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Disturbance of wintering waterbirds by simulated road traffic noise in Arkansas wetlands

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Abstract

As humans intensify their activity on landscapes, it is important to consider anthropogenic noise when managing habitat for wildlife. Wetlands along rural to urban gradients are subject to road noise pollution, and the waterbirds that live there could be at risk for behavioral disturbance. We tested the positional response of wintering waterbirds to road traffic noise (i.e., sound pressure level) in a playback study in wetlands of Arkansas, USA, from January through March 2018. Each trial consisted of 3, 20-minute phases of road noise playback designated as pre, during, and post. We repeated instantaneous scan sampling every minute during each phase to collect the number, species, and distance of each bird relative to the playback speaker. Distance bins were designated as 0-25, 26-50, 51-75, and 76-100 m from the speaker. Birds approached the speaker at closer distances during the pre phase compared to during and post phases. There was an increase in the probability of a bird occurring in the distance bin farthest from the speaker over the course of the trial. Our results suggest waterbirds might avoid noisier areas within a habitat; however, more study is needed to assess speciesspecific responses, determine thresholds for disturbance, and examine downstream effects of habitat avoidance. If these results persist at larger scales, the soundscape of a wetland could be an important consideration in conservation planning.

KEYWORDS

anthropogenic noise, Arkansas, behavior, disturbance, ducks, habitat avoidance, road, waterbirds

In the last 2 decades, anthropogenic noise (i.e., sound pressure levels produced by human activities including traffic, construction, and industrial sources) has become a growing concern in the conservation of wildlife populations (Barber et al. 2010, Francis and Barber 2013). Noise has been defined as unwanted sound (Crocker 1998); however, we use this term to indicate nothing more than pressure levels that deviate from atmospheric pressure. Several reviews highlight myriad (and often negative) effects that human-made noise has on a variety of taxa including insects, fish, birds, and mammals (Bowles 1995, Warren et al. 2006, Laiolo 2010, Shannon et al. 2016, Jerem and Mathews 2021). Noise can alter predator prey interactions (Siemers and Schaub 2011, Mason et al. 2016, Simpson et al. 2016), reduce reproductive success (Habib et al. 2007, Mulholland et al. 2018), influence population and community structure (Holles et al. 2013, Bunkley et al. 2017), act as a direct stressor (Graham and Cooke 2008, Kleist et al. 2018), and affect ecological services such as seed dispersal and pollination (Francis et al. 2012). Many studies investigating the effects of anthropogenic noise have focused on birds because of their reliance on acoustic cues for communication (Shannon et al. 2016, Jerem and Mathews 2021), and the effects have been detected across land cover types including grasslands (Rosa and Koper 2022), forests (Sánchez et al. 2022), and wetlands (Wilson et al. 2021). Road traffic is a source of noise that can reduce reproductive success for breeding birds (Halfwerk et al. 2011, Potvin and MacDougall-Shackleton 2015) and cause habitat avoidance, particularly in areas that contain resources for refueling during migration (McClure et al. 2013).

While there are >150 studies published on the responses of birds to noise (Jerem and Mathews 2021), waterbirds (defined for the purposes of our study as ducks, geese, swans, grebes, and rails) are underrepresented in this body of existing literature. We performed a systematic search of the literature that yielded 18 studies that explicitly examine the effect of noise on waterbirds (i.e., directly tested noise levels and waterbird response), with 9 of these studies focusing on aircraft stimuli (Conomy et al. 1998*a*, *b*; Goudie 2006; Gilbert et al. 2020). Only 4 studies directly examined the effect of road traffic noise on waterbirds (Reijnen et al. 1995, 1996, 1997; Payne et al. 2012). These data have indicated various responses of waterbirds to traffic noise, including a reduction in density for some species near road noise (e.g., northern shoveler [*Anas clypeata*], Eurasian coot [*Fulica atra*]; Reijnen et al. 1996) and no response from others (e.g., tufted duck [*Aythya fuligula*], mute swan [*Cygnus olor*], northern shoveler; Reijnen et al. 1996, black swan [*Cygnus atratus*]; Payne et al. 2012). In these studies, the auditory stimulus of road traffic noise was not tested independently of the visual stimulus of the vehicle, and there is a tendency in the literature to infer the effects of noise on animals without explicitly testing noise levels (Pease et al. 2005, Loesch et al. 2021). McDuie et al. 2021).

As transit networks continue to expand into less developed areas (Laurance et al. 2015, Torres et al. 2016, Howden et al. 2019) and wetland restoration projects increase in developed areas (Kusler and Kentula 1989, Kim et al. 2011), waterbirds are more likely to be exposed to road traffic noise. In a time when declines have been observed in some waterbird species in certain regions of North America (U.S. Fish and Wildlife Service 2019) and climate change and habitat loss are affecting habitat for these birds (Sofaer et al. 2016, Steen et al. 2016, Zhao et al. 2018), it is important to understand the factors that could influence how waterbirds use their environment so that we can manage these habitats to protect these species.

Our objective was to determine if wintering waterbirds are disturbed (i.e., increase their distance from source) by road traffic noise. To observe the effects of noise on waterbirds, we conducted a playback experiment in central and southwest Arkansas, USA, during winter 2018 by broadcasting simulated road traffic noise through speakers. We recorded the position of the birds relative to the speakers during 3 phases: before, during, and after the stimulus. We predicted that if noise disturbs waterbirds, individuals would position themselves farther away from the speaker during the stimulus compared to before the stimulus. We also predicted that if noise has a lingering, short-term effect, the waterbirds would remain positioned farther from the speakers after we stopped broadcasting. This study isolates the auditory stimulus of traffic noise from the visual stimulus of an automobile.

STUDY AREA

We conducted our study at 7 locations from 10 January through 26 March 2018, across central and southwest Arkansas. All sites are owned and managed by the Arkansas Game and Fish Commission and ranged in size from 9–263 ha (Figure 1). Sites ranged from 61–119 m in elevation and were located ≥500 m from major roads (Table S1, Figure S1, available in Supporting Information). According to the National Wetlands Inventory (U.S. Fish and Wildlife Service 2014), the land cover at these sites include lakes (First Old River Lake, Bois D'Arc Lake) and ponds (Southfork Lake and Lake Terre Noire at Grandview Prairie Wildlife Management Area [WMA], Smith Park Lake at Sulphur River WMA). All of these sites have water year-round. The sites at Ed Gordon Point Remove WMA and Palarm Creek Waterfowl Rest Area are moist-soil units, which are wetlands that are periodically flooded (usually during Sep through Feb) to promote growth and seed production by native wetland vegetation (Nelms et al. 2007). Kross (2006) describes dominant vegetation among Arkansas wetlands to consist of grasses (barnyard grasses [Echinochloa spp.], sprangletops [Leptochloa spp.], panicgrass [Panicum spp.]), sedges (true sedges [Carex spp.], nutsedges [Cyperus spp.]), forbs (beggarticks [Bidens spp.], knotweeds [Polygonum spp.], common cocklebur [Xanthium strumarium]), vines (trumpet vine [Campsis radicans], redvine [Brunnichia ovata]), and woody plants (willow [Salix spp.], buttonbush [Cephalanthus occidentalis]). The most abundant waterbird species observed were green-winged teal (Anas crecca), blue-winged teal (Spatula discors), and gadwall (Mareca strepera) among others (Table 1). The climate of Arkansas is humid-subtropical, with hot, humid summers (late Jun-late Sep), and mild winters



FIGURE 1 Locations of 7 field sites in relation to 3 major cities (stars) in Arkansas, USA, where we conducted playback experiments to determine waterbird response to road traffic noise from January through March 2018. We classified sites as lakes (squares) or ponds (circles) based on National Wetlands Inventory (NWI) designations. Two sites were moist-soil units (triangles), which are not a classification included in the NWI.

TABLE 1 The number of 1-minute scan samples in which each waterbird species was detected during a 1-hour trial at each site in Arkansas, USA, January through March 2018. Site codes are Bois D'Arc Lake (BODA), Ed Gordon Moist-soil Unit (EDGO), First Old River Lake (FORL), Palarm Creek Waterfowl Rest Area (PACR), Smith Park Lake (SMPA), Southfork Lake (SOFL), Terre Noire (TENO), and Smith Park Lake (SMPA). The final row represents the maximum number of all birds ever detected within a 1-minute scan sample of a site's trial.

Species	BODA	EDGO	FORL	PACR	SMPA	SOFO	TENO
Pied-billed grebe (Podilymbus podiceps)	0	0	2	0	0	0	36
Mallard (Anas platyrhynchos)	3	6	0	0	0	53	0
Gadwall (Mareca strepera)	0	2	0	0	60	21	0
Wood duck (Aix sponsa)	0	0	0	0	0	0	17
Redhead (Aythya americana)	0	0	21	0	0	0	0
Green-winged teal (Anas crecca)	1	54	0	57	0	1	0
Blue-winged teal (Spatula discors)	0	55	0	54	0	0	0
Northern shoveler (Spatula clypeata)	0	49	0	4	0	9	0
Canvasback (Aythya valisineria)	0	0	25	0	0	0	0
Lesser scaup (Aythya affinis)	0	0	8	0	0	37	0
Ring-necked duck (Aythya collaris)	0	0	1	0	0	11	8
Bufflehead (Bucephala albeola)	0	0	0	0	0	48	7
Ruddy duck (Oxyura jamaicensis)	0	0	4	0	0	0	0
Common gallinule (Gallinula galeata)	26	0	0	0	0	0	0
American coot (Fulica americana)	60	0	0	0	0	0	2
Maximum number in scan sample	45	93	23	56	20	51	10

(late Dec-late Mar). The average monthly temperature during the study period was 8.4°C and the average monthly precipitation was 54 cm (National Oceanic and Atmospheric Administration 2022b).

METHODS

Behavioral experiments

We performed 1 experimental trial per site on separate days. We obtained only 1 trial per site because of weather, budget, time, and personnel constraints. Given these constraints, we also chose to have all trials include a simulated road noise stimulus played from a set of playback speakers at the expense of also conducting true control trials (i.e., trials with no playback). Instead, we used a pre-playback period with no noise as a baseline to gauge waterbird response. Prior to dawn on each day of a trial, 1 observer set up the playback apparatus, which consisted of 2 speakers (Dayton RPH16 16" Round PA Horn with a GRS PZ1188 Piezo Horn Driver; Parts Express, Springboro, OH, USA) and an amplifier (Lepai LP-A68 2 ×15 W Mini Amplifier; Parts Express) powered by a 3-in-1 power pack (CEN-TECH, Camarillo, CA, USA). We set up the speakers at the edge of the shoreline water and concealed them with a camouflage burlap cloth (Figure 2A). The observer and amplifier were positioned 15 m behind the speakers and also concealed behind



FIGURE 2 Illustration of trial design used in playback experiments to determine waterbird response to road traffic noise including A) blind and speaker set-up and B) aerial satellite image of speaker placement and designation of distance bins. Both images are from Palarm Creek Waterfowl Rest Area at Bell Slough Wildlife Management Area in Faulkner County, Arkansas, USA, March 2018. Photo of blind and speaker set-up (A) was taken by J.T. Veon and we obtained satellite imagery from Google EarthTM.

a portable camouflage blind. The same observer conducted all trials and was well-trained in waterbird identification.

We define any waterbird as any individual within the Podicipedidae, Anatidae, and Rallidae families. We combined these families to maximize the number of individual detections to be used for analysis and because management of wetlands often influences this group collectively, especially when managers take an integrated approach to managing waterbirds (Erwin 2002). Trials began as soon as any waterbird became visible within 100 m of the shoreline (gauged by using a rangefinder, subtracting the distance between the observer and the speakers) and lasted 1 hour, which consisted of 3, 20-minute periods, which we refer to as pre (no road noise stimulus), during (road noise stimulus), and post (no road noise stimulus). Start times for trials ranged from 0623 through 0700. We acquired the road noise by recording a 4-lane interstate using a Sennheiser ME-65 microphone (Sennheiser, Hanover, Germany) and Marantz PMD-661 digital recorder (Marantz, Kanagawa, Japan). The waveform, spectrogram, and power spectral density for the first minute of the recording show how the majority of the power for this recording can be found at lower frequencies, as is typical of road traffic noise (Figure S2, available in Supporting Information). At the start of the during phase, we turned on the noise playback at an amplitude of zero decibels (dB) and gradually increased it over 30 seconds so as not to startle the birds with a loud, sudden noise. We played this recording continuously for 20 minutes at 75 dB as measured 15 m from the speaker to approximate the conditions under which the recording was made.

During each minute of the trial, the observer used a laser range finder and instantaneous scan sampling to record the closest approach (e.g., distance in meters to the speaker) of each species and the number of each species within 4 distance bins: 0–25 m, 26–50 m, 51–75 m, and 76–100 m (Figure 2B). We used distance bins instead of recording each precise distance for each bird to facilitate complete and accurate data collection when there were larger numbers of birds in motion and a greater area to scan. Furthermore, we established a cutoff of 100 m from the shoreline to ensure we could quickly and accurately identify birds through binoculars, and because this distance was enough to establish a gradient where amplitude returned to ambient levels (between 40–50 dB) at the farthest distance (though we acknowledge that we were unable to measure absolute, calibrated noise levels at each precise distance where a bird occurred). Given the number of birds present during trials, it was impossible to track individuals, and there were likely birds moving

gradually in and out of the area throughout each trial; thus, the system was not closed. The observer also recorded temperature, wind speed, and sky conditions to ensure that each trial was conducted under similar weather conditions that may have affected waterbird behavior. To minimize differences in road noise among sites due to wind speed, we conducted all trials at or under 6.4–11.3 km/hour (National Oceanic and Atmospheric Administration 2022*a*), though we did not account for wind direction. After each trial, the observer collected information on habitat characteristics (Table S1).

Data analysis

Our analysis focused on 2 response variables: closest approach to the speaker and the probability of occurring in a distance bin at different times during a trial (both phase and minutes were units of time examined). For these analyses, we pooled data across species because no species was detected commonly enough across all sites to permit species-specific analyses (Table 1).

We obtained the closest approach to the speaker (m) by identifying the single shortest distance of any individual (regardless of species) to the playback speaker detected for each phase for each site (n = 7). We then conducted a generalized linear mixed model analysis using the lme4 package (Bates et al. 2015). The phase of each trial (pre, during, post) served as our fixed effect. Site was included as our random effect. The data were right skewed, so we fit our generalized linear mixed model to a gamma distribution and log link function. We fit the model using a Laplace approximation, and assessed model fit using residual plots.

To analyze how each phase of the trial influenced the number of birds observed within each distance bin, we conducted a mixed-effects multinomial logistic regression (MMLR) using the mclogit package (Elff 2022). We assessed fixed effect collinearity using a 1-way analysis of variance. Because minute (continuous) was highly associated with phase (ordinal; $F_{2,1677}$ = 6,725, P < 0.001), minute and phase were not included within the same model. The phase MMLR model contained distance bin as the nominal response variable and phase as the fixed effect. To account for variation across sample locations, we used site as the random effect. To consider the relative frequencies of birds within a 1-minute scan sample, the number of birds observed in a bin per phase for each minute served as the model weight (with zeros being treated as true numbers and not missing values). Specifying the number of birds as the weight within our model also allowed us to account for any aggregation effects (i.e., influence of distribution across bins based on flock size), and capture error from potential decreases in the number of birds because of movement beyond the observation range (100 m), which could possibly skew the positioning of birds towards closer distance bins. We developed contrasts in the probability of waterbirds being present within specific distance bins during a specific trial phase using the emmeans package (Lenth 2022). We fit models using Fisher scoring iterations until $(|dev - dev_{old}|)/(|dev| + 0.1) < \varepsilon$ where dev is the deviation of each new iteration, dev_{old} is the deviation of the previous iteration, and ε represents the positive convergence tolerance (where ε = 1.00 × 10⁻⁰⁵). Model convergence occurred after 9 iterations, where $(|dev - dev_{old}|)/(|dev| + 0.1) = 1.04 \times 10^{-07}$ (Elff 2022).

Additionally, because we were interested in the effects of traffic noise on waterbird behavior over a finer scale of time (i.e., 1-min increments vs. 20-min phases), we conducted another MMLR analysis where distance bin served as the response and minute served as the continuous fixed effect. We included site as a random effect and the number of birds/bin/minute as the model weight for similar reasons as the MMLR analysis of phase. We also developed contrasts in the probability of a waterbird being present within a specific distance bin for each minute of the trial using the emmeans package (Lenth 2022). We assessed model fit using the same methods from the phase MMLR analysis. The model converged after 10 iterations: $(|dev - dev_{old}|)/(|dev| + 0.1) = 7.59 \times 10^{-06}$. We conducted minute MMLR analysis using the mclogit package (Elff 2022). We ran all analyses in R (R Core Team 2020) and assessed all relationships using $\alpha = 0.05$.

RESULTS

We detected 15 species during our trials with the maximum number of birds detected per minute varying from 10 to 93 (Table 1; Figure S3, available in Supporting Information). The majority of birds detected in our study were in the family Anatidae, with green-winged teal being the most commonly detected species across sites (found at 4 sites), and mallard (*Anas platyrhynchos*), gadwall, northern shoveler, and ring-necked duck (*Aythya collaris*) each

being detected across 3 sites. There were no trials in which birds flushed completely, leaving the study site entirely. The generalized linear mixed model for closest approach showed that birds approached the speaker more closely in the pre phase ($\overline{x} = 13.61 \text{ m} \pm 4.43$ [SE]) compared to the during phase ($\overline{x} = 35.00 \text{ m} \pm 11.30$; $\beta = 0.94$, t = 2.87, P = 0.004). When comparing the pre phase to the post phase, birds kept a greater distance in the post phase ($\overline{x} = 36.40 \text{ m} \pm 11.73$) from the speaker ($\beta = 0.98$, t = 3.01, P = 0.003). The closest approach for the during and post phases did not differ (t = 0.12, P = 0.90; Figure 3).

The estimated marginal means of the MMLR for phase showed that birds had a 0.31 probability (CI = 0.06-0.56) of being 51-75 m from the speaker before the road noise playback and that the probability of being present at other distances was not different from zero (Table 2). During the road noise playback, the probability of being 76-100 m from the speaker increased (probability = 0.81, CI = 0.41-1.21) and remained high (probability = 0.94, CI = 0.79-1.09) into the post phase. No other distance bins had confidence intervals that did not overlap zero in the during and post phases (Table 2).

The estimated marginal means of the MMLR for minute reflected the trends explained above for phase. During minute 1, birds had a probability of occurring at 26–50 m of 0.39 (CI = 0.02-0.77) and a probability of occurring at 51–75 m from the speaker of 0.33 (CI = 0.07-0.59). As the pre phase progressed, only the 51–75 m range had probabilities that were different from zero (min 2 through 19 in Table S2, available in Supporting Information). The probability of occurring in the 0–25 m or 76–100 m ranges was not different from zero during any minute in the pre phase. Once the road noise stimulus was introduced in the during phase, the 76–100 m distance bin was the only bin where the probability of occurrence was different from zero, occurring from minute 23 onward through minute 60 of the post phase. The probability of occurring in the 3 closer distance bins was not different from zero for any



FIGURE 3 Estimated marginal means for closest approach ($m \pm 1$ SE) of any waterbird to the speaker during each phase of a road traffic noise playback experiment. Bars represent means across sites (n = 7) for different phases of each trial: pre (before stimulus), during (during stimulus), and post (after stimulus). We collected data from January through March 2018 in wetland sites in Arkansas, USA.

	Pre		0		During				Post			
Distance from speaker (m)	Prob	SE	95% LCL	95% UCL	Prob	SE	95% LCL	95% UCL	Prob	SE	95% LCL	95% UCL
0-25	0.15	0.12	-0.09	0.39	0.01	0.01	-0.01	0.02	0.00	0.01	-0.01	0.02
26-50	0:30	0.21	-0.11	0.70	0.02	0.03	-0.04	0.08	0.00	0.01	-0.01	0.01
51-75	0.31*	0.13	0.06	0.56	0.17	0.17	-0.17	0.50	0.05	0.06	-0.07	0.18
76-100	0.24	0.28	-0.32	0.80	0.81*	0.20	0.41	1.21	0.94*	0.07	0.79	1.09
*Indicates confidence interval	does not c	verlap zero.										

Estimated marginal mean results from a mixed-effects multinomial logistic regression for the effect of phase on waterbird distance from a speaker playing road

TABLE 2

traffic noise. Results include the mean probability (Prob) that a waterbird will be positioned 0-25 m, 26-50 m, 51-75 m, or 76-100 m from the speaker during the pre

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FIGURE 4 Estimated marginal mean probability for a waterbird occurring in a bin representing distance from a speaker during each minute of a road traffic noise playback experiment. We obtained estimates from a mixed-effects multinomial logistic regression for the influence of minute for different phases in each trial: pre (0–20 min, before stimulus), during (20–40 min, during stimulus), and post (40–60 min, after stimulus). Gray bands represent 95% confidence intervals and vertical dashed lines represent separation of phases. We collected data from January through March 2018 in wetland sites in Arkansas, USA.

of the minutes of the during or post phases. Probabilities changed by minute over the course of the trials, with confidence intervals overlapping across distance bins for the entirety of the pre phase (minutes 0–20), but then diverging for the farthest distance bin (76–100 m) by minute 33 in the during phase and continuing this way through the post phase (Figure 4).

DISCUSSION

For decades, studies have steadily accumulated that document avoidance of noisy habitat in taxa such as songbirds, fish, amphibians, mammals, and insects (Shannon et al. 2016, Jerem and Mathews 2021). Our research contributes to a relatively small collection of studies that explicitly and directly examines the connection between anthropogenic noise and waterbirds (Reijnen et al. 1996, Patón et al. 2012, Payne et al. 2012, Tyler et al. 2016, Wang et al. 2022). In our small-scale study, wintering waterbirds in Arkansas distanced themselves from simulated road traffic noise in a wetland. This work is unique among the waterbird literature because we isolated the acoustic stimulus from the visual stimulus through a playback experiment. This design allowed us to show that road noise could be an important aspect of disturbance, and that it might not necessarily be just the visual stimulus of vehicle traffic that could prompt birds to move away from the road. This finding does not diminish the role that visual cues play in disturbance for even humans on foot influence waterbird movement (Pease et al. 2005, McDuie et al. 2021), but it does suggest that road noise could be a sufficient stimulus for causing disturbance. This information could be important to take into account when planning for mitigation of noise disturbance, especially if considering vegetation or noise walls, which block visual stimuli but allow sound to persist.

Our results also suggest a short-term, sustained effect of road noise disturbance; once birds moved farther from the speaker, they remained there even when the playback ended. Though it is possible that some birds may have rapidly habituated to the noise and subsequently moved closer to the speaker during or after playback, an overall trend in this direction was not evidenced by the closest approach of birds to the speaker or the likelihood of birds occurring closer to the speaker during or after noise playback. If some birds, but not others, habituated and moved closer during or after playback, this effect would have been captured within our models as larger standard error values around model estimates. These standard error values decreased over the course of the trials for each distance bin. We only measured a short-term, sustained effect of noise from road disturbance 20 minutes beyond the end of the playback. Therefore, we cannot conclude how long this effect might have lasted. Nor can we infer whether these birds would have habituated to the noise if exposed for extended periods of time, as has been reported for aircraft noise in American black ducks (*Anas rubripes*; Conomy et al. 1998b). Future work could examine the possibility of habituation by conducting multiple trials at the same site (with longer observation periods after noise stimulus) or by playing noise continuously through a phantom road experiment, similar to McClure et al. (2013, 2017), which would also address the limitation that our noise stimulus was a stationary point source instead of a simulated moving point source. We also recommend measuring noise levels at distances where birds position themselves to distinguish whether they are demonstrating avoidance to a characteristic distance or one associated with specific noise levels.

Our study examined positional response to simulated road noise; however, there are many other ways that birds can respond to noise, and these potential responses were not accounted for in our study. The rich literature on the effects of noise on birds shows that responses can include increased vigilance behavior and reduced foraging (Barber et al. 2010, Klett-Mingo et al. 2016), greater energy expenditure through vocalization (Brumm 2004), elevated stress hormones (Blickley et al. 2012, Kleist et al. 2018), reduced body condition (Ware et al. 2015), and reduced reproductive success (Habib et al. 2007, Schroeder et al. 2012, Kleist et al. 2018, Williams et al. 2021). In addition, responses can be species-specific (Francis et al. 2011, McClure et al. 2013), which highlights the value of studies focused on single species. We were not able to analyze individual species, or even groups such as dabbling ducks (Anatini) and diving ducks (Aythyini), because our sample size was limited. Understanding how particular species respond to road (and other) noise, and considering the specifics of their biology (e.g., migratory vs. resident), will be important in thinking about how best to protect groups that are showing population declines, particularly those susceptible to anthropogenic disturbances (Singer et al. 2020).

There are other aspects of our study design worth noting when interpreting the results. First, because we were unable to keep track of individual birds, it is possible that some birds moved beyond our study area, which could have truncated the data to the outer distance bin, suggesting that bird responses could have averaged greater distances. If this phenomenon influenced our results, we would have expected the opposite trend (i.e., relatively more birds at distances closer to the speaker), which suggests our results are conservative. Second, our sample size of 7 sites was small, but this number met the minimum requirement for mixed models (Gelman and Hill 2007, Harrison 2015). Thus, we suspect increasing sample size would improve model fit, which was already acceptable with 7 sites. Third, we acknowledge that the distributions of birds across distance bins from 1 minute to the next could have been autocorrelated, as is common with time series data. Because we assigned minute as a fixed effect within our MMLR for minute, we chose not to include this variable as a random effect (Hedeker 2003), and we acknowledge this limitation of our analysis. Finally, our study design did not include a control in the form of trials where the during phase included no noise stimulus. While the pre-playback phase serves as a baseline observation, we recommend future studies include a true control.

Additional research needs include understanding precisely under which conditions disturbance by traffic noise occurs. Reviews of literature on the effects of noise on wildlife highlight the need for studies to establish the nature of the relationship between the qualities of the noise stimulus (e.g., duration, amplitude, frequency) and the response of wildlife (Gill et al. 2015, Shannon et al. 2016). For example, relationships between noise and response can be linear or threshold (Francis and Barber 2013), and understanding at what point waterbirds exhibit a response will provide guidance for mitigating negative outcomes of noise disturbance (Goudie and Jones 2004). It would also be prudent to compare simulated road noise to other sources of noise pollution to establish whether it is specifically road noise, or just noise pollution in general, that waterbirds avoid.

Finally, it is also important to connect apparent disturbance responses (e.g., avoiding noisier parts of a given habitat, as was demonstrated in our study) to habitat use patterns. Road noise is just one of a suite of factors determining habitat quality, and so habitat degradation from this noise, especially at low to moderate levels, could be offset by other factors (e.g., availability of quality food, access to cover) that contribute to habitat use decisions by waterbirds. Thus, there is potential for the biological consequences of road noise avoidance to be negligible if the benefits of using the habitat override the noise aversion. The full picture is likely nuanced, however, and could involve differential effects depending on demographics as had been reported for songbirds exposed to road noise (McClure et al. 2017) and gas compressor noise (Habib et al. 2007). Even if road noise in isolation is not as important as other factors in determining habitat use, it could contribute to an overall effect on waterbirds that is synergistic with other sources of disturbance (Madsen and Fox 1995).

For birds that are excluded from habitat, there could be downstream consequences. For example, sensitive species that experience reduced access to high energy food resources might fail to meet energetic demands, thus leading to a decline in body condition, with consequences for reproductive output. The issue of disturbance and waterbirds has been an urgent topic for decades (Madsen and Fox 1995), but the implications for fitness are less well understood (Gill et al. 2001). Madsen and Fox (1995) describe any disturbance activity as equating to net habitat loss, and more recent studies have reported that changes in habitat availability are implicated in changes in body condition for waterbirds, including northern pintails (*Anas acuta*; Moon et al. 2007) and dabbling ducks (Fleskes et al. 2016). Thus, if waterbirds avoid noisier habitats, the effectiveness of management efforts for adequate cover and food resources is diminished if noise remains a disturbance factor.

CONSERVATION IMPLICATIONS

Our results suggest that road noise pollution could affect the way that waterbirds use habitat by causing them to avoid areas where noise is more pervasive. As transit networks continue to spread into natural areas, conservation planning might need to take into consideration the integrated soundscape and measures for mitigating noise. Unfortunately, there are no well-established guidelines for how quiet a wetland should be to minimize disturbance to wildlife. Thus, we recommend that future work emphasize detecting thresholds for disturbance; however, that disturbance may be defined in terms of behavioral, physiological, or ecological responses.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to declare.

ETHICS STATEMENT

This study adhered to the relevant regulations required by the Hendrix College's Institutional Animal Care and Use Committee (protocol F1217).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available on GitHub at https://github.com/jonvon16/ WaterBirds_Noise_Study.git.

ORCID

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SUPPORTING INFORMATION

Additional supporting material may be found in the online version of this article at the publisher's website.

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