Global Ecology and Conservation 23 (2020) e01102

Contents lists available at ScienceDirect

Global Ecology and Conservation

journal homepage: http://www.elsevier.com/locate/gecco

Original Research Article

Ineffectiveness of light emitting diodes as underwater deterrents for Long-tailed Ducks *Clangula hyemalis*

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ARTICLE INFO

Article history:
Received 23 January 2020
Received in revised form 30 April 2020
Accepted 4 May 2020

Keywords:
Foraging
LED lights
Seaduck bycatch
Visual deterrents
Visual fields

ABSTRACT

Gillnet bycatch accounts for over 400,000 bird mortalities worldwide every year, affecting a wide variety of species, especially those birds that dive when foraging. Technological solutions to improve gillnet visibility or deter birds from approaching nets, such as LED lights, are essential for aiding diving birds to perceive nets as a hazard. Designing such solutions requires obtaining visual and behavioural ecology information from species to assess their ability to see the warning devices, and to examine their behavioural responses to them. Seaducks, particularly Long-tailed Ducks *Clangula hyemalis*, have high bycatch mortality rates. We examined the visual fields of four Long-tailed Ducks to understand their three-dimensional view around the head. The visual field characteristics of this species indicate a reliance on visual guidance for foraging associated with their capture of varied, mobile prey in their generalist diet. We subsequently conducted dive tank trials to test the effectiveness of 12 different LED treatments as visual deterrents to the underwater foraging behaviour of 8 Long-tailed Ducks. During each trial, ducks were offered food rewards from a specific underwater location in a dive tank, having the choice of whether to take the food or not. At the same time, they were exposed to either one LED light or the control (no light) to determine whether the presence of each light affected the foraging success rate of dives compared to the control. Exposure of ducks to all 13 treatment combinations was randomised over the trial period. White lights with an increasing flash rate were shown to have a significant positive effect on foraging success, and likely acted as a visual attractant, rather than as a deterrent. No light treatment significantly reduced the foraging success of ducks. LED lights did not inhibit the feeding of Long-tailed Ducks. Such lights may be ineffective as underwater visual deterrents when deployed on gillnets, while white flashing lights may make foraging sites more attractive to Long-tailed Ducks.

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https://doi.org/10.1016/j.gecco.2020.e01102

1. Introduction

Worldwide, at least 400,000 birds are killed annually as bycatch in gillnet fisheries with over 148 species being susceptible, particularly auks (Alcidae), penguins (Spheniscidae), divers (Gaviidae), and ducks (Anatidae) (Žydelis et al., 2013). The impact on seabird populations (Regular et al., 2013) and the global nature of gillnet fisheries (Waugh et al., 2011) highlights the urgent requirement to find suitable mitigation strategies to reduce bird bycatch.

Existing techniques to improve the visibility of gillnets, such as high-visibility net mesh (Melvin et al., 1999), reflective barium sulphate (Trippel et al., 2003), high contrast monochrome net panels (Field et al., 2019), and illumination with LED (light emitting diode) lights (Field et al., 2019; Mangel et al., 2014, 2018), have varied in their effectiveness to decrease bird bycatch. Of these, LED lights may provide a relatively inexpensive method for reducing bycatch of specific vertebrate taxa without affecting target fish catch (Bielli et al., 2020; Mangel et al., 2014; Ortiz et al., 2016; Wang et al., 2010). More information, however, is required to determine if LED lights may benefit the wide range of bird species recognised to be highly vulnerable to gillnet entanglement.

Birds foraging underwater are likely to have restricted vision due to the alteration of key optical properties upon immersion (focus, visual fields and image brightness) that reduce their ability to detect gillnets (Martin and Crawford, 2015). Understanding the sensory abilities and behaviour of seabirds may further assist the development of appropriate visual warning devices for gillnets (Martin and Crawford, 2015). Previous studies have combined the examination of avian visual abilities and perception with behavioural responses to objects in air, for informing the design of visual alerts to reduce collisions at airports (Blackwell et al., 2009, 2012; Hausberger et al., 2018). Similar methods have yet to be applied to bycatch-susceptible birds approaching novel threats underwater.

Bird species vary considerably in the arrangement of their visual field for each eye (monocular fields) and how they are combined (the binocular overlap of the two eyes) with the blind areas above and behind the head, to produce the total visual field (Martin, 2017). These determine the volume of space around the head from which visual information can be extracted by the bird at any instant (Martin, 2017). Species-specific variation in visual field characteristics are primarily associated with foraging ecology, dependent upon whether the bird species relies on visual or non-visual cues for feeding (Martin, 2014). These differences have been reported in multiple seabirds, including auks (Martin and Wanless, 2015), penguins (Martin, 1999; Martin and Young, 1984; Sivak et al., 1987), cormorants (Phalacrocoracidae) (White et al., 2007), albatrosses (Diomedeidae) (Martin, 1998), skimmers (Laridae) (Martin et al., 2007b), petrels, and shearwaters (Procellariidae) (Martin and Brooke, 1991; Martin and Prince, 2001). To date, no visual field data have been published for seaducks, and this information could determine whether this taxon can visually detect fishing nets and warning devices (Martin and Crawford, 2015).

Long-tailed Ducks *Clangula hyemalis* are diving seaducks highly impacted by gillnet bycatch (Žydelis et al., 2013). This species forages underwater for molluscs, crustaceans and fish (Ouellet et al., 2013) reaching a maximum diving depth of 25 m (Žydelis and Richman, 2015) where ambient light levels are lower than at the sea surface (Martin and Crawford, 2015), thus reducing the visual information available to them during foraging. The high number of gillnet bycatch mortalities recorded for this species (at least 25,000 from bycatch studies over four decades) in the North and Baltic Seas likely under-represents the actual magnitude of annual mortalities (estimated as tens of thousands), which has contributed to significant population declines in these regions (Bellebaum et al., 2013; Žydelis et al., 2009, 2013).

Our goals were: (1) to measure the visual field characteristics of Long-tailed Ducks to assess the importance of visual cues for foraging associated with these parameters of avian vision, and (2) to investigate their behavioural responses to submerged LED lights of a prototype designed to illuminate gillnets. We predicted that Long-tailed Ducks would have a visual field topography associated with a reliance on visual cues for accurate bill control at close range (Martin, 2017), in relation to them capturing a variety of mobile prey as generalist foragers (Jamieson et al., 2001; Žydelis and Ruškytė, 2005). Our prediction would then support the rationale for experimental trials to expose the ducks to different LED light combinations during diving to test efficacy for deterrence. We hypothesised that the presence of each LED light placed underwater would act as a visual deterrent to foraging and reduce the number of successful foraging dives (dives in which the food was eaten from the target location) compared to a control (no light).

2. Methods

2.1. Study location and subjects

We conducted research at the U.S. Geological Survey Patuxent Wildlife Research Center in Maryland, USA during October and November 2018 using a captive colony of Long-tailed Ducks held in outdoor enclosures and a purpose-built dive tank (Crowell et al., 2016). Adult Long-tailed Ducks had been bred in captivity and were individually identified with plastic leg rings. Twelve ducks (seven females and five males) were selected for the experiment based on their health and breeding status, which included six birds that had previously been exposed to the dive tank. These 12 birds were randomly divided into two mixed sex groups, each containing six individuals, and placed in two enclosures adjacent to the dive tank facility 48 h prior to the start of training.

Ethical approval for the experimental procedures was organised through Patuxent Wildlife Research Center in accordance with their Animal Care and Use Committee policies (IACUC approval number 2018-04). Ethical permission was also obtained from Royal Holloway University of London and the Royal Society for the Protection of Birds (RSPB) Animal Ethics Committee for the handling and restraint of birds.

2.2. Visual field measurements

The visual field parameters of adult Long-tailed Ducks were measured in four individuals (two females and two males) selected randomly from the birds in the experimental groups. Measurements from individual birds were taken during the dive tank training period (as discussed later), and not during the LED light trial period. Measurements were conducted for two afternoons once training sessions had finished. Each bird was placed in a plastic container and taken to a windowless room which provided suitable quiet and darkened conditions for the procedure. The ophthalmoscopic reflex technique (Martin and Katzir, 1994) was used to measure the visual field characteristics of individuals. This involved restraining an alert bird to immobilise its body, while keeping its head fixed in position at the centre of a visual perimeter, by placing its bill in a specially designed holder (Martin et al., 2007a). The standard procedure described in previous studies was followed (Martin and Katzir, 1994; Martin and Portugal, 2011; Martin and Wanless, 2015) and is summarised below.

Each bird was placed in a foam rubber cradle using straps made from velcro which wrap upon themselves. The feet and legs were tucked away beneath the bird and the head was held in position at the centre of a visual perimeter by a bill holder specially manufactured for this species. The bill was taped in position using Micropore tape (3M Health Care, Hammfelddamm, Neuss, Germany) without covering the nostrils. Each bird was restrained for approximately 30 min whilst the measurements were made. The head was positioned such that the angle of the bill to the horizontal approximated that which the birds adopt spontaneously when held in the hand. The visual perimeter has a coordinate system which follows conventional latitude and longitude with the equator aligned vertically in the birds' median sagittal plane and this coordinate system is used for the presentation of visual field data.

The eyes were examined using a Welch Allyn standard ophthalmoscope (Hillrom UK, Ashby de la Zouch, Leicester, UK) set at zero dioptres and mounted on the perimeter arm. For each eye, the visual projections of the limits of the retinal visual field and maximum binocular overlap were determined as a function of elevation in the median sagittal plane. It was possible to measure limits of the visual field at 10-degree intervals of elevation in an arc from directly behind the head down to 60° below the horizontal in front of the head. During the measurements, the bill holder intruded into the view of the eyes at some elevations below the bill. We could not record visual field data at these elevations and binocular field width was estimated as the mean value of the binocular field widths above and below these elevations. Collection of these visual field data enabled topographical maps of the visual field and its principal components to be constructed for this species (provided in the results section).

2.3. Dive tank experiment

2.3.1. Training

The purpose of the training period was to habituate the 12 Long-tailed Ducks (divided into two mixed sex groups) to the experimental set up in the dive tank (width 1.8 m, length 2.4 m, depth 2.5 m) without exposure to any LED lights. Individuals were trained in several stages to receive food rewards of mealworms *Tenebrio molitor* (a highly palatable food item in their diet) released into the water at different depths (see below), until they learned to forage from a square wooden tray (side 0.55 m) on the dive tank floor (Figs. 1 and 2). The overhead lights were switched on during training so the observer could view the behaviour (e.g. foraging, bathing, preening, resting, swimming) of the ducks both while on the surface of the water and underwater. This allowed the observer to determine whether any bird exhibited behaviours suggestive of stress (e.g. excessive vocalisations, attempted escape) that would necessitate their removal from the dive tank; although this did not occur. Four cameras (960H waterproof colour camera, Speco Technologies, New York, USA) placed above the dive tank and on the windows (Fig. 1) were connected to a computer screen. This allowed the behaviour of individuals during dives to be observed. A fifth camera (GoPro Hero 3, GoPro Inc, San Mateo, USA) positioned on the largest window (Fig. 1) provided video recording during the experimental trials when LED lights were deployed.

Each group of ducks were trained on alternate days and underwent food restriction for 17 h prior to entering the dive tank, to experience positive reinforcement operant conditioning to food (Enstipp et al., 2001; Grémillet et al., 2006; White et al., 2007). Ducks were placed in plastic carriers and taken a short distance (<30 m) to the dive tank building, where individual identification and body mass were recorded prior to their release into the tank. Birds were carried in the container up steps to the top of the tank, the container was placed on a small platform at the water's surface and the door was opened, they chose when to leave the container. On entering the water, birds were allowed a period of 5 min to acclimatise to the dive tank prior to starting the training. This acclimatisation period was not necessary once the LED trials commenced. The period of "working time" per bird was limited to 45 min per day. During training and trial periods, the body mass of each bird was recorded every 24-h to check for any significant reduction in mass (loss of more than 10% body mass compared to the value at the start of the study), which could indicate stress due to disruption in their food intake. Any individual with significant mass reduction would be removed from the study, although this did not occur.

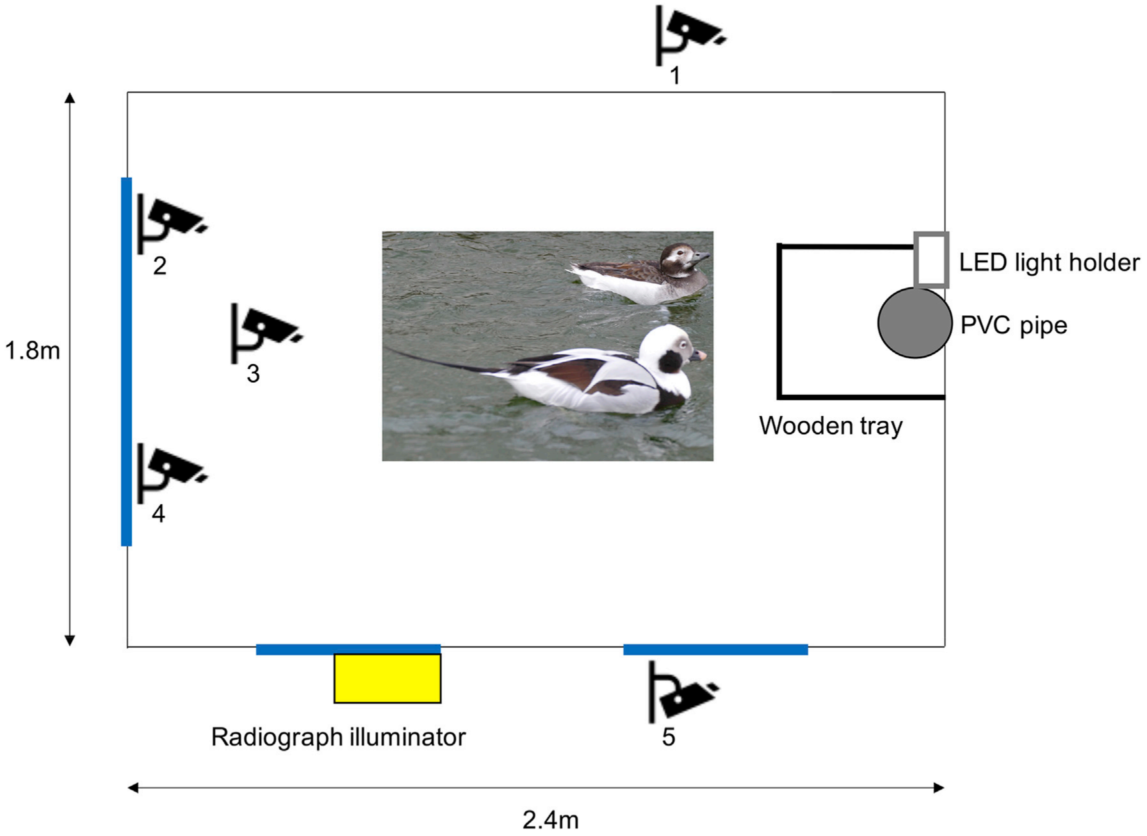

Fig. 1. Plan view of the experimental set up in the dive tank, with the Long-tailed Ducks swimming towards the food dispenser. There are 3 windows present in the dive tank (1 main window and 2 side windows), shown as lines on the tank walls, with the radiograph illuminator placed in one side window. The square wooden tray is on the bottom of the tank, with the PVC pipe and LED light holder positioned above the tray. Cameras 1 and 3 are located above the tank, cameras 2, 4 and 5 are placed on the windows of the dive tank, with camera 2 providing the video recording from the main window.

To get the birds to forage at depth, training progressed through a series of stages. In stage one, each individual was trained to receive the food reward at the water's surface. During the initial period, individual birds were observed searching for their conspecifics and we subsequently trained birds in pairs to allow for social interactions that facilitate foraging behaviour (White et al., 2009). In stage two, ducks were placed in six mixed-sex pairs and trained to receive the food reward underwater at shallow depths (<1.0 m). These pairs remained the same for the training period. Initially mealworms were released by the experimenter from their hand at 0.45 m depth underwater. Subsequently, bird pairs were trained to receive the mealworms from a short PVC pipe (depth of 0.80 m) connected to a food dispenser. The final stage involved teaching the bird pairs to dive down to the bottom of the tank to consume mealworms from the wooden tray (Fig. 2). The mealworms were released from the food dispenser down a long pipe (2.30 m) onto the tray. A weighted rope was used as a marker to indicate a depth of 1.5 m; in this experimental set-up when ducks dived below this depth, we considered it to be a deep foraging dive relative to the overall depth of the tank. Once individual ducks were feeding from the tray consistently, their training period was completed. The total training period lasted 14 days.

2.3.2. LED light trials

The training period identified four individuals that frequently failed to dive for mealworms, and these were removed from the study. This led to a reduction in the overall sample size to eight individuals, which were divided into two groups (each group contained two specific male-female pairs) to undergo 17-h food restriction prior to the light trials. Groups were trialled on alternative days. This trial schedule provided rest days for birds without food restriction.

Each day, the bird pairs from one group underwent consecutive trials in the morning, with bird pairs being kept fixed for the period of the trials. Before each trial, the overhead lights were switched off (to reduce the background illumination) and a radiograph illuminator for film X-rays was switched on (its rectangular shape ensured it fitted in one window of the tank; Figs. 1 and 3), which provided sufficient, low level illumination from the side window to enable clear observation of the birds. Prior to the start of the trial, one LED light or the control was positioned in the correct underwater location (as described below). This ensured that ducks were immediately exposed to the LED or control at the start of the trial once they entered the

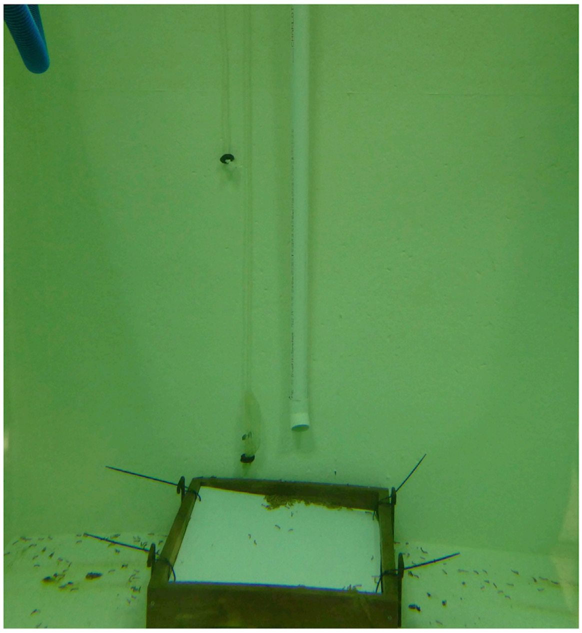

Fig. 2. Experimental set up during training viewed from the main dive tank window (see Fig. 1). The plastic LED light holder is threaded through a weighted rope (2.35 m length) positioned just above the wooden tray to the left side of the PVC pipe. In this photo, no LED light is placed in the holder, as this is the control treatment. The PVC pipe has a 45-degree angled end to allow the mealworms to fall out onto the tray. The white plastic sheet on the tray provides a light background in contrast to the dark colour of the mealworms, which can be seen on the photograph as small brown shapes. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

water, since the LED light switched on automatically when immersed in water. Mealworms were released from the food dispenser, and down the pipe onto the tray for the start of the trial.

Trials started at 08:30 (UTC-5) and each trial lasted 30 min from when one bird of the pair first entered the water. The total mass of mealworms (80 g) in the dispenser was delivered in small amounts to the tray to encourage foraging throughout the trial. During each 30-min trial, the birds were constantly exposed to one single stimulus, either one LED light (Table 1) placed in its holder, or the control (an empty holder with no light) that was attached to the rope positioned just above the feeding tray and adjacent to the pipe exit ((Fig. 2). The LED lights known as “net-lights” (Fishtek Marine, Devon, UK) varied in colour and strobe frequency combinations and their technical specifications are provided (Table 1). Whilst the spectral sensitivities of the photopigments found in Long-tailed Ducks are unknown, Mallards *Anas platyrhynchos* have tetrachromatic colour discrimination in the visible spectrum and ultraviolet sensitivity (Jane and Bowmaker, 1988). It is likely that Long-tailed Ducks have similar spectral sensitivities to Mallards, which would enable this species to differentiate the colours amongst the LED lights and provided the rationale for testing them. Birds’ behaviour was recorded by monitoring live cameras and verified using recorded video footage from the GoPro camera after the trial.

During each 30-min trial, two variables were recorded per individual bird: (*i*) the number of successful foraging dives (successful foraging was defined as a dive during which at least one mealworm was consumed from the tray or as it fell out of the pipe), and (*ii*) the number of attempted foraging dives (attempted foraging was defined as a dive to a depth of 1.5 m or more, but the bird did not forage from the tray, either because it did not forage at all, or because it foraged elsewhere in the dive tank, and this was regarded as unsuccessful).

Overall, the bird pairs were exposed to each of the 13 treatments (12 LED lights and the control) only once on separate trial days. The orders of treatment exposure were randomised over the different trial days. Consequently, one trial for each treatment exposure led to 13 trials per pair (and hence per individual), which has provided data from eight individual Long-tailed Ducks ($n = 8$). Thus, each pair took 13 days to cycle through all treatments. On completion of the trial, the pair were removed from the tank and immediately returned to their enclosure to minimise their time away from the group.

2.3.3. Data analysis

Boxplots were created for the number of successful foraging dives, number of attempted foraging dives and the proportion of successful foraging dives (total number of successful foraging dives divided by the total number of dives) across treatments. A repeatability estimation for body mass of individual ducks was conducted prior to model analysis. Generalised linear mixed models (GLMM) were used to evaluate whether each LED light treatment (coded in Table 1) influenced foraging success of the ducks in comparison to the control (coded as “A”). The number of successful foraging dives and the number of attempted (hence unsuccessful) foraging dives were combined into the binary response variable of “forage success” whereby each dive

Fig. 3. The dive tank showing the rectangular, radiograph illuminator placed in the side window, which provided sufficient illumination to view the ducks in the water when the overhead lights were switched off during the trials.

was coded as successful (1) or not successful (0) per individual. The sample size of 8 provided sufficient statistical power for the GLMM, similar to other behavioural studies (White et al., 2007). Subsequent statistical analyses of the dataset used a binomial error distribution and GLMM fit by maximum likelihood (Laplace Approximation). Full models included the fixed factors of treatment (each LED light combination compared to the control) and/or day (of the trial), and the random effect of individual (since bird pairs remained fixed for the trial period). Model selection was performed by creating models including all possible combinations of the variables listed and assessing model performance based on AIC values (Akaike Information Criterion). The final model included both treatment and day factors with the random effect of individual. Statistical analyses were conducted in R version 3.5.3. (R Core Team 2019) using the *lme4* package (Bates et al., 2015) for the GLMM (glmer function), the *rptR* package (Stoffel et al., 2017) for repeatability estimation and *ggplot2* (Wickham, 2016) for visualisation. Effects were considered significant when $p < 0.05$. The direction of the effect was evaluated from the standard estimate values.

3. Results

3.1. Visual field measurements

Visual field data were combined to provide mean values of the angular separation of the retinal field margins at each elevation in the median sagittal plane of the head (Fig. 4). Topographical maps illustrate the visual fields in different planes (Fig. 5): the visual fields in the frontal sector (Fig. 5a), a horizontal section through the visual fields in the horizontal plane (Fig. 5b), and a vertical section through the binocular field in the median sagittal plane (Fig. 5c).

The binocular field of Long-tailed Ducks is vertically long and relatively narrow (Fig. 5a), with a maximum width of approximately 38° (Fig. 4) and vertical extent of approximately 121° that could be measured below the bill (Fig. 5c). The projection of the bill at 110° is within the binocular field just below its centre (Fig. 5a, c). Across the recorded elevations, the blind area of this species extends from in front of the head to the rear of the head (Figs. 4 and 5a), with a maximum width of 33° directly behind the head (Fig. 5b). Below the elevation of −90°, it was not possible to record the limits of the retinal visual fields due to the bird's body obstructing the measurements, although the blind area continues to extend behind and below the head. No spontaneous eye movements were observed in this species and eye movements could not be induced using methods previously described (Martin and Katzir, 1994).

3.2. LED light trials

The repeatability estimation showed that body masses of ducks were highly repeatable across individuals ($R = 0.95$, $p < 0.001$) over the trials, which led to the exclusion of body mass as a variable in the GLMM. In total, we completed 52 trials (four bird pairs each undertook 13 trials), which provided 1178 dive observations from the eight individuals. Overall, there were 859 successful foraging dives; 72.9% of total dives. All individuals achieved successful foraging dives during every trial (Fig. 6a), and the number of successful foraging dives was greater than that of attempted (unsuccessful) foraging dives for each treatment (Fig. 6a and b). Variation in the numbers of successful and attempted foraging dives among LED light combinations compared to the control is apparent (Fig. 6a and b). The highest proportion of successful foraging dives compared to the control (A) occurred on exposure to the white increasing flash (WI) LED (WI median = 0.95, A median = 0.76; Fig. 6c). Exposure to the WI LED increased the forage success of ducks compared to the control (GLMM: $\beta \pm SE = 1.05 \pm 0.47$, $z = 2.26$, $p = 0.02$; Table A1). For all other light treatments, there was no significant difference in forage success between each treatment and the control ($z < 1.84$, $p > 0.05$; Table A1).

Table 1
Specifications for the 12 “Fishtek Marine net-light” LED light combinations.

LED light combination & code	Wavelength at peak intensity (nm)	Light output (lumens)	Flash duration & flash rate interval (ms) & seconds (s)
White Continuous (WC)	NA (polychromatic)	1.3	NA
White Flash Constant (WF)	NA (polychromatic)	10	52 ms flash duration, 2 s flash interval
White Flash Increase (WI)	NA (polychromatic)	10	52 ms flash duration, increasing flash rate from 2 s to 250 ms flash intervals. Flash sequence repeated every 16 s
Green Continuous (GC)	520	1.6	NA
Green Flash Constant (GF)	520	12	52 ms flash duration, 2 s flash interval
Green Flash Increase (GI)	520	12	52 ms flash duration, increasing flash rate from 2 s to 250 ms flash intervals. Flash sequence repeated every 16 s
Red Continuous (RC)	623	0.5	NA
Red Flash Constant (RF)	623	3.7	52 ms flash duration, 2 s flash interval
Red Flash Increase (RI)	623	3.7	52 ms flash duration, increasing flash rate from 2 s to 250 ms flash intervals. Flash sequence repeated every 16 s
Blue Continuous (BC)	465	0.2	NA
Blue Flash Constant (BF)	465	1.3	52 ms flash duration, 2 s flash interval
Blue Flash Increase (BI)	465	1.3	52 ms flash duration, increasing flash rate from 2 s to 250 ms flash intervals. Flash sequence repeated every 16 s

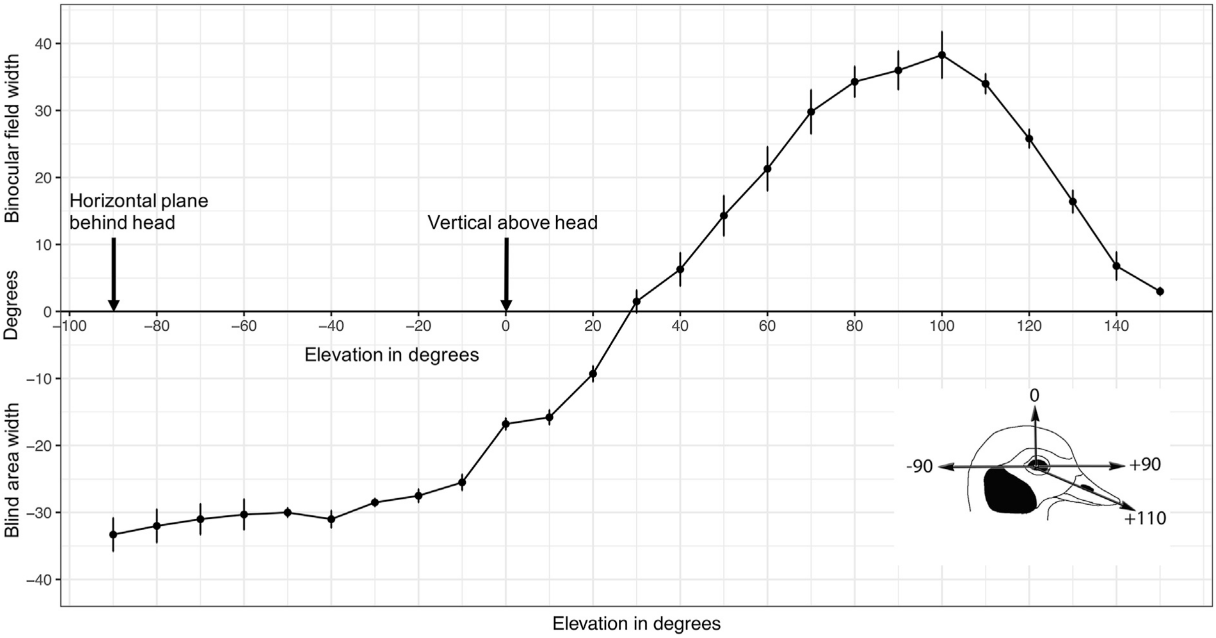

Fig. 4. The mean ± SE angular separation of the retinal field margins as a function of elevation in the median sagittal plane in Long-tailed Ducks ($n = 4$). Positive values indicate overlap of the field margins (binocular vision) and negative values indicate the width of the blind area. The coordinate system is such that the horizontal plane is defined by the elevations −90° (behind the head) and +90° (in front of the head), and 0° is directly above the head. The drawing shows the duck’s head in profile with the key coordinates indicated, with the projection of the eye-bill tip axis (mean value of 110°). This is the head position spontaneously adopted by a bird held in the hand.

4. Discussion

Long-tailed Ducks have similar visual field characteristics to several bird species that are primarily visually guided foragers, which include a relatively narrow and vertically long binocular field, the bill tip projecting close to the centre of the binocular field, and the maximum binocular width occurring at or near the bill tip projection (Martin, 2007, 2014). These characteristics are found in a wide range of avian species with varied foraging ecologies reliant on visual cues for precise control of the bill (or feet) for prey capture (Martin, 2014), including several gillnet-bycatch susceptible seabirds such as Great

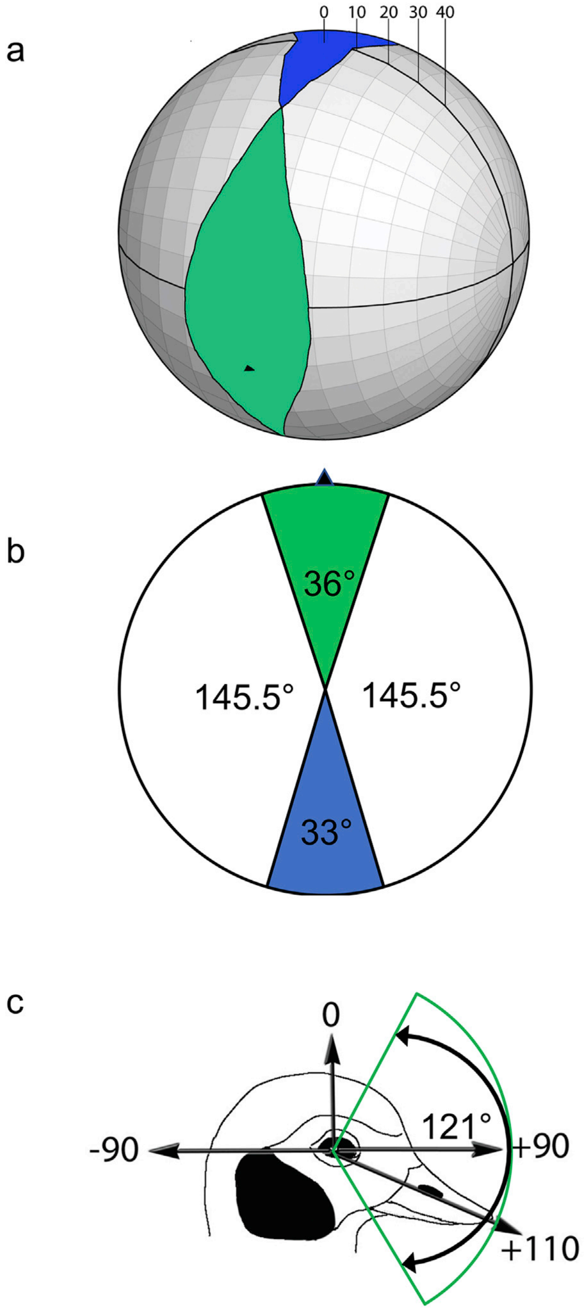

Fig. 5. Visual field diagrams of Long-tailed Ducks in three views based upon mean measurement values ($n = 4$). **(a)** A perspective view of an orthographic projection of the retinal field boundaries of the two eyes, with the bill tip projection indicated by a black triangle. The diagram uses a conventional longitude and latitude coordinate system with the equator aligned vertically in the median sagittal plane of the bird (grid at 10° intervals). The bird's head can be visualised to be positioned at the centre of a transparent sphere with the bill tip and field boundaries projected onto the surface of the sphere. **(b)** Horizontal section through the visual fields in the horizontal plane (defined by elevations $-90°$ and $+90°$) showing the widths of the visual field components in degrees, with the direction of the bill indicated by a black triangle. **(c)** Vertical section through the binocular field in the median sagittal plane. For all diagrams, the green areas represent the binocular field, blue areas represent the blind areas and white areas represent the lateral fields. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Cormorants *Phalacrocorax carbo* (Martin et al., 2008), Humboldt Penguins *Spheniscus humboldti* (Martin and Young, 1984), and Common Guillemots *Uria aalge* (Martin and Wanless, 2015). Ducks (e.g. Pink-eared Ducks *Malacorhynchus membranaceous*) which rely primarily upon tactile cues to guide their foraging have different visual field configurations, primarily a narrower and vertically longer binocular field which extends behind the head, and the projection of the bill tip at the lower periphery of the visual field (Martin, 2007, 2017).

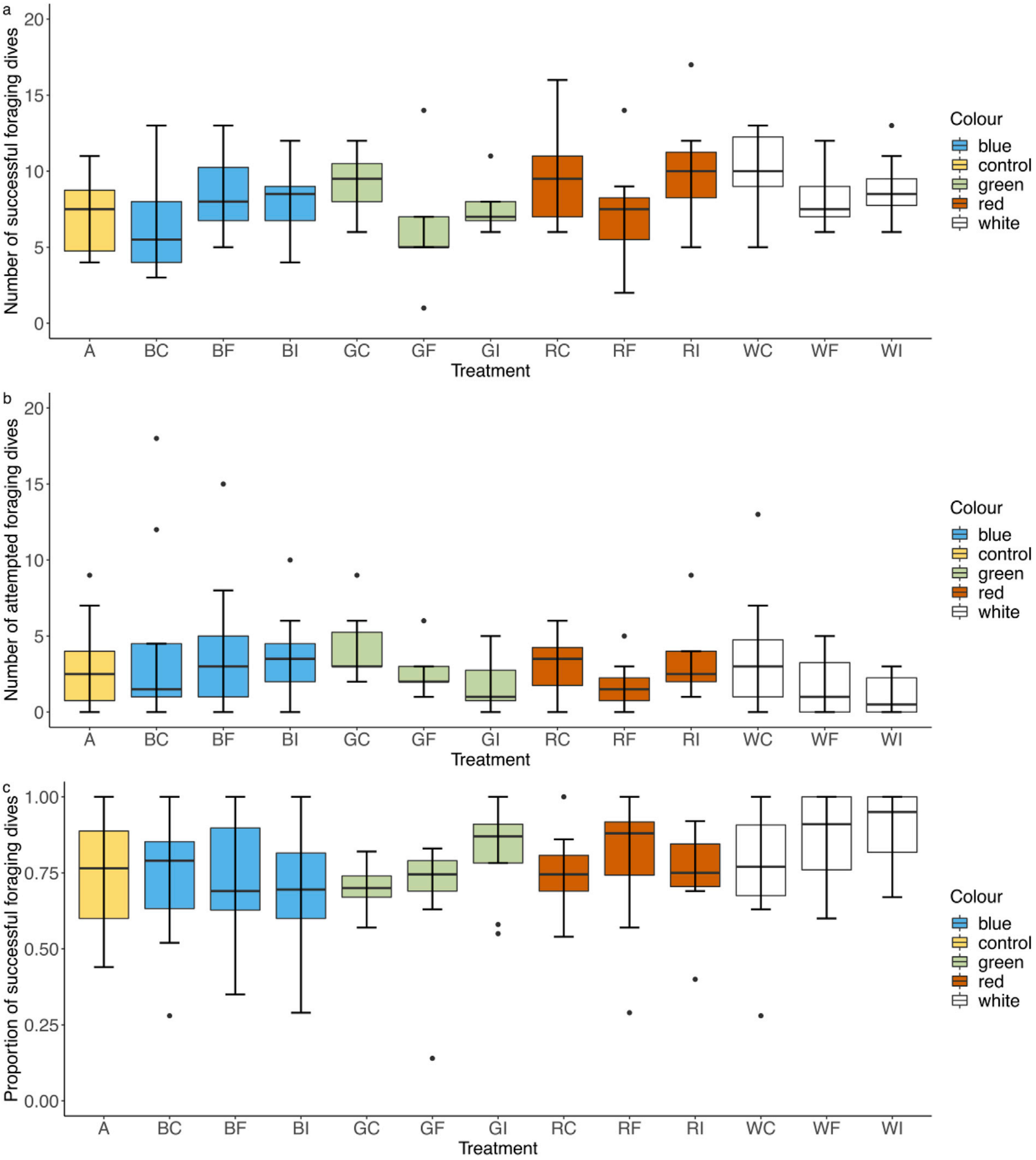

Fig. 6. Box-whisker plots showing **(a)** the number of successful foraging dives, **(b)** the number of attempted (unsuccessful) foraging dives, and **(c)** the proportion of successful foraging dives (total number of successful foraging dives divided by the total number of dives) during each 30-min trial, for the eight Long-tailed Ducks exposed to the 12 different LED light treatments (codes in Table 1) and the control (code A). The box plots show 25% and 75% percentiles (box), medians (lines in boxes), ranges (whiskers) and outliers (black circles).

Long-tailed Ducks capture a wide variety of mobile prey in their generalist diet that suggests a reliance upon visual guidance for foraging. They take both benthic and pelagic prey mainly during diurnal foraging bouts (White et al., 2009; Žydelis and Richman, 2015; Žydelis and Ruškytė, 2005). Birds are most vulnerable to gillnet bycatch in winter when they feed offshore on marine organisms (e.g., bivalves, crustaceans, gastropods, fish, fish eggs, annelids and echinoderms); in summer, they consume freshwater prey (e.g., insects, insect larvae, crustaceans and molluscs) in Arctic wetlands (Cramp et al., 1978; Johnsgard, 2010). Precise bill control provided by the binocular field is important for capture of mobile prey found in these habitats. In addition, wild Long-tailed Ducks are known to inspect and manipulate larger prey items brought to the surface prior to swallowing (Žydelis and Richman, 2015).

Thus, Long-tailed Duck visual field characteristics support ecological evidence indicating the primary use of visual cues while foraging. This validated the reason for testing the different LED lights as potential visual alerts for these species in the dive tank experiment.

We predicted that the exposure of Long-tailed Ducks to different LED light treatments would decrease the number of successful foraging dives (whereby the food reward was consumed at the target location) compared to the control (no light), since we expected that the lights would be a visual deterrent to foraging. However, our results did not support this hypothesis; none of the LED light combinations reduced the foraging success of the ducks compared to the control. The presence of lights near the tray of food in all treatments did not stop the birds from consuming mealworms. Indeed, the white increasing flash LED had a significant positive effect on foraging success from the tray.

Recent field trials with Baltic Sea fisheries tested the effectiveness of similar lights placed on the headlines of gillnets as visual deterrents (Field et al., 2019). Those trials specifically tested green constant flash and white increasing flash light combinations and found that white increasing flash rate net-lights increased bycatch rates of Long-tailed Ducks. The combination of our experimental findings and the at-sea trials lead us to advise against using this light type on gillnets, since it is likely to increase bycatch of Long-tailed Ducks.

Our results suggest that none of the LED light combinations are applicable as underwater visual deterrents on gillnets for this species. There was no significant effect on bycatch rates of Long-tailed Ducks when green constant flash net-lights were trialled with gillnet fisheries (Field et al., 2019), which supports our findings for this light combination being an ineffective deterrent. However, our results contrast with trials in Peru, where green LED lights placed on float lines of bottom-set gillnets led to an 85% reduction in bycatch of Guanay Cormorants *Phalacrocorax bougainvillii* (Mangel et al., 2018) without negatively impacting catch rates of target fish species. A more recent study in Peru (using a similar trial set-up with green LED lights on float lines) provided mean nominal bycatch per unit effort figures indicating an 84% reduction in seabird bycatch (including White-chinned Petrels *Procellaria aequinoctialis* and Humboldt Penguins) in the presence of LEDs (Bielli et al., 2020), although its statistical significance could not be determined for the small dataset. Such variation across trials may be due to differences in foraging behaviour (e.g., dive pattern and depth) and visual ecology among species, or differences in trial methodologies between locations. This highlights the importance of conducting species-specific LED light trials (considering both *in situ* experiments and gillnet fisheries trials at sea) when determining seabird-bycatch mitigation strategies.

Overall, the continued foraging success of Long-tailed Ducks across light combinations likely reflected their high motivation to obtain the energy-dense food reward, as they had been fasted overnight prior to the trials. Similarly, wild populations of Long-tailed Ducks have high mass specific energy requirements (the negative relationship between energy content of the diet and species' body mass) compared to other seaducks, such as eiders (*Somateria* and *Polysticta* spp.) and scoters (*Melanitta* spp.) (Ouellet et al., 2013). This necessitates their consumption of energy dense prey for maintaining their metabolism, associated with temporal and spatial variations in foraging behaviour (Systad et al., 2000; White et al., 2009; Žydelis and Ruškytė, 2005). Therefore, we suggest that the motivation of the ducks to obtain food was more significant than their neophobia (aversion to approaching novel stimuli) to the lights. Some individual ducks were highly motivated to consistently forage from the tray, showing a high number of successful foraging dives across different light combinations. This may be explained by the Neophobia Threshold Hypothesis, which links the level of neophobia to the ecological plasticity of the species. Birds with specialised diets have higher levels of neophobia than those with more general diets (Greenberg, 2003). Since Long-tailed Ducks are generalist foragers (Jamieson et al., 2001; Žydelis and Richman, 2015), the Neophobia Threshold Hypothesis predicts that they would have low levels of neophobia.

Interestingly, the increased level of foraging in Long-tailed Ducks in the presence of the white increasing flash may represent a neophilic response to this light. If so, this information would contraindicate using this specific light treatment as a visual alert, since it appeared to have acted as an attractant rather than deterrent for tray foraging, and its attachment to gillnets may have attracted rather than repelled ducks (Field et al., 2019). Further work is necessary to test the Neophobia Threshold Hypothesis for Long-tailed Ducks to better understand the mechanisms underlying their behavioural responses towards visual alerts, such as LED lights.

While our findings do not support the use of LED lights for mitigating bycatch of Long-tailed Ducks, other types of visual warning devices should be tested, such as coloured monofilament threads, or moving predator shapes (Hanamseth et al., 2018; Wang et al., 2010). The design of visual alerts should be carefully examined for this species, as a recent study determined that submerged monochrome net panels (providing high contrast patterns) were ineffective as visual deterrents since they failed to reduce duck bycatch in set net fisheries (Field et al., 2019). We recommend investigation of above-water distraction methods to deter birds from the vicinity of nets perhaps based upon aerial deterrent devices such as "eye-spot balls" (McLennan et al., 1995) or "looming eyes" (Hausberger et al., 2018).

Additionally, the placement of visual alerts on gillnets in relation to Long-tailed Duck visual field topography should be considered. It is important to decide where to position the visual alert for it to fall within the bird's binocular or monocular fields of view, rather than the blind areas. This information is likely to be relevant for determining the appropriate spacing of alerts on gillnets for enabling ducks to see them. We suggest that minimising the spacing distance or using continuous sections of alerts (Melvin et al., 1999; Trippel et al., 2003) could increase the likelihood of their detection by this species, in contrast to the wide spacing of alerts (10 m and above) used in other studies (Field et al., 2019; Mangel et al., 2014). We advise further visual studies should investigate the optimum placement and spacing of visual alerts for Long-tailed Ducks.

Other sensory cues (e.g. tactile, auditory) apart from vision may be involved in prey capture underwater for Long-tailed Ducks. Underwater behavioural hearing trials of Long-tailed Ducks indicated that they have peak underwater acoustic sensitivity between 1.0 and 3.0 kHz (McGrew, 2019), which may have a role in their capture of noise-making prey (e.g. bivalves, crustaceans, fish). The tactile sensitivity of this species has been demonstrated by the recent analysis of sensillar mechanoreceptors (tactile epithelial structures) in the bill tip organs of 35 waterfowl species, which included Long-tailed Ducks (Avilova, 2018). Future research should investigate the relative importance of different sensory information available to Long-tailed Ducks during foraging in order to apply a holistic sensory approach to the design of warning devices for gillnets.

5. Conclusions

Long-tailed Ducks have the visual field characteristics of visually guided foragers associated with their capture of mobile prey at close range. Their reliance on vision for foraging supported our rationale for testing the effectiveness of different LED light combinations as visual deterrents in a dive tank experiment. The underwater exposure of captive Long-tailed Ducks to 12 different LED net-lights did not reduce foraging success compared to the control, suggesting the lights would be ineffective as aversive visual alerts on gillnets. The ducks' positive response to white increasing flash rate light contraindicates its use as a visual deterrent.

Whilst the combination of our findings and at-sea trials do not support the use of LED lights as visual deterrents for Long-tailed Ducks, we recommend trialling other types of visual warning devices deployed on or near gillnets, specifically aimed at this, and other, species of diving ducks.

Data accessibility

The accompanying datasets for the study (Cantlay et al., 2020) are available at https://doi.org/10.17637/rh.11672748.v1.

Role of the funding sources

Funding was received from the RSPB to conduct this research project at Patuxent Wildlife Research Center. J.C.C. is funded by the Natural Environment Research Council (grant number NE/L002485/1) and is a London NERC Doctoral Training Partnership candidate. None of the funders had any role in the study design, collection, analysis and interpretation of data.

Declaration of competing interest

J.C.C. has CASE partnership funding from the RSPB provided for her doctoral research. The authors declare that there are no known conflicts of interest with our proposed submission or any other related work that is in press.

Acknowledgements

We thank Robert Enever and Peter Kibel at Fishtek Marine, Devon, UK for providing the net-light devices. Sincere thanks are due to staff and volunteers at USGS Patuxent Wildlife Research Center, Maryland, USA for their valuable assistance in this research: Randall Mickley, Peter Blake and Pamela Kellett. Additional thanks are given to Sean Gibson at Royal Holloway University of London, who constructed the bill holder necessary to obtain visual field measurements from the ducks. The RSPB and the Natural Environment Research Council (grant number NE/L002485/1) provided funding for this research. Comments from anonymous reviewers improved this manuscript. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2020.e01102.

References

Avilova, K.V., 2018. Spatial organization of the epithelial structures in the bill tip organ of waterfowl (Anseriformes, Aves). Biol. Bull. Rev. 8, 234–244.

Bates, D., Maechler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Software 67, 1–48.

Bellebaum, J., Schirmeister, B., Sonntag, N., Garthe, S., 2013. Decreasing but still high: bycatch of seabirds in gillnet fisheries along the German Baltic coast. Aquat. Conserv. Mar. Freshw. Ecosyst. 23, 210–221.

Bielli, A., Alfaro-Shigueto, J., Doherty, P.D., Godley, B.J., Ortiz, C., Pasara, A., Wang, J.H., Mangel, J.C., 2020. An illuminating idea to reduce bycatch in the Peruvian small-scale gillnet fishery. Biol. Conserv. 241, 108277.

Blackwell, B.F., DeVault, T.L., Seamans, T.W., Lima, S.L., Baumhardt, P., Fernández-Juricic, E., 2012. Exploiting avian vision with aircraft lighting to reduce bird strikes. J. Appl. Ecol. 49, 758–766.

Blackwell, B.F., Fernández-Juricic, E., Seamans, T.W., Dolan, T., 2009. Avian visual system configuration and behavioural response to object approach. Anim. Behav. 77, 673–684.

Cantlay, J., Portugal, S.J., Wells-Berlin, A., Bond, A.L., 2020. Accompanying data for the study "Ineffectiveness of light emitting diodes as underwater deterrents for Long-tailed Ducks Clangula hyemalis. Figshare. https://doi.org/10.17637/rh.11672748.v1. Dataset.

Cramp, S., Simmons, K.E., Ferguson-Lees, I.J., Gilmor, R., Hollom, P.A.D., Hudson, R., Nicholson, E.M., Ogilvie, M.A., Olney, P.J.S., Voous, K.H., Wattel, J., 1978. Anatidae: Mergini Long-tailed Duck Clangula hyemalis. In: Handbook of the Birds of Europe, the Middle East and North Africa, the Birds of the Western Palearctic, 1. Oxford University Press, Oxford University Press, Oxford, UK, pp. 626–634. Ostrich to Ducks.

Crowell, S.E., Wells-Berlin, A.M., Therrien, R.E., Yannuzzi, S.E., Carr, C.E., 2016. In-air hearing of a diving duck: a comparison of psychoacoustic and auditory brainstem response thresholds. J. Acoust. Soc. Am. 139, 3001–3008.

Enstipp, M.R., Andrews, R.D., Jones, D.R., 2001. The effects of depth on the cardiac and behavioural responses of double-crested cormorants Phalacrocorax auritus during voluntary diving. J. Exp. Biol. 204, 4081–4092.

Field, R., Crawford, R., Enever, R., Linkowski, T., Martin, G., Morkūnas, J., Morkūnė, R., Rouxel, Y., Oppel, S., 2019. High contrast panels and lights do not reduce bird bycatch in Baltic Sea gillnet fisheries. Glob. Ecol. Conserv. 18, e00602.

Greenberg, R., 2003. The role of neophobia and neophilia in the development of innovative behaviour of birds. In: Reader, S.M., Laland, K.N. (Eds.), Animal Innovation. Oxford University Press, New York, NY, US, pp. 175–196.

Grémillet, D., Enstipp, M.R., Boudiffa, M., Liu, H., 2006. Do cormorants injure fish without eating them? An underwater video study. Mar. Biol. 148, 1081–1087.

Hanamseth, R., Baker, G.B., Sherwen, S., Hindell, M., Lea, M.-A., 2018. Assessing the importance of net colour as a seabird bycatch mitigation measure in gillnet fishing. Aquat. Conserv. Mar. Freshw. Ecosyst. 28, 175–181.

Hausberger, M., Boigné, A., Lesimple, C., Belin, L., Henry, L., 2018. Wide-eyed glare scares raptors: from laboratory evidence to applied management. PLoS One 13, e0204802.

Jamieson, S.E., Robertson, G.J., Gilchrist, H.G., 2001. Autumn and winter diet of long-tailed duck in the Belcher Islands, Nunavut, Canada. Waterbirds. Int. J. Waterbird Biol. 24, 129–132.

Jane, S.D., Bowmaker, J.K., 1988. Tetrachromatic colour vision in the duck Anas platyrhynchos: microspectrophotometry of visual pigments and oil droplets. J. Comp. Physiol. 162, 225–235.

Johnsgard, P.A., 2010. Ducks, geese and swans of the world: Tribe Mergini (Sea ducks). In: Johnsgard, P.A. (Ed.), Ducks, Geese and Swans of the World. Lincoln Libraries. University of Nebraska, Lincoln, USA, pp. 313–361.

Mangel, J.C., Alfaro-Shigueto, J., Wang, J., Swimmer, Y., Wallace, G., 2014. Tests of visual cues and sub-surface nets as bycatch mitigation measures in small-scale gillnet fisheries in Peru. In: Sixth Meeting of the Seabird Bycatch Working Group, Punta del Este, Uruguay.

Mangel, J.C., Wang, J., Alfaro-Shigueto, J., Pingo, S., Jimenez, A., Carvalho, F., Swimmer, Y., Godley, B.J., 2018. Illuminating gillnets to save seabirds and the potential for multi-taxa bycatch mitigation. Roy. Soc. Open Sci. 5, 180254.

Martin, G.R., 1998. Eye structure and amphibious foraging in albatrosses. Proc. R. Soc. Lond. Ser. B Biol. Sci. 265, 665–671.

Martin, G.R., 1999. Eye structure and foraging in King penguins Aptenodytes patagonicus. Ibis 141, 444–450.

Martin, G.R., 2007. Visual fields and their functions in birds. J. Ornithol. 148, 547–562.

Martin, G.R., 2014. The subtlety of simple eyes: the tuning of visual fields to perceptual challenges in birds. Philos. Trans. R. Soc. Lond. B Biol. Sci. 369, 20130040.

Martin, G.R., 2017. What drives bird vision? Bill control and predator detection overshadow flight. Front. Neurosci. 11, 1–16.

Martin, G.R., Brooke, M.d.L., 1991. The eye of a procellariiform seabird, the Manx shearwater, Puffinus puffinus: visual fields and optical structure. Brain Behav. Evol. 37, 65–78.

Martin, G.R., Crawford, R., 2015. Reducing bycatch in gillnets: a sensory ecology perspective. Glob. Ecol. Conserv. 3, 28–50.

Martin, G.R., Jarrett, N., Williams, M., 2007a. Visual fields in Blue Ducks Hymenolaimus malacorhynchos and Pink-eared Ducks Malacorhynchus membranaceus: visual and tactile foraging. Ibis 149, 112–120.

Martin, G.R., Katzir, G., 1994. Visual fields and eye movements in herons (Ardeidae). Brain Behav. Evol. 44, 74–85.

Martin, G.R., Mcneil, R., Rojas, L., 2007b. Vision and the foraging technique of skimmers (Rynchopidae). Ibis 149, 750–757.

Martin, G.R., Portugal, S.J., 2011. Differences in foraging ecology determine variation in visual fields in ibises and spoonbills (Threskiornithidae). Ibis 153, 662–671.

Martin, G.R., Prince, P.A., 2001. Visual fields and foraging in procellariiform seabirds: sensory aspects of dietary segregation. Brain Behav. Evol. 57, 33–38.

Martin, G.R., Wanless, S., 2015. The visual fields of Common Guillemots Uria aalge and Atlantic Puffins Fratercula arctica: foraging, vigilance and collision vulnerability. Ibis 157, 798–807.

Martin, G.R., White, C.R., Butler, P.J., 2008. Vision and the foraging technique of Great Cormorants Phalacrocorax carbo: pursuit or close-quarter foraging? Ibis 150, 485–494.

Martin, G.R., Young, S.R., 1984. The eye of the Humboldt penguin, Spheniscus humboldti: visual fields and schematic optics. Proc. R. Soc. Lond. Ser. B Biol. Sci. 223, 197–222.

McGrew, K.A., 2019. Reducing gillnet bycatch: seaduck underwater hearing thresholds and auditory deterrent devices. MS thesis. Department of Entomology and Wildlife Ecology. The University of Delaware, USA.

McLennan, J.A., Langham, N.P.E., Porter, R.E.R., 1995. Deterrent effect of eye-spot balls on birds. N. Z. J. Crop Hortic. Sci. 23, 139–144.

Melvin, E.F., Parrish, J.K., Conquest, L.L., 1999. Novel tools to reduce seabird bycatch in coastal gillnet fisheries. Conserv. Biol. 13, 1386–1397.

Ortiz, N., Mangel, J.C., Wang, J., Alfaro-Shigueto, J., Pingo, S., Jimenez, A., Suarez, T., Swimmer, Y., Carvalho, F., Godley, B.J., 2016. Reducing green turtle bycatch in small-scale fisheries using illuminated gillnets: the cost of saving a sea turtle. Mar. Ecol. Prog. Ser. 545, 251–259.

Ouellet, J.-F., Vanpé, C., Guillemette, M., 2013. The body size-dependent diet composition of North American sea ducks in winter. PLoS One 8, e65667.

Regular, P., Montevecchi, W., Hedd, A., Robertson, G., Wilhelm, S., 2013. Canadian fishery closures provide a large-scale test of the impact of gillnet bycatch on seabird populations. Biol. Lett. 9, 20130088.

Sivak, J., Howland, H.C., McGill-Harelstad, P., 1987. Vision of the Humboldt penguin Spheniscus humboldti in air and water. Proc. R. Soc. Lond. Ser. B Biol. Sci. 229, 467–472.

Stoffel, M.A., Nakagawa, S., Schielzeth, H., 2017. rptR: repeatability estimation and variance decomposition by generalized linear mixed-effects models. Methods Ecol. Evol. 8, 1639–1644.

Systad, G.H., Bustnes, J.O., Erikstad, K.E., 2000. Behavioural responses to decreasing day length in wintering sea ducks. Auk 117, 33–40.

Trippel, E.A., Holy, N.L., Palka, D.L., Shepherd, T.D., Melvin, G.D., Terhune, J.M., 2003. Nylon barium sulphate gillnet reduces porpoise and seabird mortality. Mar. Mamm. Sci. 19, 240–243.

Wang, J.H., Fisler, S., Swimmer, Y., 2010. Developing visual deterrents to reduce sea turtle bycatch in gill net fisheries. Mar. Ecol. Prog. Ser. 408, 241–250.

Waugh, S.M., Filippi, D.P., Blyth, R., Filippi, P.F., 2011. Assessment of bycatch in gill net fisheries, report to the convention on migratory species. In: Tenth Meeting of the Conference of the Parties, Bergen, 20-25 November 2011, Agenda Item 19.

White, C.R., Day, N., Butler, P.J., Martin, G.R., 2007. Vision and foraging in cormorants: more like herons than hawks? PLoS One 2, e639.

White, T.P., Veit, R.R., Perry, M.C., 2009. Feeding ecology of long-tailed ducks Clangula hyemalis wintering on the Nantucket shoals. Waterbirds 32, 293–299.

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York, ISBN 978-3-319-24277-4. https://ggplot2.tidyverse.org.

Žydelis, R., Bellebaum, J., Österblom, H., Vetemaa, M., Schirmeister, B., Stipniece, A., Dagys, M., van Eerden, M., Garthe, S., 2009. Bycatch in gillnet fisheries–An overlooked threat to waterbird populations. Biol. Conserv. 142, 1269–1281.

Žydelis, R., Richman, S.E., 2015. Foraging behaviour, ecology and energetics of sea ducks. In: Savard, J.-P.L., Derksen, D.V., Esler, D., Eadie, J.M. (Eds.), Ecology and Conservation of North American Sea Ducks. CRC Press, Boca Raton, pp. 243–267.

Žydelis, R., Ruškytė, D., 2005. Winter foraging of Long-tailed Ducks Clangula hyemalis exploiting different benthic communities in the Baltic Sea. Wilson Bull. 117, 133–141.

Žydelis, R., Small, C., French, G., 2013. The incidental catch of seabirds in gillnet fisheries: a global review. Biol. Conserv. 162, 76–88.