



# Variation in Avian Vocalizations during the Non-Breeding Season in Response to Traffic Noise

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## Abstract

Low-frequency traffic noise that leads to acoustic masking of vocalizations may cause birds to alter the frequencies or other components of their vocalizations in order to be heard by conspecifics and others. Altering parts of a vocalization may result in poorer vocal performance or the message contained in the vocalization being received incorrectly. During the winters of 2011–2012 and 2012–2013, we recorded and measured the ‘chick-a-dee’ call of Black-capped Chickadees (*Poecile atricapillus*) and the ‘po-ta-to-chip’ call of American Goldfinches (*Spinus tristis*) to determine whether components of the calls produced in areas of high traffic noise and low traffic noise differed in any way. We found that both chickadee and goldfinch calls had higher minimum frequencies in areas with high traffic-noise than in low traffic-noise areas. The maximum frequencies showed no differences in either species’ calls. This suggests that chickadees and goldfinches alter the part of their calls that are acoustically masked by traffic noise in effort to better transmit the vocalization. These differences suggest that increasing anthropogenic noise may influence avian communication and that noise management should be included in conservation planning.

## Introduction

Sound is an attribute of every landscape (Slabbekoorn & Ripmeester 2008; Pijanowski et al. 2011). With the encroachment of human populations into previously undeveloped areas, the acoustic characteristics of many landscapes are being modified by anthropogenic sounds that are different in pitch, amplitude, and acoustic structure from natural sounds. These anthropogenic sounds are generally more continuous in quality than sounds produced naturally in the environment (Wood & Yezerinac 2006; Slabbekoorn & Ripmeester 2008; Pijanowski et al. 2011). Traffic noise is one of the main anthropogenic sounds that have been added to the landscape; in fact, the surface area that roads and traffic sounds have an effect on cover an estimated 20% of the entire land mass in the United States (Forman & Alexander 1998). Thus, it is important to better understand the impact of these structures on local ecosystems and the behavior of local populations.

Birds produce some of the most complex and elaborate vocal signals in the animal kingdom (Marler 2004). Birds are able to vocalize at many different frequencies, most commonly ranging between 1000 Hz and 9000 Hz, although certain species have vocalizations that are higher or lower in pitch (Rheindt 2003). Traffic noise associated with roads is of lower frequency, generally falling between 0 Hz and 4000 Hz, as shown in Appendix 1 (Patricelli & Blickley 2006; Nemeth & Brumm 2010). Consequently, lower frequency bird vocalizations may overlap with traffic noise causing acoustic interference or acoustic masking. Those bird species with components of their vocalizations falling in the lower frequency spectrum will likely experience greater acoustic masking than those species with vocalization components at higher frequencies (Wood & Yezerinac 2006; Parris & Schneider 2008; Luther & Baptista 2010).

Most research to date has focused on impacts of acoustic masking on bird vocalizations occurring

during the breeding season when birds vocalize in order to attract mates and defend territories. During this time, if a male's vocalizations are masked, other males may encroach into his territory, the number of aggressive encounters he experiences may increase, or his ability to attract mates may be reduced (Slabbekoorn & den Boer-Visser 2006; Mockford & Marshall 2009). If a male does not sing the 'correct' song or sings a lower quality song, females may not be attracted to him or may leave him for a male with a higher quality song (Halfwerk et al. 2011). Impacts of acoustic masking on avian vocalizations during the non-breeding season have received less attention; however, these impacts should not be overlooked. Communication during the non-breeding season is necessary for an individual to survive, and individuals will only have the opportunity to reproduce if they survive the non-breeding season.

Vocalizations during the non-breeding season may occur for different reasons than those occurring during the breeding season (Freeberg & Lucas 2002). They may be used for individual and flock recognition (Mammen & Nowicki 1981), maintenance of multi-season pair bonds, alerting to possible predators, and predator deterrence through mobbing (Marler 1957). Vocalizations may be important for sharing the location of food sources (Brown et al. 1991). When food is scarce, species-specific aggression calls may be beneficial to avoid physical confrontations between conspecifics (Marler 1957). If any of these vocalizations are masked or modified, individual survival to the next breeding season may be compromised.

Birds have developed a variety of ways to overcome or avoid acoustic masking. The most common response of birds to traffic noise is to vocalize at a higher minimum frequency (Slabbekoorn & den Boer-Visser 2006; Mockford & Marshall 2009). Individuals living in areas that are close to noisy roads may increase the absolute amplitude (Lowry et al. 2012) or change the relative amplitude or frequency of different components of the vocalization in order to be heard (Wood & Yezerinac 2006). Others may change the time of day they vocalize in an attempt to not compete with high traffic noise (Fuller et al. 2007). Some may vary their vocalization structure by increasing the length of or increasing the redundancy in one vocalization before switching to another vocalization type (Brumm & Slater 2006). Others may alter behaviors associated with vocalizations, moving closer or turning their head toward the receiver, to have a better chance of their vocalization being heard (Dooling 2005). The ability to change specific characteristics of vocalizations likely

reflects the learned acquisition of vocalizations (Slabbekoorn & Peet 2003).

There is evidence for learning in the development of Black-capped Chickadee's (*Parus atricapillus*) 'chick-a-dee' call (Ficken & Popp 1995; Hughes et al. 1998; Charrier & Sturdy 2005); young chickadees are known to utilize their first year of life to practice their vocalizations (Shackleton & Ratcliffe 1993). The 'chick-a-dee' call is commonly used by both sexes during the non-breeding season (Ficken et al. 1978, 1985) for individual recognition (Mammen & Nowicki 1981), to indicate mild alarm or the location of food, to maintain flock cohesion, and to coordinate flock movements (Nowicki 1989). There have been fewer studies of American Goldfinch (*Spinus tristis*) vocalizations during the non-breeding season. Both males and females give a flight call ('po-ta-to-chip') that can be individually recognized (Mundinger 1970). This call may be changed as a result of learning during pair and flock formation (Mundinger 1970). Wintering flocks may be an important time for young goldfinches to learn calls and vocalizations (Coutlee 1967). Acoustic masking of vocalizations during the non-breeding season may impair the learning process in both species, and so the impacts of masked vocalizations may extend beyond the breeding season.

In this study, we asked whether the components or structure of Black-capped Chickadee and American Goldfinch calls produced during the non-breeding season were different in the presence of anthropogenic sound, specifically, vehicle traffic noise. This is the first study, of which we are aware, that addresses the effects of anthropogenic sound on bird vocalizations during the non-breeding season. We predicted the minimum frequency of Black-capped Chickadee and American Goldfinch calls would be higher in areas adjacent to high traffic sites as the lower frequency portions of a vocalization have the greatest likelihood of being masked by traffic noise. We also predicted there would be no change in the maximum frequencies of either species' calls as the maximum frequencies for both are at a higher frequency than traffic noise. There may be benefits to maintaining the consistency of the components of a vocalization, such as the maximum frequency, in order to reduce the effects on the vocalizations' functionality.

## Methods

### Study Species

We chose two species for this study: the Black-capped Chickadee and the American Goldfinch due to their

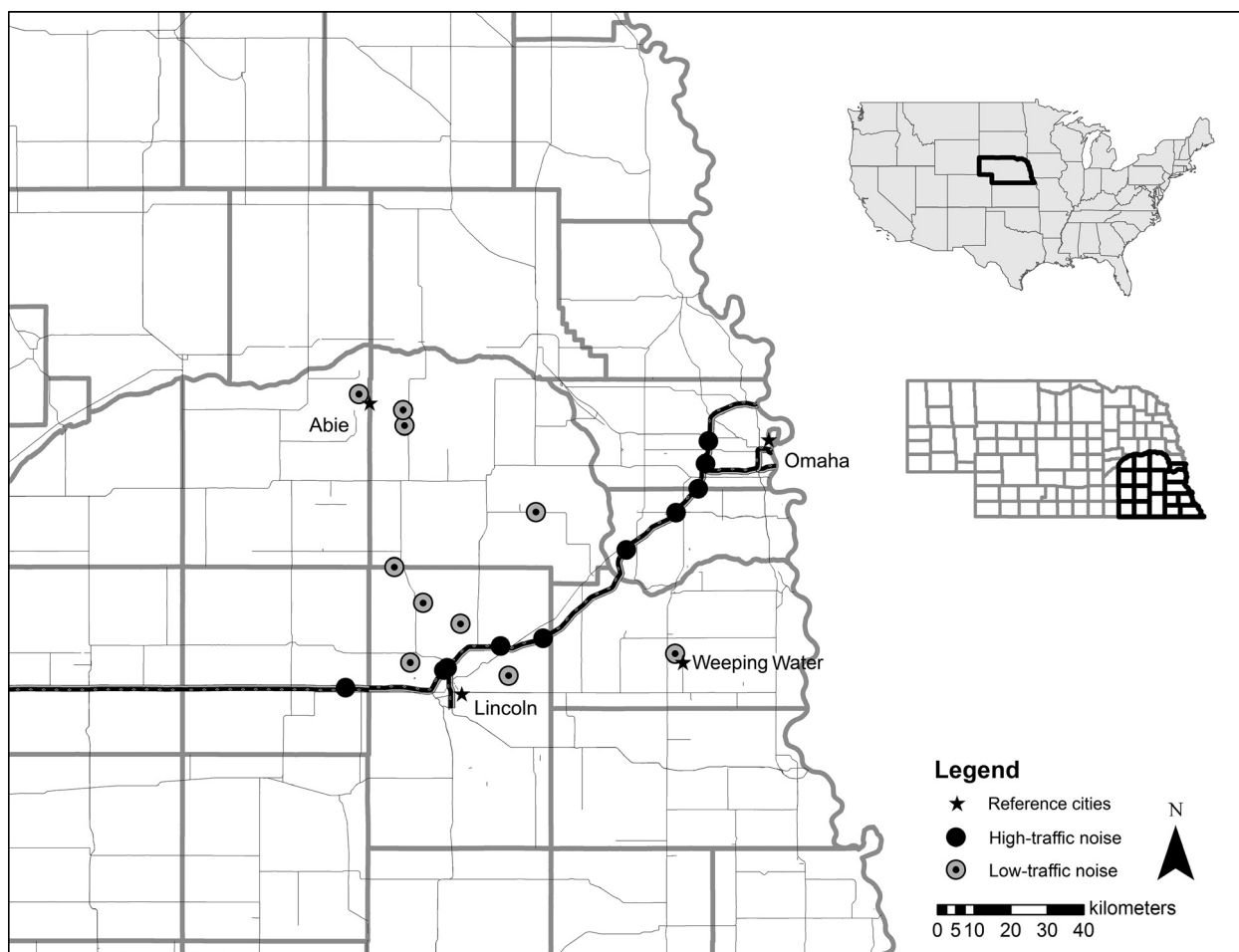
distinctive vocalizations, highly vocal habits, and occurrence in flocks during the non-breeding season. We focused on the 'chick-a-dee' call of the Black-capped Chickadee and the 'po-ta-to-chip' call of the American Goldfinch. We chose these two vocalizations because they (i) are frequently given by birds in single- and mixed-species flocks during the non-breeding season, (ii) are easily identifiable in recordings and spectrograms, and (iii) have clearly identifiable minimum and maximum frequencies in spectrograms (e.g., no low-amplitude residues).

### Study Sites

All study sites were in eastern Nebraska, USA, within Douglas, Sarpy, Cass, Lancaster, Seward, Saunders, and Butler counties (Fig. 1). All recordings were made in linear, mixed conifer and deciduous woodlots

immediately adjacent to roadways. Prairies, urban areas, and agricultural fields were the most abundant land cover types surrounding the woodlots. The structural similarity between recording sites allowed us to focus on acoustic differences and not differences in the physical environment.

To compare calls from high traffic and low traffic sites, we established recording locations that were a minimum of 1.45 km apart. This distance was chosen to ensure that our recordings came from distinct flocks; the average chickadee wintering flock home range is 22.4 ha (0.224 km<sup>2</sup>) (Desrochers & Fortin 2000). High-noise-level sites were identified and established within 450 m of Interstate I-80 (Fig. 1). This four-lane interstate highway supports traffic loads of 40 000 to 60 000 vehicles per day, including over 8000 heavy commercial vehicles (NE Department of Roads 2011, 2012). Based on this high traffic



**Fig. 1:** Location of study sites in eastern Nebraska, USA along Interstate 80. High traffic-noise sites are in black and low traffic-noise sites in gray. The thick black line is Interstate 80, and thin black lines are minor roads. Counties are shown in gray.

volume, we assumed a high-ambient background noise level at these sites. Low-ambient noise level sites were located within 450 m of less traveled county roads (Fig. 1). Visual inspection of spectrograms taken from recordings from these high and low traffic areas supported our assumption of high and low noise levels (Appendix 1).

### Recording Methodology

We recorded chickadee and goldfinch calls, along with the corresponding traffic noise, during the non-breeding season from November to February in 2011–2012 and 2012–2013. We recorded at 12 sites (6 in high noise and 6 in low noise) in 2011–2012 and at those same 12 sites, with an additional 8 sites (totaling 10 in high noise and 10 in low noise) in 2012–2013. We used Song Meter SM2 automated recording units (ARU; Wildlife Acoustics Inc., Maynard, MA, USA, 2013) to capture chickadee and goldfinch calls; each ARU was programmed to record at the same time of day, which allowed for concurrent sampling across all study sites. We recorded for 10 min on the hour between 0800 CST and 1700 CST for a total of 10 recordings per day. This design allowed for sufficient sampling despite the low detection probability of flocking birds during the non-breeding seasons (Quinn et al. 2011). We attached each ARU to a tree, approximately 1.5 m above the ground. The recorders were left to record automatically for 1 mo; at that time, we changed the batteries and collected the memory card in each recorder. Recorders were kept on consistent settings throughout the study, with a sampling rate of 16000 Hz, 0.0 dB gain (left and right), and compression set to off. We uploaded the data onto a computer and used standard settings to sort and analyze the recordings using Song Scope version 3.0 (Wildlife Acoustics Inc., Maynard, MA, USA, 2013).

### Data Analysis

We measured the minimum and maximum frequency (Hz) for each Black-capped Chickadee '*chick-a-dee*' and American Goldfinch '*po-ta-to-chip*' call we selected from the recordings. We selected calls for analysis that were not distorted from reverberation or faint due to the vocalizing bird's physical distance from the recorder. The maximum frequency of vocalizations has a much greater likelihood of being weakened or degraded by interference with obstacles or by traveling long distances (Mockford et al. 2011). By not selecting weak or distorted vocalizations in our

recordings, we greatly reduced the possibility that the maximum or minimum frequency would be altered by degradation instead of acoustic masking. Recordings were viewed and measured on spectrogram view with a frequency range of 0–7000 Hz on the *y*-axis and time in seconds on the *x*-axis. Only calls that appeared 'bright' on the sonogram (louder than 25 dB) were used for measurement.

To reduce the likelihood of measuring the calls of the same bird more than once during the study, only one vocalization was selected from each 10-min recording for analysis. As individuals were not marked and identified during recordings and calls were not identifiable to individuals on the spectrograms, we are not certain that calls from the same individuals were not included in the data more than once. However, we are confident in the low likelihood of pseudo-replication within and between sites given the distance between recording sites and that for all analyses we used the average of all the calls from a site as a single analysis point. For the average frequency of traffic noise, we chose, at random, 100 recordings each from our high traffic-noise sites and low traffic-noise sites to measure the highest frequency, in Hertz, of traffic noise. We compared the average minimum and maximum frequencies (Hz) in the calls between sites with high traffic and low traffic noise for each species with a Kruskal–Wallis rank sum test using an alpha value of 0.05. All analyses were performed with Program R v3.0 (R Core Team 2013).

### Results

A total of 3208 usable calls were identified from over 26 000 recordings. Of these vocalizations, 1297 calls came from the first season (2011–2012) and 1911 calls were from the second season (2012–2013). We recorded 882 chickadee calls and 415 goldfinch calls in 2011–2012 and 1099 chickadee calls and 812 goldfinch calls in 2012–2013. The ambient background noise on the sites with high traffic had an average maximum frequency of 2556 Hz (range = 1437 Hz–3687 Hz) for both years combined. The average maximum frequency of ambient background noise in sites with low traffic was 766 Hz (range = 132 Hz–1437 Hz) for both years combined.

#### Frequency Measurements of Black-Capped Chickadee Calls

A total of 1981 Black-capped Chickadee '*chick-a-dee*' calls were measured (recordings from 2011–2012 and 2012–2013 combined). In areas of high traffic noise,

the minimum frequency ranged from 2562 to 4000 Hz and the maximum frequency ranged from 3562 to 4750 Hz. In areas of low traffic noise, the minimum frequency of these calls ranged from 2250 to 3625 Hz and the maximum frequency ranged from 3652 to 5250 Hz (Fig. 2).

There was no significant difference between the maximum frequencies of chickadee calls recorded near high traffic-noise and low traffic-noise areas (Kruskal–Wallis  $\chi^2 = 0.125$ ,  $df = 1$ ,  $p = 0.724$ ). However, minimum frequencies in high traffic-noise areas were significantly higher than minimum frequencies in low traffic-noise areas (Kruskal–Wallis  $\chi^2 = 6.786$ ,  $df = 1$ ,  $p = 0.009$ ) (Fig. 2).

#### Frequency Measurements of American Goldfinch Calls

A total of 1227 American Goldfinch '*po-ta-to-chip*' calls were analyzed (recordings from 2011–2012 and 2012–2013 combined). In areas of high traffic noise, the minimum frequency ranged from 2187 to 4187 Hz and the maximum frequency ranged from 3437 to 5500 Hz. In areas of low traffic noise, the minimum frequency ranged from 2187 to 4652 Hz and the maximum frequency ranged from 3437 to 5312 Hz (Fig. 3).

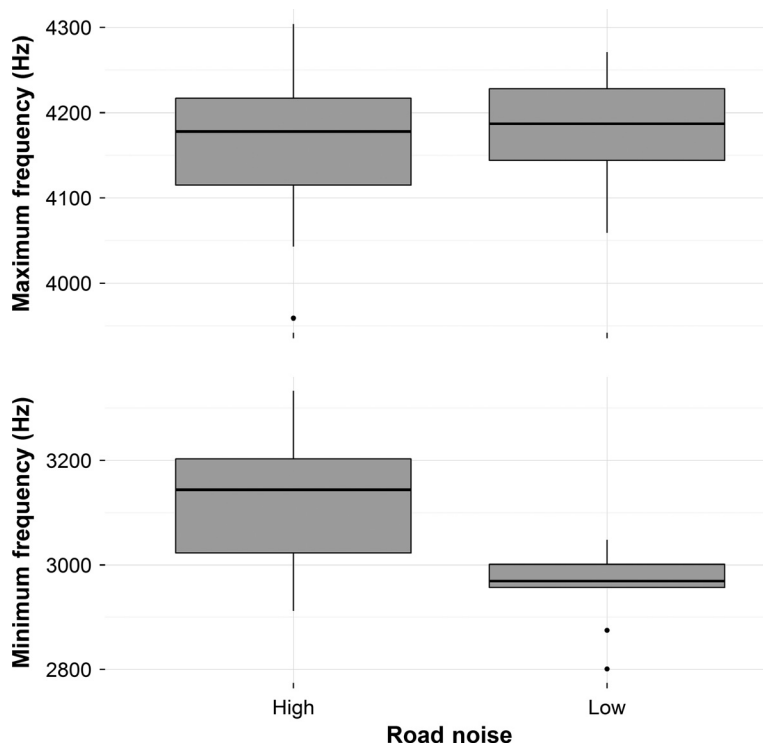
There was no significant difference between the maximum frequencies of goldfinch calls recorded

near high traffic-noise and low traffic-noise areas (Kruskal–Wallis  $\chi^2 = 3.604$ ,  $df = 1$ ,  $p = 0.058$ ). However, minimum frequencies in high traffic-noise areas were significantly higher than minimum frequencies in low traffic-noise areas (Kruskal–Wallis  $\chi^2 = 4.685$ ,  $df = 1$ ,  $p = 0.030$ ) (Fig. 3).

#### Discussion

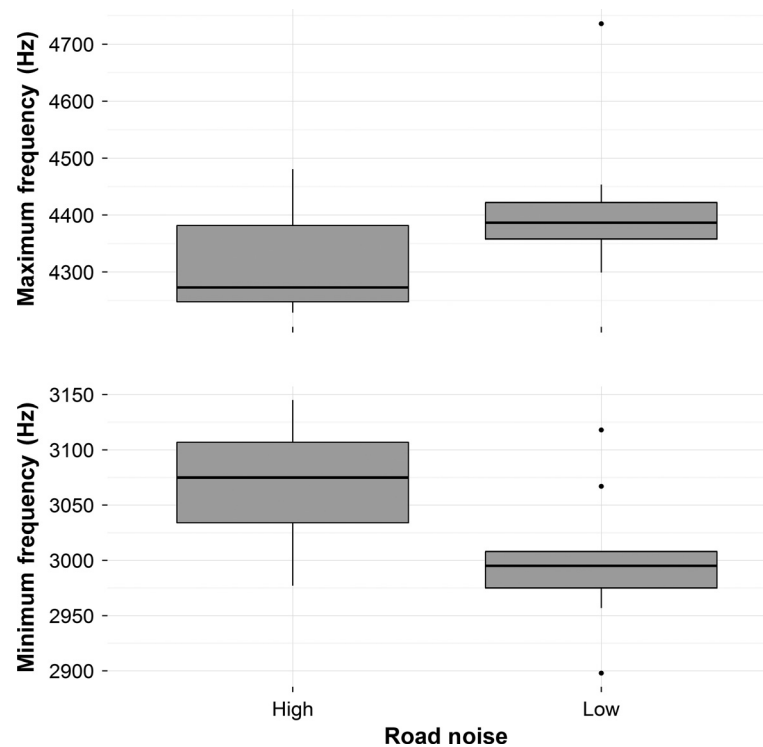
Our results show that in areas of high traffic noise, during the non-breeding season, the minimum frequencies of Black-capped Chickadee and American Goldfinch calls are significantly higher than in areas of low traffic noise. The minimum frequency of the chickadee's '*chick-a-dee*' shifted approximately 190 Hz higher (6%), and the minimum frequency of the goldfinch's '*po-ta-to-chip*' shifted approximately 50 Hz higher (1.6%). The maximum frequency did not differ; thus, the entire frequency structures of the calls did not shift, rather they compressed as a result of the greater minimum frequencies and stable maximum frequencies.

This difference in minimum frequencies is not unexpected as the lower frequency components of chickadee and goldfinch calls overlapped the frequency components of traffic noise in our study area, which may result in acoustic masking. Birds are known to avoid acoustic masking by changing the fre-



**Fig. 2:** Boxplots of measured maximum and minimum frequency ranges of non-breeding season Black-capped Chickadee '*chick-a-dee*' vocalizations in high ( $n = 10$ ) and low ( $n = 10$ ) traffic-noise sites in eastern Nebraska, USA.





**Fig. 3:** Boxplots of measured maximum and minimum frequency ranges of non-breeding season American Goldfinch 'po-ta-to-chip' vocalizations in high ( $n = 10$ ) and low ( $n = 10$ ) traffic-noise sites in eastern Nebraska, USA.

quency structure of their vocalizations to prevent negative impacts on their ability to communicate and perhaps, ultimately on their survival and reproduction (Rheindt 2003). Producing vocalizations with higher minimum frequencies is one solution birds may implement to avoid acoustic masking (Slabbekoorn & den Boer-Visser 2006; Wood & Yezerinac 2006; Luther & Baptista 2010). These studies did not report on the maximum frequency of the vocalizations, so it is unclear whether the vocalizations they studied were compressed or whether the entire vocalization structure shifted to a higher frequency. As the maximum frequency of the calls produced by chickadees and goldfinches in our study was well above the frequency range of the high and low traffic noise in our study area, it is perhaps not surprising that the maximum frequencies were not changed. Not changing the maximum frequency of calls may help maintain the quality of the vocalization and therefore help transmit the correct message to conspecifics and other flock members (Nowicki et al. 2002; Wood & Yezerinac 2006; Mockford & Marshall 2009). Further studies are needed to better understand the reasons why the maximum frequency is kept constant in bird vocalizations.

Sending clear auditory signals is necessary when foraging in dense cover, as many flocks do during the non-breeding season; even in a fairly tight flock, it may not be easy to maintain visual contact (Mammen

& Nowicki 1981). Vocalizations can inform the receiver of the location and identity of the sender to maintain flock cohesion (Slabbekoorn & Halfwerk 2009). If part of a vocalization is masked by traffic noise, it may be harder to detect and recognize the presence of conspecifics or to hear and respond to alarm calls. Producing vocalizations that are clearly broadcast ensures the correct message is transferred, to the advantage of both the sender and the receiver. As both chickadees and goldfinches show evidence of learning the components of their 'chick-a-dee' and 'po-ta-to-chip' vocalizations (Mundinger 1970; Ficken & Popp 1995; Hughes et al. 1998), they have the option of increasing the low-frequency components of their vocalizations to higher frequencies to avoid the negative impacts of acoustic masking. Young chickadees may require extensive practice and hearing conspecific vocalizations repeatedly over the first year of life, including the non-breeding season, to develop their vocalizations correctly (Shackleton & Ratcliffe 1993). The impacts of acoustic masking thus may extend beyond the breeding season into non-breeding months.

## Conclusion

Our results show that the minimum frequencies of the Black-capped Chickadee and American Goldfinch vocalizations during the non-breeding season are significantly higher in areas of high traffic noise than in

areas of low traffic noise; the maximum frequencies of the calls were not changed. We suggest this change is the result of avoidance of acoustic masking by noise associated with high traffic noise. As changes in vocalizations may cause complications in identification, flock maintenance, predator response, vocalization learning, and information sharing, more research is needed during the non-breeding months to better understand the consequences of vocalization shifts within flocks and between flocks. These data suggest the need to consider alteration of the soundscape when working to protect birds in managed ecosystems.

### Acknowledgements

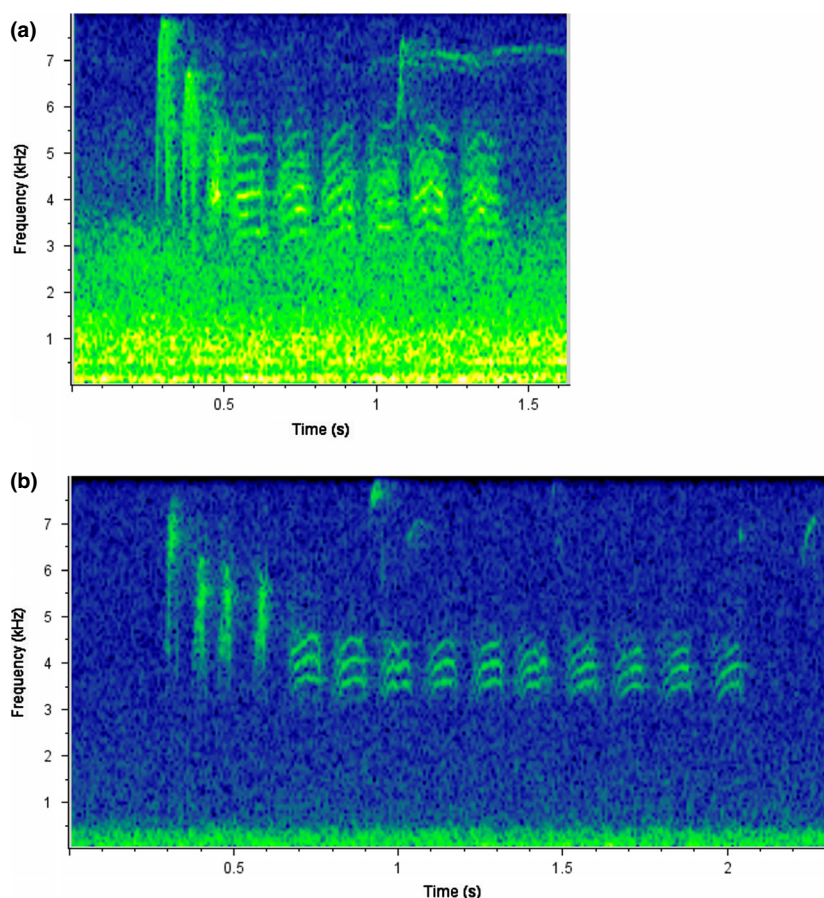
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### Literature Cited

- Brown, C. R., Brown, M. B. & Shaffer, M. L. 1991: Food-sharing signals among socially foraging Cliff Swallows. *Anim. Behav.* **42**, 551–564.
- Brumm, H. & Slater, P. J. B. 2006: Ambient noise, motor fatigue, and serial redundancy in Chaffinch song. *Behav. Ecol. Sociobiol.* **60**, 475–481.
- Charrier, I. & Sturdy, C. B. 2005: Call-based species recognition in Black-capped Chickadees. *Behav. Process.* **70**, 271–281.
- Coutlee, E. L. 1967: Agnostic behavior in the American Goldfinch. *Wilson Bull.* **79**, 89–109.
- Desrochers, A. & Fortin, M. 2000: Understanding avian responses to forest boundaries: a case study with chickadee winter flocks. *Oikos* **91**, 376–384.
- Dooling, R. J. 2005: Estimating effects of highway noise on the avian auditory system. UC Davis: Road Ecology Center. Retrieved August, 1, 2010 from: <http://escholarship.org/uc/item/60z8s62w>.
- Ficken, M. S. & Popp, J. W. 1995: Long-term persistence of a culturally transmitted vocalization of the Black-capped Chickadee. *Anim. Behav.* **50**, 683–693.
- Ficken, M. S., Ficken, R. W. & Witkin, S. R. 1978: Vocal repertoire of the Black-capped Chickadee. *Auk* **95**, 34–48.
- Ficken, M. S., Ficken, R. W. & Apel, K. M. 1985: Dialects in a call associated with pair interactions in the Black-capped Chickadee. *Auk* **102**, 145–151.
- Forman, R. T. T. & Alexander, L. E. 1998: Roads and their major ecological effects. *Annu. Rev. Ecol. Syst.* **29**, 207–231.
- Freeberg, T. M. & Lucas, J. R. 2002: Receivers respond differently to chick-a-dee calls varying in note composition in Carolina Chickadees, *Poecile carolinensis*. *Anim. Behav.* **63**, 837–845.
- Fuller, R. A., Warren, P. H. & Gaston, K. J. 2007: Daytime noise predicts nocturnal singing in urban robins. *Biol. Lett.* **3**, 368–370.
- Halfwerk, W., Bot, S., Bulkx, J., van der Velde, M., Komdeur, J., ten Cate, C. & Slabbekoorn, H. 2011: Low-frequency songs lose their potency in noisy urban conditions. *Proc. Natl Acad. Sci.* **108**, 14549–14554.
- Hughes, M., Nowicki, S. & Lohr, B. 1998: Call learning in Black-capped Chickadees (*Parus atricapillus*): the role of experience in the development of ‘chick-a-dee’ calls. *Ethology* **104**, 232–249.
- Lowry, H., Lill, A. & Wong, B. B. M. 2012: How noisy does a Noisy Miner have to be? Amplitude adjustments of alarm calls in an avian urban adapter. *PLoS ONE* **7**, e29960.
- Luther, D. & Baptista, L. 2010: Urban noise and the cultural evolution of bird songs. *Proc. R. Soc. B* **277**, 469–473.
- Mammen, D. L. & Nowicki, S. 1981: Individual differences and within flock convergence in chickadee calls. *Behav. Ecol. Sociobiol.* **9**, 179–186.
- Marler, P. 1957: Specific distinctiveness in the communication signals of birds. *Behaviour* **11**, 13–39.
- Marler, P. 2004: Bird calls their potential for behavioral neurobiology. *Ann. N. Y. Acad. Sci.* **1016**, 31–44.
- Mockford, E. J. & Marshall, R. C. 2009: Effects of urban noise on song and response behavior in Great Tits. *Proc. R. Soc. B* **276**, 2979–2985.
- Mockford, E. J., Marshall, R. C. & Dabelsteen, T. 2011: Degradation of rural and urban Great Tit song: testing transmission efficiency. *PLoS ONE* **6**, e28242.
- Munding, P. C. 1970: Vocal imitation and individual recognition of finch calls. *Science* **168**, 480–482.
- Nebraska Department of Roads. 2011: Traffic Noise Model 2.5. P.O. Box 94759 Lincoln, Nebraska 68509-4759. [www.transportation.nebraska.gov](http://www.transportation.nebraska.gov). Retrieved: October 5, 2011.
- Nebraska Department of Roads. 2012: Traffic Flow Map of the State of Nebraska. P.O. Box 94759 Lincoln, Nebraska 68509-4759. Retrieved September 1, 2014 from: <http://www.transportation.nebraska.gov/maps/Statewide%20Traffic%20Flow%20Maps/2012-Statewide-Traffic-Flow-Map.pdf>.
- Nemeth, E. & Brumm, H. 2010: Birds and anthropogenic noise: are urban songs adaptive? *Am. Nat.* **176**, 465–475.
- Nowicki, S. 1989: Vocal plasticity in captive Black-capped Chickadees: the acoustic basis and rate of call convergence. *Anim. Behav.* **37**, 64–73.
- Nowicki, S., Searcy, W. A. & Peters, S. 2002: Quality of song learning affects female response to male bird song. *Proc. R. Soc. Lond. B* **269**, 1949–1954.

- Parris, K. M. & Schneider, A. 2008: Impacts of traffic noise and traffic volume on birds of roadside habitats. *Ecol. Soc.* **14**, 29.
- Patricelli, G. L. & Blickley, J. L. 2006: Avian communication in urban noise: causes and consequences of vocal adjustment. *Auk* **123**, 639—649.
- Pijanowski, B. C., Villanueva-Rivera, L. J., Dumyahn, S. L., Farina, A., Krause, B. L., Napoletano, B. M., Gage, S. H. & Pieretti, N. 2011: Soundscape ecology: the science of sound in the landscape. *Bioscience* **61**, 203—216.
- Quinn, J. E., Brandle, J., Johnson, R. & Tyre, A. 2011: Accounting for detectability in the use and application of indicator species: a case study with birds. *Ecol. Indic.* **11**, 1413—1418.
- R Core Team. 2013: R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
- Rheindt, F. E. 2003: The impact of roads on birds: does song frequency play a role in determining susceptibility to noise pollution? *J. Ornithol.* **144**, 295—306.
- Shackleton, S. A. & Ratcliffe, L. 1993: Development of song in hand-reared Black-capped Chickadees. *Wilson Bull.* **105**, 637—644.
- Slabbekoorn, H. & den Boer-Visser, A. 2006: Cities change the songs of birds. *Curr. Biol.* **16**, 2326—2331.
- Slabbekoorn, H. & Halfwerk, W. 2009: Behavioural ecology: noise annoys at community level. *Curr. Biol.* **19**, R693—R695.
- Slabbekoorn, H. & Peet, M. 2003: Birds sing at a higher pitch in urban noise. *Nature* **424**, 267.
- Slabbekoorn, H. & Ripmeester, E. A. P. 2008: Birdsong and anthropogenic noise: implications and applications for conservation. *Mol. Ecol.* **17**, 72—83.
- Wood, W. E. & Yezerinac, S. M. 2006: Song Sparrow (*Melospiza melodia*) song varies with urban noise. *Auk* **123**, 650—659.

### Appendix



**Appendix 1:** Sonograms showing the visual differences between (a) high traffic noise, with frequencies of up to 4000 Hz that masks the lower frequencies of a Black-capped Chickadee 'chick-a-dee' vocalization, and (b) low traffic noise, with frequencies lower than 1000 Hz.