

A test of the nonlinearity hypothesis: Is noise any different than deterministic chaos?

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Abstract

Noisy, unpredictable sounds are often present in the vocalizations of fearful and stressed juvenile animals across many taxa. A variety of structural characteristics, called nonlinear acoustic phenomena, which include subharmonics, rapid frequency modulations, and deterministic chaos are responsible for the harsh quality of these vocalizations. Exposure to nonlinear sound can elicit increased arousal in birds and mammals. Past experiments have used white noise to test for effects of deterministic chaos on perceivers. However, deterministic chaos differs structurally from white noise, and unlike white noise (which is random energy at all frequencies) may differ dramatically depending on how it is produced. In addition, the subtle structural variation of chaos may not be distinguishable in the environment due to the attenuation and degradation of sound over distance and different habitat types. We designed two experiments to clarify whether American robins (*Turdus migratorius*) and warbling vireos (*Vireo gilvus*) discriminate between white noise and deterministic chaos. We broadcast and re-recorded white noise and two exemplars of deterministic chaos at 1, 10, 20, 30, 40, and 80 m across open and forested habitat and compared spectrogram correlation among stimuli. Spectrogram correlation results indicated that sounds degraded similarly in both habitats when compared to reference distances of 1 m. Comparing pairs of stimuli across distance suggested that Chua chaos was more easily distinguishable from noise and logistic chaos. In addition, all stimuli became more distinctive over increased distance. The second experiment tested behavioral responses of robins and warbling vireos to control sounds of tropical kingbird (*Quiscalus mexicanus*), white noise, and two exemplars of deterministic chaos (Logistic waveform and Chua). For both species, there was no overall effect of stimulus and 95% confidence intervals indicated some patterns in difference of proportion of time spent in relaxed behavior and looking. These results suggest that species responded to all stimuli but did not discriminate among them. White noise and deterministic chaos could be potentially perceived differently by birds but this is dependent on the structure of the deterministic chaos. Increasing sample size may provide stronger results since effect sizes are small. Also, using an alternate control stimulus may aid in resolving whether birds are able to discriminate among noise and chaos.

Introduction

Typically, unpredictable sounds elicit attentive responses better than melodic, pure tones. For example, the cries of human babies cause physiological responses in adult listeners associated with preparation for caregiving (Tkaczyszyn et al. 2013). Often, noisy screams, cries, and other sounds contain specific structural characteristics that are particularly evocative to receivers. Specifically, nonlinear acoustic phenomena, are evident in the vocalizations of a variety of taxa including terrestrial mammals (Wilden et al. 1998, Tokuda et al. 2002, Riede et al. 2007, Blumstein et al. 2008, Rendall et al. 2008), marine mammals (Tyson et al. 2007), frogs (Pettitt et al. 2012), toadfish (Rice et al. 2011), and birds (Fee et al. 1998).

Nonlinear acoustic phenomena, such as rapid frequency jumps, subharmonics, biphonation, and deterministic chaos, can affect the behavior of listeners. These sounds, whether natural or artificially synthesized, appear to decrease time spent engaged in relaxed behaviors in marmots (Blumstein & Recapet 2009), meerkats (Townsend & Manser 2011), and birds (Slaughter et al. 2013, Blesdoe & Blumstein in review). Further, nonlinear phenomena present in film soundtracks have been shown to elicit fearful responses in humans (Blumstein et al. 2010) and some singers intentionally incorporate biphonation, subharmonics, and abrupt frequency changes into their vocal performances to add musical effect (Neubauer et al. 2003).

Nonlinear acoustic phenomena may result from asymmetries in the sound production system of birds (Fee et al. 1998, Larsen & Goller 1999, Zollinger et al. 2008) and mammals (Wilden et al. 1998, Fitch et al. 2002), or it may result from overblowing a symmetrical sound production system. For instance, in birds, the syringeal structures vibrate to produce songs, calls, and other vocalizations (Arneodo et al. 2011). When too much air is pushed through the syrinx, complex sounds may be produced. While mechanical strain on vocal structures is responsible for the production of nonlinear sound, evidence of nonlinear phenomena is found in the vocalizations of a wide variety of animal taxa indicating that they may serve adaptive functions (Morton 1997, Fitch et al. 2002).

Vocalizations with nonlinearities may allow listeners to differentiate between individuals of the same species (Rendall et al. 2009) and, in particular, subharmonics may alter the way listeners behave around the communicating individual by indicating size or dominance (Morton 1977, Fitch et al. 2002). Also, calls containing noise or rapid jumps in frequency from tonal sound to noise may be more difficult to habituate to and function as an attention getting signal

(Blumstein & Recapet 2009, Townsend & Manser 2011). Nonlinearities in vocalizations of giant panda (*Ailuropoda melanoleuca*) neonates communicate cub arousal and ensure attention from the mother (Stoeger et al. 2012).

Structure and function are closely tied in many systems and this relationship has been studied extensively. In regard to behavior, Darwin asserted that body positions and intention are connected (Darwin 1872). For example, the act of being startled (physically flinching and closing the eyelids) may serve a protective function by evading danger. Body positions associated with particular emotions or behaviors seem to align with the action the individual is preparing to carry out. Darwin uses the example of the various postures dogs exhibit when approaching a human friendly, aggressive, or submissive ways. Following Darwin's lead, Morton's motivation-structure rules provide additional insight to the importance of structure to behavior (Morton 1977). Morton suggested that physical behaviors, such as aggression, are associated with more subtle, acoustic signals that are used to communicate dominance. In support of this, Morton noticed that birds and mammals use noisy, low-frequency sounds while engaging in aggressive behavior and higher-frequency, pure tone sounds when submissive or frightened. Extending this structure-function relationship to noisy, nonlinear acoustic attributes, we see that noisy sounds in vocalizations are produced when animals are in fearful, stressful conditions, and are particularly evocative to receivers.

Most studies regarding nonlinear sound function have used mammals as model systems while only two experimental studies have investigated the effects of nonlinear sound on birds (Slaughter et al. 2013, Blesdoe & Blumstein in review). In addition, previous studies have used short sequences of white noise to simulate vocalizations containing nonlinear phenomena while overblown vocal systems actually produce deterministic chaos, not noise (Fitch et al. 2002).

It is unclear whether animals can discriminate between noise and deterministic chaos and whether noise could be used interchangeably with chaos in experiments testing nonlinear sound hypotheses. While the two nonlinear phenomena have similar harsh sound quality, they differ in signal structure. Unlike the equal energy at all frequencies present in white noise, deterministic chaos retains some periodic oscillations observable in spectrograms (Fitch et al. 2002). Since deterministic chaos differs from white noise, experiments using white noise may affect behavior in a way different than naturally produced chaos would.

However, deterministic chaos can be produced in many different ways. The structure of synthetically produced deterministic chaos varies widely due to the large space for parameter manipulation in production. For example, Chua's oscillator is based on an electronic circuit capable of producing nonlinear phenomena dependent on how parameters (α , β , $-\gamma$, a , b , k) are varied (Figure 1) (Pivka et al. 1994, Chua 1995). A variety of chaotic attractors (state a variable evolves to over time) have been observed in Chua circuits which may translate to different sound structure (Matsumoto 1984, Leonov et al. 2012). Another method of producing chaos is to use a parameter above the Hopf bifurcation ($r > 3.57$) in a logistic equation. Although Chua and logistic chaos are both considered deterministic chaos, their structure varies.

Therefore, deterministic chaos represents a diverse class of nonlinear sound. Since noise and chaos are structurally different, their effects on listeners may differ. Slight variations in signal may affect the way sounds are perceived and may have implications on the level of arousal incited in listeners.

However, it is unclear whether the structural differences of noise and chaos are perceptible over increasing spatial distances. Slight structural differences among nonlinearities such as noise and deterministic chaos may be obscured at increasing distance. With increasing distance between the signaler and receiver, degradation and attenuation of sound increases due to atmospheric absorption, ground attenuation, signal scattering, and deflection of sound by layered surfaces such as spaces between tree canopy and the ground (Wiley & Richards 1978). These effects may (or may not) vary by habitat type. Thus, we might expect that different types of noise and chaos would become systematically less discriminable over distance. Transmission experiments are required to test the fidelity of sound over distance and different habitat types. Spectrogram correlation could then be used to determine whether sounds are potentially distinguishable at increased distances. Spectrogram correlations range from 0 and 1.0; higher correlations would indicate the sounds are similar.

If noise and chaos differ in their discriminability according to spectrogram correlations, animals may be able to distinguish among them. Audio playback experiments are required to determine whether animals respond differently to noise versus deterministic chaos. By collecting behavior data from individuals before, during, and after playback, it is possible to identify changes in proportion of time spent engaged in relaxed behaviors, latency to returning to relaxed behaviors after hearing playback, and other signs of disruption from baseline behavior

prior to playback. Similar playback experiments have been used on White-crowned Sparrows (*Zonotrichia leucophrys*) (Blesdoe & Blumstein in review) and Great-tailed Grackles (*Quiscalus mexicanus*) (Slaughter et al. 2013).

To investigate birds' ability to perceive structural differences among nonlinear phenomena, American Robins (*Turdus migratorius*) and Warbling Vireos (*Vireo gilvus*) were exposed to four stimuli: white noise, deterministic chaos produced by Arik Kershenbaum's logistic waveform, deterministic chaos produced by the Chua Oscillator, and a tropical kingbird control. The two types of deterministic chaos differ in waveform with Chua chaos exhibiting more clicks (frequency jumps) and logistic waveform having a fuller spectrum without clicks (Figure 3). Also, the amplitude declined at higher frequencies for Chua. Birds' behavioral responses to noise, Chua and logistic waveform-derived deterministic chaos, and pure tones were evaluated by recording focal behavior data and comparing mean differences in baseline behaviors in the time following playback of stimuli.

Methods

Study Site and Species

From 30 May 2013 – 8 July 2013, playback experiments were conducted on American Robins (*Turdus migratorius*) and Warbling Vireos (*Vireo gilvus*) near the Rocky Mountain Biological Laboratory in Gothic, Colorado. Experiments were performed from sunrise until mid-morning under calm weather conditions when the wind was $\leq$ Beaufort Scale 3.

Sound Degredation Experiment

We broadcast the three experimental stimuli across representative open and forested habitats where the birds were found. Stimuli were broadcast and re-recorded with an Audix OM-3xb microphone (Audix Microphones, Wilsonville, OR) and Marantz PMD 660 solid state recorder (16 bit, 44.1 kHz sampling) 1, 10, 20, 30, 40, and 80 m from the speaker. We replicated this 5 times in each habitat type. Stimuli were edited to 5.5 s files and we used Raven 1.4 (Bioacoustics Research Program. 2011) to calculate spectrogram correlation values (256 sample spectrogram with Hann window, hop size 128, 50% overlap) for each stimulus compared to other stimuli at the same distance or itself across the increasing distances. We fitted a general linear model where stimulus, distance, and habitat types were main effects (all interactions were included) to explain spectrogram correlation variation in degradation over distance. Specifically, we fitted two models. The first set of spectrogram correlation values compared each stimulus

recorded at 10, 20, 40, 80 m to its 1 m value. This analysis was designed to compare the degradation of the three stimuli over distance in the two habitat types. The second compared pairs of stimuli at each distance. This analysis was designed to determine which stimuli were most distinguishable or more similar to each other with increased distance. We could then predict which sounds would elicit different responses in birds based upon their discriminability.

Playback Experiment

Four stimuli were used for the playback experiments including three experimental stimuli and one control stimulus (Figure 3). Experimental stimuli included white noise and two types of deterministic chaos (logistic wave form and a type created with the Chua oscillator). Control stimuli consisted of six Tropical Kingbird (*Tyrannus melancholicus*) vocalizations not containing nonlinear acoustic attributes. The kingbird stimuli provided a novel control for comparison to the novel experimental stimuli. The amplitude on each track was RMS normalized (to 95% of peak amplitude) in Sound Studio then 1.5-5.0 kHz bandpass filtered in Raven 1.4 (Bioacoustics Research Program 2011). Stimuli were stored on an Apple iPod (Apple, Inc., Cupertino, CA) in AIF format for subsequent playback.

A single observer quietly positioned herself 10-15 m (11.85 ± 1.76) from a subject and waited for it to relax. Relaxed behavior was inferred if the bird was foraging, walking, or preening. Stimuli were broadcast from a PAL Speaker (Tivoli Audio, Boston, MA) at a peak amplitude of 85 dB SPL (measured 1 m away, weighting A). A 30 s period of silence marked the beginning of each playback to allow baseline behavior to be recorded. Following the 30 s of silence, the brief stimulus was broadcast and followed by an additional 60 s of silence, which allowed the behavior of the focal individual to be recorded to determine whether there was any reaction to the stimulus.

For the duration of each playback trial, all behavioral transitions, based on a predetermined ethogram (Table 1), were dictated into a digital audio recorder. Also, the GPS location, wind speed (measured on the Beaufort scale; no experiments conducted if above 3), percentage of cloud cover (no experiments conducted during rain), distance from observer (in m), number of conspecifics within 10 m, number of heterospecifics within 10 m, and, if obvious from plumage, the subject's age and sex were recorded. Playback trials were conducted with at least a 40 m radius between focal subjects in an attempt not to repeat trials on any bird (American Robins 185

± 194.26 , warbling vireos 98 ± 110.78). Subsequent trials were conducted a minimum of five minutes apart (American robins 46.52 ± 101.68 , warbling vireos 24.7 ± 27.33) and the four stimuli were played according to a predetermined script to ensure a balanced number of playbacks per stimulus and to reduce any possible systematic carryover effects on subjects that might have heard a previous sound.

We explored whether any other recorded factors—distance from observer to bird, height of bird in tree, distance of the bird from the road, distance of bird from town, distance between birds, number of conspecifics within 10 m, and the number of heterospecific birds within 10 m—varied significantly by sound stimuli used for both species.

For American robins, the distance from observer to bird did not vary significantly with treatment and was not included in models ($p = 0.179$). Distance from bird to road, town, and to conspecific birds used in experimental trials did not vary significantly with treatment ($p = 0.070$, $p = 0.777$, $p = 0.564$). The number of conspecifics and heterospecifics within 10 m did not vary significantly with treatment and were also not used as covariates ($p = 0.117$, $p = 0.514$).

For vireos, the distance from observer to bird did not vary significantly with treatment and was not included in models ($p = 0.126$). Distance from bird to road, town, and to conspecific birds used in experimental trials did not vary significantly with treatment ($p = 0.736$, $p = 0.739$, $p = 0.764$). The number of conspecifics and heterospecifics within 10 m did not vary significantly with treatment and were also not used as covariates ($p = 0.384$, $p = 0.234$).

Data Analysis

A total of 81 playback experiments were conducted on robins (20 using the tropical kingbird stimulus, 21 white noise, 20 logistic waveform chaos, and 20 Chua chaos) and a total of 80 playback experiments were conducted on warbling vireos (20 using the tropical kingbird stimulus, 20 white noise, 20 logistic waveform chaos, and 20 Chua chaos).

We used JWatcher (v1.0 Blumstein & Daniel, 2007) to calculate the proportion of time in sight for all individual scored behaviors. Based on these calculations, we defined two additional collective behaviors. Relaxed behavior included time allocated to foraging, preening, and walking for robins. We noticed that warbling vireos spent much of their observed time singing

so we included vocalization in ‘relaxed’ for them. Total locomotion was defined to include hopping, flying, and walking.

Birds spent a large proportion of time looking in the baseline period (Figure 4) and there were no significant differences in baseline vigilance across treatments with kingbird included (Figure 5, Figure 6). Following stimulus playback, we noticed an immediate increase in vigilance and subsequent increase in relaxed behavior over time. Thus, we formally analyzed time allocation by comparing time allocated in final 30 s after playback to time allocation in the baseline 30 s. Time allocation estimates were arcsine transformed to normalize variation before analysis.

Results

Sound Degredation

Spectrogram correlation values compared between individual stimuli and 1 m reference distances showed significant habitat and distance effects ($p = 0.001$, $p < 0.001$, adjusted $r^2 = 0.588$) For both forest and open habitat, decreased spectrogram correlation values indicated that sounds became less similar to 1 m reference distances with increased distance (Figure 7). Noise and logistic waveform chaos showing similar values at 80 m and chua chaos slightly lower.

Spectrogram correlation values for paired comparisons at each distance showed significant pair and distance effects (all p values < 0.001) while there was no significant effect of habitat on correlation ($p = 0.068$). In both forest and open habitats, individual sounds became more distinguishable from each other with increased distance (Figure 8). Noise and logistic chaos showed higher correlation and were most similar. Chua chaos was most distinguishable from logistic chaos and noise.

Playback Experiments

American Robin

There was no main effect of stimulus on the difference between the last 30 s time interval and the 30 s baseline period in terms of the time allocated to relaxed behavior, looking, and locomotion ($p = 0.674$, $p = 0.318$) (Figure 5). Pair-wise comparisons between the control kingbird vocalization and each experimental stimulus revealed that robins responded to all stimuli without discriminating among them. Effect sizes were small, indicated by low d -scores

(Table 2) (Cohen 1988). In difference from baseline in proportion of time spent in relaxed behavior, it appears that birds suppressed relaxed behavior slightly, although not significantly ($p = 0.873$) robins after hearing logistic chaos and noise (Figure 5).

Warbling Vireo

A significant treatment effect was found for warbling vireos when tropical kingbird stimuli data were excluded ($p = 0.047$, adjusted $r^2 = 0.070$). Pair-wise comparisons indicated increased looking for logistic waveform chaos which significantly differed from noise ($p < 0.014$). A similar pattern of decreased difference from baseline proportion time spent relaxed was found for warbling vireos although there was no significant effect ($p = 0.610$).

Discussion

Our results suggest that birds, particularly warbling vireos, may differentially respond to white noise and chaos and that the sounds used in this experiment could vary in ease of discriminability over distance. However, the ability of birds to discriminate between noise and chaos is not a straightforward structure-function relationship. Deterministic chaos represents a category of sound rather than a clearly defined nonlinear sound (such as white noise). In this experiment, we used two exemplars of deterministic chaos generated via different means. Logistic chaos and Chua chaos differed in degradation over space and in how birds responded to them. Specifically, Chua degraded much differently than noise and logistic chaos and had a lower amplitude at higher frequencies. The frequency range of a bird's hearing may also affect whether certain nonlinearities are perceived. In the only specific treatment effect, warbling vireos looked more after hearing logistic waveform chaos. Surprisingly, warbling vireos did not show increased time spent looking after exposure to white noise. White noise had similar spectral characteristics and degraded most similarly to logistic chaos. This result provides subtle evidence that the structure found in chaos may be especially evocative.

If deterministic chaos is to be used in place of white noise in future tests of nonlinear sound hypotheses, the type of deterministic chaos most similar to the overblowing of vocal structures should be identified. Clearly, deterministic chaos should not be treated as a single type of nonlinear sound, like frequency shifts or subharmonics. Our analysis revealed small effect sizes and great variance which made it difficult to draw strong conclusions. Increasing

sample size and using a control stimulus other than tropical kingbird may improve our understanding of how white noise and chaos differ.

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$$\left. \begin{aligned} \frac{dx}{d\tau} &= k\alpha(y-x-f(x)) \\ \frac{dy}{d\tau} &= k(x-y+z) \\ \frac{dz}{d\tau} &= k(-\beta y-\gamma z) \\ f(x) &= bx + \frac{1}{2}(a-b)\{|x+1|-|x-1|\} \end{aligned} \right\} \quad (2)$$

where

$$\left. \begin{aligned} x &= \frac{v_1}{E}, \quad y = \frac{v_2}{E}, \quad z = i_3 \left(\frac{R}{E} \right) \\ \alpha &= \frac{C_2}{C_1}, \quad \beta = \frac{R^2 C_2}{L}, \quad \gamma = \frac{RR_0 C_2}{L} \\ a &= RG_a, \quad b = RG_b, \quad \tau = \frac{t}{|RC_2|}, \quad \text{and} \quad \begin{cases} k = 1 & \text{if } RC_2 > 0 \\ k = -1 & \text{if } RC_2 < 0. \end{cases} \end{aligned} \right\} \quad (3)$$

Figure 1. From Pivka, L. et al. 1994, Nondimensionalized form of Chua Oscillator equation used as an approximating method to solve differential equations.

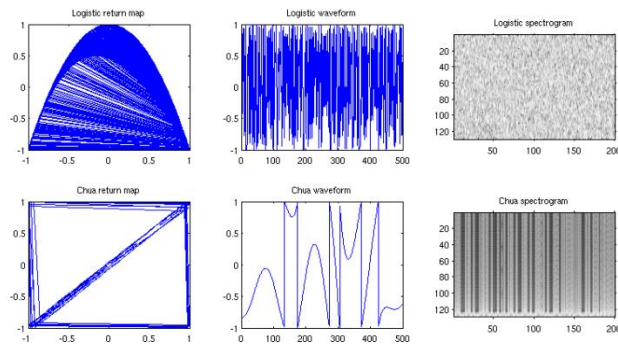


Figure 2. Return maps for Chua and logistic waveform chaos from Arik Kershenbaum.

Table 1. Ethogram of behaviors recorded during playbacks, modified from Slaughter et al. 2013.

Behavior	Description
Stand and look	Standing or perching, scored each time head moved and fixated
Forage	Moving head towards the ground to forage or having food in beak
Preen	Moving beak through feathers
Walk	Taking steps, moving legs individually
Hop	Jumping from one location to another, scored by each discrete hop
Other	Other behaviors such as shaking, feather ruffling, scratching, etc.
Vocalization	Singing or non-song vocalization, excluding chinking
Flight	Flying, but not out of sight
Out of sight	No longer in sight

Table 2. D-scores for arcsine transformed difference from baseline in locomotion, relaxed, and look behaviors for American robins (AMRO) and warbling vireos (WAVI) in the last 30 s following playback.

Species	Behavior	Stimuli Compared	Cohen's D
AMRO	AT Dif Base Locom 3060	Noise-TKB	0.075
AMRO	AT Dif Base Locom 3060	Logistic-TKB	-0.349
AMRO	AT Dif Base Locom 3060	Chua-TKB	0.443
WAVI	AT Dif Base Relax 3060	Noise-Logistic	-0.107
WAVI	AT Dif Base Relax 3060	Noise-Chua	-0.272
WAVI	AT Dif Base Relax 3060	Chua-Logistic	-0.198
WAVI	AT Dif Base Relax 3060	Noise-TKB	-0.409
WAVI	AT Dif Base Relax 3060	Logistic-TKB	-0.329
WAVI	AT Dif Base Relax 3060	Chua-TKB	-0.062
WAVI	AT Dif Base Look 3060	Noise-Logistic	-0.717
WAVI	AT Dif Base Look 3060	Noise-Chua	-0.273
WAVI	AT Dif Base Look 3060	Chua-Logistic	0.549
WAVI	AT Dif Base Look 3060	Noise-TKB	-0.253
WAVI	AT Dif Base Look 3060	Logistic-TKB	0.568
WAVI	AT Dif Base Look 3060	Chua-TKB	0.024
WAVI	AT Dif Base Locom 3060	Noise-Logistic	0.328
WAVI	AT Dif Base Locom 3060	Noise-Chua	-0.15
WAVI	AT Dif Base Locom 3060	Chua-Logistic	-0.485
WAVI	AT Dif Base Locom 3060	Noise-TKB	0.444
WAVI	AT Dif Base Locom 3060	Logistic-TKB	0.098
WAVI	AT Dif Base Locom 3060	Chua-TKB	0.614

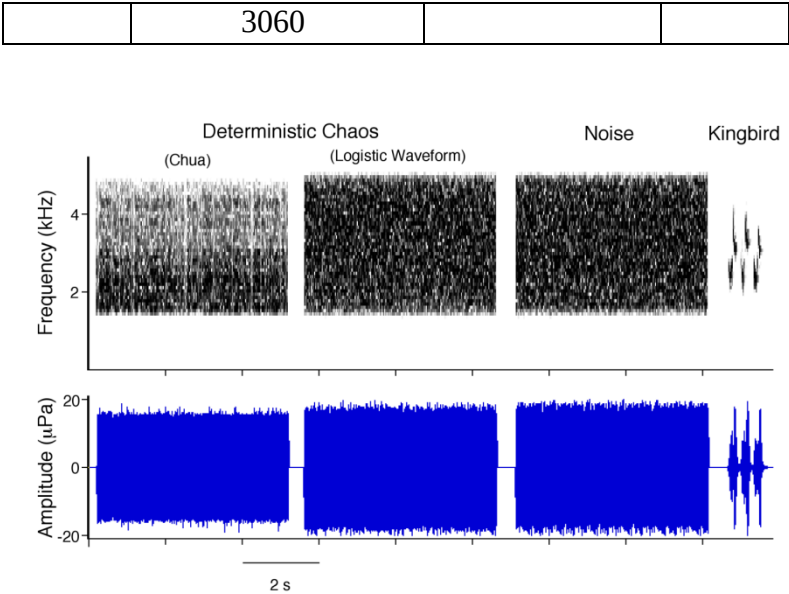
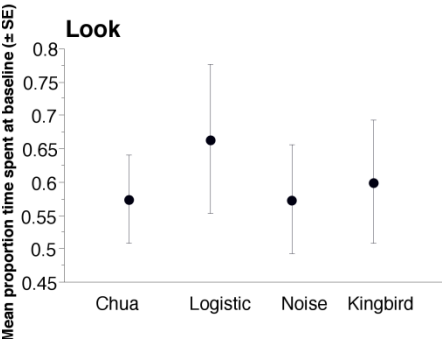


Figure 3. Spectrogram and amplitude plot of hree experimental stimuli (Chua, logistic waveform, white noise) and exemplar of kingbird vocalization used in playback experiments.

Robin



Warbling Vireo

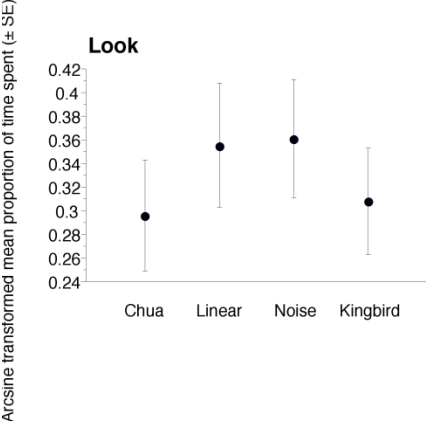


Figure 4. Mean proportion time spent looking at baseline for American robins and warbling vireos.

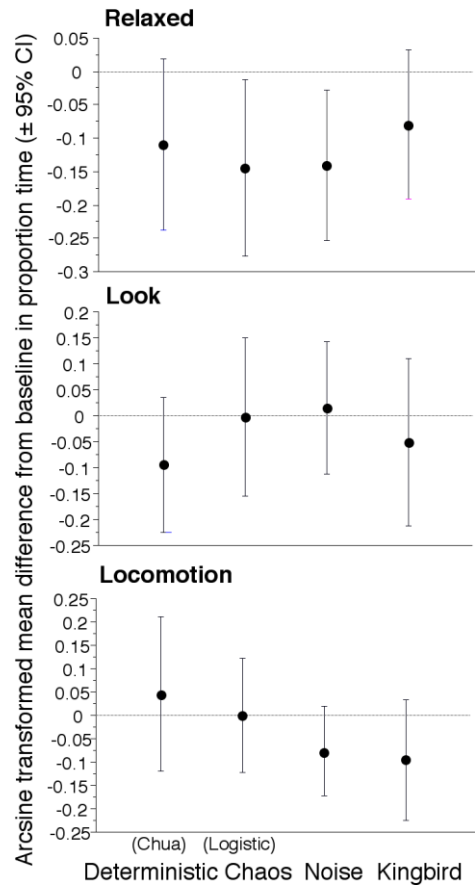


Figure 5. Arcsine transformed mean differences from baseline ($\pm$ 95% CI) in relaxed (preen, walk, forage), look, locomotion (walk, hop, flight) for American robins.

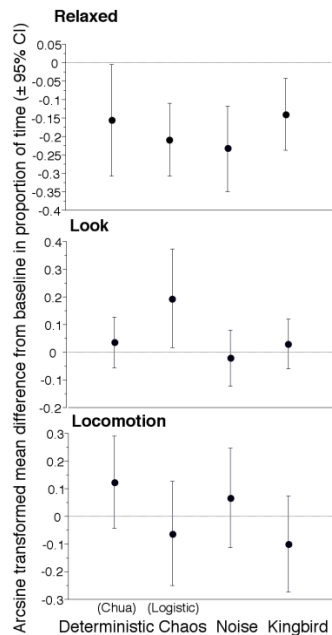


Figure 6. Arcsine transformed mean differences from baseline ($\pm$ 95% CI) in relaxed (preen, walk, forage), look, locomotion (walk, hop, flight) for warbling vireos.

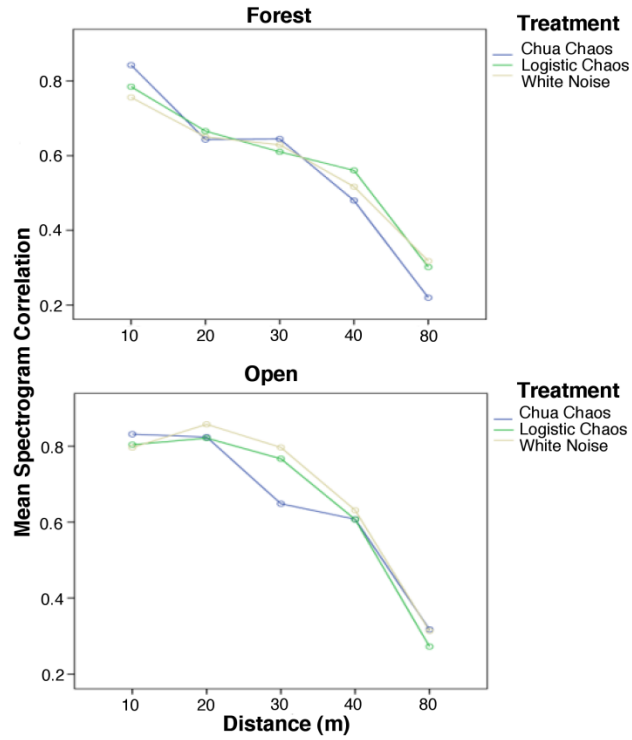


Figure 7. Spectrogram correlation of stimuli compared to 1 m reference distances. Significant habitat ($p = .001$) and distance effect ($p = 0.001$, $p < 0.001$).

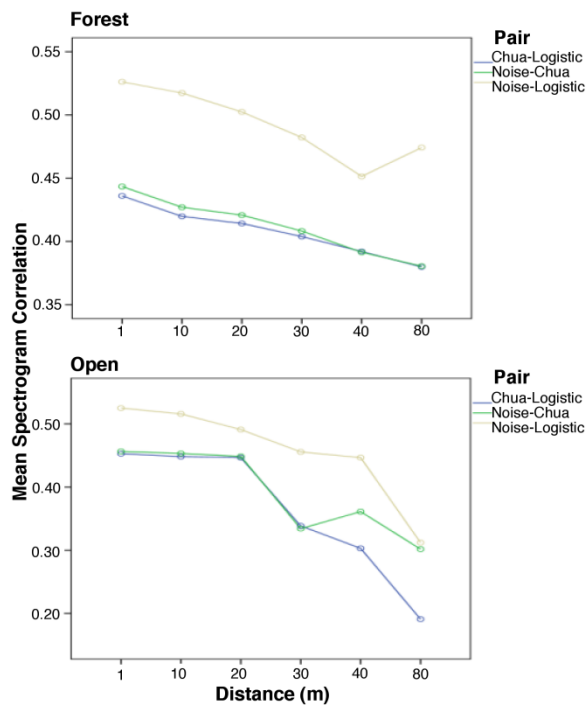


Figure 8. Spectrogram correlation pairs of stimuli compared over increasing distance. Significant pair and distance effects ($p < 0.001$, $p < 0.001$).