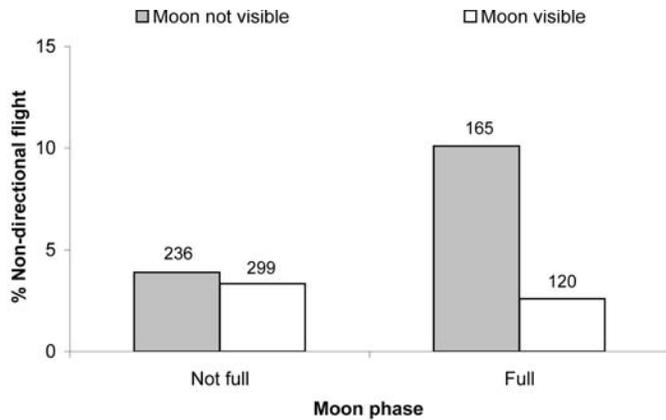


FIG. 4. Proportion of “eider” radar targets exhibiting non-directional flight behavior near Northstar Island, northern Alaska, fall 2001–04, by moon phase and moon visibility. Numbers above columns are total numbers of observations in each category. The moon phase  $\times$  moon visibility interaction was significant.

### Effect of Course Changes on Net Passing Distance

Another way to examine these data is to examine the net change in passing distance by subtracting the original distance estimated (i.e., what it would have been without a course change) from the actual passing distance resulting from the course change (Fig. 6). The mean net change in the innermost distance zone was positive (away from the island) by  $\sim 155$  m, whereas it was about 0 m in the 500–999 m distance zone and negative in zones beyond that, suggesting a net movement away from the island at close distances, no effect at intermediate distances, and slight movement toward the island at great distances. This variable effect with distance explains the lack of a significant effect of lights on island-passing distances seen earlier. Although there was a net movement away from the island in the innermost distance zone, the lights had no significant effect on the response in any distance zone ( $p \geq 0.085$  for all). The net passing distance with the lights on was 17% larger than it was when lights were off, but, again, the difference was not statistically significant. Because the statistical distribution of net changes in this innermost zone indicated that nearly all changes were either zero or away from the island, rather than toward it, we conclude that collision avoidance was occurring but that the lights had no significant effect on that net change.

## DISCUSSION

If all of the 928 radar targets that we studied in 2001–04 had an average size similar to that of flocks we located visually ( $23.4 \pm 95\%$  CI 6.5 birds/flock), we would have collected data on  $\sim 21\,750 \pm 6032$  migrating eiders in the vicinity of Northstar Island. For context,  $\sim 450\,000+$  eiders pass Barrow each fall (Suydam et al., 2000a, b).

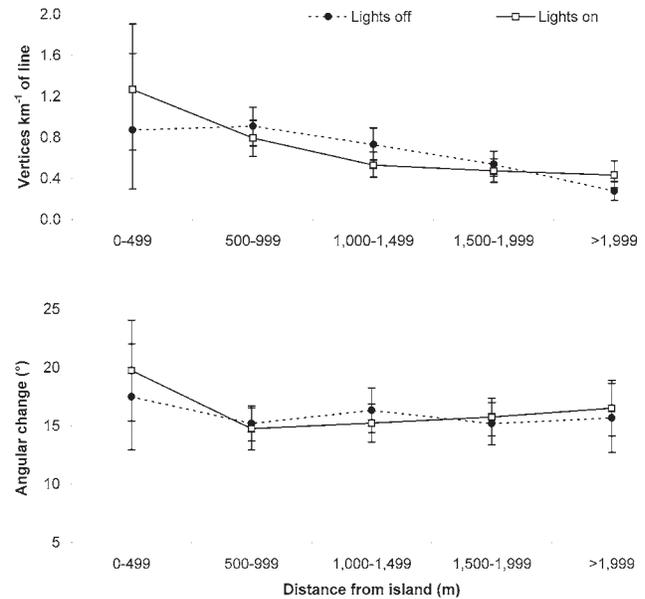


FIG. 5. Changes in the mean number of course changes/km of flight trackline (top) and mean angular change of course changes (bottom) of “eider” radar targets near Northstar Island, northern Alaska, by distance from the island and anti-collision lighting setting. Data are plotted as mean  $\pm$  95% confidence intervals.

### Movement Rates

Eiders exhibited a pulsed pattern of migration at Northstar in all years. Movement rates varied substantially among nights, indicating pulses of migratory movement and presumably reflecting conditions favorable or unfavorable for migration. This pulsed movement pattern of eider migration has also been seen at Barrow (Thompson and Person, 1963; Suydam et al., 1997; Day et al., 2004) and along the Beaufort Sea coast of Alaska (Johnson and Richardson, 1982).

Movement rates at Northstar were higher when ice was present, higher without precipitation, and highest with tailwinds and crosswinds; lights had no effect. At Barrow, tailwinds also resulted in larger movement rates and headwinds resulted in lower movement rates (Thompson and Person, 1963; Day et al., 2004). Interaction between wind direction and wind strength also affected movement rates at Barrow (Day et al., 2004), but not at Northstar. The association between movement rates and tailwinds may be explained by the fact that it is energetically more beneficial for birds to migrate with tailwinds than with headwinds. At Barrow, heavy fog (i.e., precipitation and poor visibility) also depressed movement rates (Day et al., 2004). Migrating birds in general avoid flying in precipitation (Alerstam, 1990; Richardson, 1990), although one would assume that the effect would be smaller on waterbirds, whose plumage is kept waterproof, than on terrestrial passerines and smaller in fog than in heavy rain. Many eiders also migrated past Northstar Island at night, a pattern similar to that seen at Barrow (Day et al., 2004) and in the Baltic Sea (Alerstam et al., 1974) under good migration conditions.

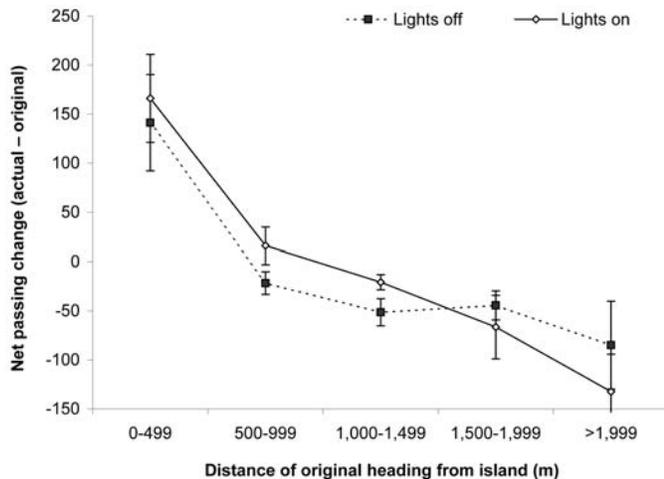


FIG. 6. Mean net change in passing distance (actual distance after course change – original estimated distance before course change) of flight tracklines of “eider” radar targets near Northstar Island, northern Alaska, by distance from the island and anti-collision lighting setting. Positive numbers indicate that targets passed the island at a greater distance than they would have if they had not changed course. Negative numbers indicate that targets passed the island at a shorter distance than if they had not changed course. Data are plotted as mean  $\pm$  95% confidence intervals.

Finally, the association of higher migration rates with sea ice is obscure but may be associated with a narrow zone of open water near the coast into which migrating birds are funneled during years of high sea ice in the Beaufort Sea. In contrast, in years in which the ice-edge was hundreds of kilometers offshore, migrating eiders were able to migrate across a broad front of open water, which dramatically reduced the number of birds passing within radar range of Northstar Island.

#### Flight Velocity

Overall flight velocities averaged  $\sim$ 48 mi/h ( $\sim$ 77 km/h) at Northstar and ranged from 40–129 km/h. Factors affecting flight velocity were ice conditions, relative wind direction, wind direction  $\times$  wind strength, and lights  $\times$  time of day. Encouragingly, the lights  $\times$  time of day interaction indicated that eiders slowed  $\sim$ 3.5% when the lights were on at night, which suggests they were responding to lights by slowing down, thereby increasing the probability of avoiding collision. To our knowledge, this is the first study to document a slowing effect of bright lights on flight velocity of birds.

Eiders averaged a flight speed of  $\sim$ 77 km/h, which is similar to velocities recorded in the Baltic Sea (70–110 km/h; Alerstam et al., 1974) and at Barrow (84 km/h; Day et al., 2004). At the latter location, velocities were greater with good visibility, greater with tailwinds and crosswinds than with headwinds (as in this study), greater with weak headwinds than with strong ones, and larger with strong tailwinds (as in this study) and crosswinds than with weak ones (Day et al., 2004).

#### Flight Behavior

Although the proportion of non-directional flight behavior varied little ( $\sim$ 5% overall), several factors affected it: ice conditions, wind direction, wind strength, and moon phase  $\times$  moon visibility. The proportion of birds exhibiting non-directional flight was larger when ice was present, with tailwinds, during weak winds, and (during a full moon) when the moon was not visible, being either not risen yet or obscured by clouds. During many of these periods when the full moon was not visible, stars were visible in parts of the night sky. These results suggest that eiders at high latitudes use the moon for help in orientation during nocturnal migration; thus, behavioral confusion (non-directional flight) or attraction to large light sources may result if the full moon is not visible, as seen in Newell’s Shearwaters in Hawaii (Reed et al., 1985; Telfer et al., 1987). This hypothesis is supported by the fact that 30 (83%) of the 36 eiders found downed (i.e., dead or on the ground but alive) at Northstar and nearby oil-production islands in fall 2001–04 were downed near a full moon, which occurred naturally on 36% of the nights, and 97% were downed during a waxing moon, which occurred on 50% of the nights (Day et al., 2005). In addition, 89% were downed during a period of weak barometric change (occurred on 57% of the nights), and the few available data suggested that the one night with downing likely had fog (probably occurred on 41% of the nights; however, we had complete weather records for only some nights). Wind speed and direction during downings were not harsh; in fact, mean wind speed during downings (10.2 mi/h; 16.4 km/h) was below the overall average across the four years of fall data (13.7 mi/h; 22.0 km/h). Hence, lunar phase and trend appeared to exert a strong effect on downing rates, whereas overall weather did not appear to be exceptionally harsh, judging by indications such as wind speed and rate of barometric change. We also suspect an effect of fog, although sample sizes are too small for certainty.

Some research has been done on the effects of the moon on light attraction and collision-related mortality. Crawford (1981) found a bimodal pattern of bird kills at tall structures centered on both the new moon and the full moon. In addition, most large kills of birds on autumn migration in eastern North America occur during cloudy, inclement weather that blocks the birds’ ability to see the night sky and lowers flight altitudes (e.g., Overing, 1936, 1938). Migrating birds are most strongly attracted to light at offshore oil platforms in the North Sea during cloudy nights (Sage, 1979; Hope-Jones, 1980; Wallis, 1981; Wiese et al., 2001). They leave as soon as dawn arrives (Alerstam, 1990), which suggests that the visibility of the moon and stars is important in nocturnal orientation and that in its absence, birds may be attracted to other large light sources (also see Telfer et al., 1987).

TABLE 3. Summary of effects of lights on migratory movements and behavior of presumed eiders, fall 2001–04. For those analyses that showed significant effects of lights on a response variable, the nature of that response is described; ns = not statistically significant.

Response variable	Response
Movement rates	ns
Velocity	higher in daytime when lights on; slower at night when lights on
Non-directional flight behavior	ns
Number of course changes	46% higher when lights on; however, ns
Angular changes	13% higher when lights on; however, ns
Net passing distance	17% higher when lights on; however, ns

### *Fine-Scale Movements*

Eiders clearly saw Northstar Island and responded to it by increasing the number of course changes and by increasing their mean angular change per course change as they approached the island. The result was a net movement of tracklines away from the island in the closest distance zone (0–499 m). All three of these types of responses to the island appeared to be enhanced 13%–46% by having the lights on, but the differences were not statistically significant; however, the strength of the responses falls off with increasing distance from the island, suggesting a natural response that was enhanced by the lights. Because the variability in movements increased as birds approached the island, the variability in the data also increased, creating what we suspect was low statistical power to detect small differences in movements with this study design. It is possible that the lights had no effect on the birds' responses, but near the island, the stronger responses were seen only when the lights were on. This idea leads us to believe that there is a real response to the lights, but it was swamped by variability near the island.

## LIGHTS

Migrating eiders responded to lights in some ways that suggest the lights enhanced natural collision-avoidance behavior (Table 3). The lights formed a hazing and alerting system pointed out to sea that produced extremely bright strobe flashes painful to a human's eyes at ~1400–1700 m and that presumably had a similar effect on the eyes of migrating eiders, which averaged approximately that distance from land when passing the island. These lights reduced flight velocity at night and resulted in a spatial redistribution away from the island. Hence, the natural avoidance response of these birds appeared to be enhanced only intermittently. On the other hand, there was no evidence that the lights were disrupting any aspect of migration, in that birds still successfully passed the island and migratory behavior was not radically different in different light settings during our study. Eider collisions may occur primarily under certain weather conditions that

may occur only rarely. We observed no collisions during our sampling for this study, whereas some birds were killed during periods in which we were not sampling. This episodic nature of bird collisions complicates monitoring studies such as this one. Although we factored different weather variables into the study design and the analysis, any lighting effects on eider movements that vary with weather conditions will result in lower statistical power.

One effect of the lights was seen in the fine-scale movements of birds as they approached the island. Although the behavior was not statistically significant, birds approaching the island tended to change direction more often, exhibit greater angular changes when they did change directions, and move away from the island more when the lights were on than they did when the lights were off. These responses were estimated to be 13%–46% greater when the lights were on than when they were off. The lights  $\times$  time of day interaction indicated that mean velocities at night were smaller when the anti-collision lights were on than when they were off. That is, anti-collision lights caused eiders to slow at night, giving them more time to react and avoid collision by changing course. The exact cause for this slowing is unknown, but we presume that it is because the birds were slowing as a reaction to extremely bright lights that temporarily would cause them to lose some of their night vision for short periods. Alternatively, this is probably the only location where they encounter bright flashing lights, so it is possible that their slowing is simply a response to a novel phenomenon in their environment. The opposite daytime results suggest that eiders become confused by these lights during the daytime or that the higher power of the daytime lights (20 000 ca vs. 2000 ca at night) may have caused some of this difference.

Other research at communications towers indicates that flashing lights, preferably white lights similar to those used in this study, significantly reduce the frequency of avian collisions (Gehring et al., 2009). Although we are aware of no information on whether waterfowl see lights at night the same way that passerines and other birds that often are killed at towers do (e.g., Wiltschko et al., 1993), the low frequency of collisions at Northstar Island suggests that they may. Recent research in western Greenland shows that Common Eiders in particular are susceptible to being attracted to bright, non-flashing searchlights and deck-lights on ships, particularly in mid-winter (Merkel and Johansen, 2011).

Although this particular hazing-light system shows some effects that are important for reducing the probability of collision by migrating eiders, we suggest two questions leading to additional research about whether this type of system can be modified to achieve additional effectiveness in hazing and alerting birds. The first question involves the effectiveness of synchronicity of flashing by the lights themselves. These lights were wired electrically into three groups (western side of the island, northern side, eastern side) that fired independently of the others; in addition, all of the lights on one side of the island fired independently

of each other. Hence, the first logical question is whether synchronicity of firing would improve or decrease the effectiveness of hazing; alternatively, it is possible that a synchronous blast of light that bright (~30 000 ca if all lights fired at once) could disrupt migratory behavior.

The second question involves the wavelength of light used in the hazing lights. There is evidence that lights in red wavelengths can disrupt migratory behavior and increase attraction of migrating passerines (Wiltschko et al., 1993; Poot et al., 2008), although light intensity may moderate the effects of different wavelengths (Muheim et al., 2002). In particular, the work by Poot et al. (2008) shows that changing external lighting systems to green wavelengths dramatically reduces the attraction of passerines to structures. Hence, a logical question is whether eiders respond to lights of different wavelengths the same way that passerines do, or whether certain wavelengths are more effective at hazing eiders from a structure than others.

#### ACKNOWLEDGEMENTS

This study was funded by BP Exploration (Alaska) Inc.; however, the conclusions are ours and do not necessarily represent those of BP Exploration. We thank P. Martin for help with analytical design; A. Erickson and W. Cullor for logistical help; and on-island personnel for assistance. At ABR, L. Atanas, J. Keen, T. Obritschkewitsch, J. Parrett, J. Shook, A. Stickney, and M. Vekasy helped collect data; and D. Dissing, A. Gall, J. Plissner, and A. Zusi made the figures. This manuscript has been improved by the review of A.E. Gall and two anonymous reviewers. This paper is dedicated to the memory of Robert H. Day's late friend R.S. Hadley (1943–2015).

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