

THE INFLUENCE OF THE SENSORY ENVIRONMENT ON AVIAN  
REPRODUCTIVE SUCCESS AND HUMAN WELL-BEING

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## ABSTRACT

### The Influence of the Sensory Environment on Avian Reproductive Success and Human Well-Being

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Sensory pollutants such as anthropogenic noise and night lighting now expose much of the world to evolutionarily novel sound and night lighting conditions, which can have detrimental effects on humans and wildlife. In my first chapter, we exposed wild Western Bluebird (*Sialia mexicana*) nestlings to noise, light, and combination (i.e., noise and light) treatments. Nests exposed to noise and light together experienced less predation than control and light-exposed nests, and noise-exposed nests experienced less predation than control nests, yet overall nest success was only higher in noise-exposed nests compared to light-exposed nests. Although exposure to light decreased nestling body condition and evidence was mixed for the singular effects of noise or light on nestling size, those exposed to noise and light together were smaller across several metrics than nestlings in control nests. Our results support previous research on the singular effects of either stimuli, including potential benefits, such as reduced nest predation with noise exposure. However, our results also suggest that noise and light together can negatively affect some aspects of reproduction more strongly than either sensory pollutant alone. This finding is especially important given that these stimuli tend to covary and are projected to increase dramatically in the next several decades. In my second chapter, we used a field-based manipulation to explore the role of audition in biodiversity perception and self-reported well-being of hikers. We used a “phantom chorus” consisting of hidden speakers playing bird vocalizations to experimentally increase audible birdsong biodiversity during “on” and “off” blocks on two hiking trails and surveyed hikers to record their self-reported perceptions of avian biodiversity and concepts reflective of attention restoration. We found that hikers exposed to the phantom chorus reported higher levels of restorative effects compared to those that experienced ambient conditions on both trails, although the causal relationships differed for each trail. Specifically, increased restorative effects were directly linked to the phantom chorus on one trail and indirectly linked to the phantom chorus on the other trail through perceptions of avian biodiversity. Our findings add to a growing body of evidence linking mental health improvements to nature experiences and, via our field-based manipulation, we identified audition as an important modality by which natural environments confer well-being. Finally, our results suggest that maintaining or improving natural soundscapes within protected areas may be an important component to maximizing human experiences, especially as tourism and noise pollution in protected areas grow.

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## 1 INTRODUCTION

Noise and light pollution are increasing around the world as a result of the increasing human population and urbanization. In fact, researchers predict that by 2030, an additional 1.2 million km<sup>2</sup>—a landmass equivalent to the size of South Africa—will become urbanized, inevitably leading to more noise and light pollution (Seto, Guneralp, and Hutya 2012). Because anthropogenic noise pollution and night lighting are evolutionarily novel to all life on Earth including humans, they are likely to affect a large variety of taxa in different ways. Many effects of these sensory pollutants have already been documented, including behavioral, physiological, and community-shifting effects. Furthermore, while noise and light pollution are most highly concentrated in cities, seemingly remote “natural” areas are increasingly affected by these problems, largely due to the far-reaching effects of transportation infrastructure. However, previous studies on noise and light pollution have often failed to isolate these factors from covarying factors present in urban landscapes, leading to a potential gap in our understanding of how they affect organisms in more natural landscapes. Additionally, most of these studies have considered noise or light pollution on their own, without considering the combined effect of both. As noise and light pollution are highly likely to coexist spatially, it is crucial to fill in this knowledge gap.

In 2015, Tracy Mulholland, a previous graduate student in the Francis lab, developed a study system here at Cal Poly which allows us to study the effects of sensory pollutants on wild birds in isolation from the factors that typically accompany them in urban habitats, such as roads, buildings, introduced predators, and pollution. Her project focused on the effects of noise pollution on Western Bluebird reproductive success and

nestling development. My project builds upon her work by adding light and combined (i.e., noise and light) treatments in addition to noise. We found that although none of the treatments experienced reduced nest success relative to the control, nestlings in all 3 treatments are smaller relative to the control, with combination-treated nestlings being the smallest across multiple measurements. Because fledgling birds face many threats to their survival and larger ones are more likely to survive (Naef-Daenzer and Gruebler 2016), our findings could have large-scale implications for Western Bluebirds and other species exposed to noise and light pollution. While this study does not measure fledgling survival or explore the specific mechanisms by which noise and light affect fledgling growth, it is the first of its kind to expose developing nestlings to these combined stimuli and paves the way for future research both at Cal Poly and in the broader scientific community.

Humans, too, are affected by these sensory pollutants endemic to the places they live and work. Light pollution is known to reduce sleep quality (Cho et al. 2013) and noise pollution is linked to a variety of detrimental effects ranging from hearing loss to heart problems (Goines and Hagler 2007). Additionally, noise and light pollution may also reduce the quality of recreational experiences in nature. Although people often recreate in nature as an escape from their daily routines, many of the qualities that make these places restorative in the first place, such as natural quiet, dark skies, and unique biodiversity, are under attack by the same sensory pollutants that threaten Western Bluebirds and other organisms. As tourism to protected natural areas has surged in recent years, noise pollution from increased visitor numbers and the associated vehicular traffic has become a growing issue. Not only is traffic noise unpleasant and stress-inducing on its own (Raggam et al. 2007), but it can also deter wildlife from the area and mask

psychologically restorative natural sounds such as running water and birdsong (Alvarsson, Wiens, and Nilsson 2010). Maintaining natural soundscapes is one of the many challenges of the “park paradox”—that is, maintaining the integrity of public lands’ natural resources (including sounds) without restricting access to the park.

While the benefits of spending time in nature are widespread and well-documented, the specific mechanisms that confer these benefits are less understood. Research suggests that higher levels of biodiversity can improve human experiences in nature, although there is conflicting evidence as to whether actual or perceived levels of biodiversity are responsible (Fuller et al. 2007, Dallimer et al. 2012). In the summer of 2017, we conducted a field experiment on public hiking trails in Boulder, Colorado to explore whether trail users could perceive auditory increases in biodiversity (in the form of birdsong), and whether or not this increase led to a more psychologically restorative experience on the trail. To test this idea, we set up a “phantom chorus” of hidden speakers broadcasting realistic birdsong on two hiking trails alternated with quiet weeks of no broadcast, and surveyed hikers about their experiences on the trail, including questions about how many bird species they estimated to be on the trail and questions about how the sounds on the trail made them feel. We found that the phantom chorus treatment did improve hikers’ experiences on both trails, although the mechanisms on each trail differed slightly: on one trail the phantom chorus had a direct positive effect on hiker well-being (regardless of their perceived biodiversity levels), while on the other trail, this relationship was mediated by biodiversity perception (i.e., the hikers must have perceived the higher levels of biodiversity to experience the benefits of the phantom chorus). These results both underscore the need to preserve natural soundscapes for the

benefit of people and wildlife, as well as raise interesting questions for future research regarding biodiversity perception and human well-being.

Though unrelated on the surface, both of these studies highlight the need to reduce noise (and light) pollution, particularly in natural areas that are meant to be a refuge for both people and wildlife. As the “shifting baseline” continues to normalize degraded environmental conditions to an increasingly urban human population, it is more important than ever that people understand what is at stake and work to protect natural sounds and dark skies to benefit both wildlife and themselves.

## 2 COMBINED EFFECT OF ANTHROPOGENIC NOISE AND ARTIFICIAL NIGHT LIGHTING NEGATIVELY AFFECT WESTERN BLUEBIRD CHICK DEVELOPMENT

### ***2.1 INTRODUCTION***

Urbanization is a growing threat to biodiversity worldwide. Urban lands are projected to grow by an additional 1.2 million km<sup>2</sup>, an area the size of South Africa, by 2030, which represents a near tripling of global urban land cover since 2000 (Seto et al. 2012).

Although habitat loss is the most direct threat to biodiversity (Dirzo and Raven 2003), a variety of other factors can negatively impact species remaining in and around urban areas, such as vehicle collisions, depredations by introduced predators, habitat fragmentation, window strikes, and chemical pollution (Chace and Walsh 2006; Morrissey et al. 2014). Sensory pollutants, such as anthropogenic noise and artificial night lighting (henceforth “noise pollution” and “light pollution”), are omnipresent in cities, but can also extend far beyond urban borders into seemingly remote natural areas (Buxton et al. 2017; Kyba et al. 2017). These altered sensory environments represent novel evolutionary challenges and may represent strong stressors shaping the ecology and evolution of organisms (Swaddle et al. 2015).

A growing body of research has documented physiological, behavioral, and community responses to noise and light pollution in a variety of taxa (reviewed in Swaddle et al. 2015; Shannon et al. 2016; Longcore and Rich 2004). For example, noise pollution reduces foraging efficiency in birds (Ware et al. 2015) and bats (Siemers and Schaub 2011); alters the timing (Fuller et al. 2007) and frequency (Kight and Swaddle

2015; Slabbekoorn and Peet 2003; Derryberry et al. 2016) of bird song; impedes communication and foraging efficiency in cetaceans (reviewed in Weilgart 2007); increases call frequency in frogs (Parris et al. 2009); and alters community structure and species interactions (Francis et al. 2009, 2012). Light pollution has similarly diverse effects across taxa, such as disorienting, sometimes fatally, sea turtle hatchlings (Salmon et al. 1995), migrating birds (Ogden 1996), and insects (Justice and Justice 2016); suppressing melatonin secretion in humans, other mammals (Robert et al. 2015; Le Tallec et al. 2016) and birds (Dominoni et al. 2013); altering reproductive behaviors of frogs (Rand et al. 1997), birds (Kempnaers et al. 2010), and moths (van Geffen et al. 2015); and altering foraging behaviors of mammals, reptiles, fish, and aquatic invertebrates, with the potential to alter community structure (reviewed in Longcore and Rich 2004).

Clearly, noise and light pollution can have profound effects on species and ecosystems; however, many aspects remain poorly understood. With some exceptions (e.g. Ware et al. 2015; Blickley et al. 2012), few field studies of free-living animals have effectively isolated noise and light pollution from other covarying factors common to urban habitats. Similarly, investigations of the influence of co-exposure to noise and light are sparse. Da Silva et al. (2014) found that variation in artificial night lighting, but not noise, influenced the timing of song among several common European songbirds. McMahon et al. (2017) found interactive effects of noise and light exposure on the presence of frog-biting midges (*Corethrella* spp.) in Panama. However, to our knowledge, no studies have examined the combined effects of noise and light on avian reproductive success. It is critical to address this knowledge gap for several reasons. First, noise and light pollution will inevitably increase as more of the earth's surface becomes



urbanized. Studies that identify the sensory pollutants or other factors common to urbanization with the strongest negative consequences will allow policy makers and managers to more effectively mitigate their impacts on biodiversity. Second, the projected increases in noise and light pollution will not only impact cities, but also more remote “natural” areas as more resources (food, timber, minerals, water, fuel, etc.) are extracted to sustain the growing human population. Such operations require heavy machinery as well as a network of roads to access and distribute these resources, all of which generate noise and light pollution. Finally, noise and light pollution tend to covary, especially in urban environments. Thus, knowledge of the singular and combined effects of these stimuli will be crucial to untangle their impact on wildlife for proper mitigation measures.

Here, we investigated the combined effects of noise and light pollution on avian reproductive success using a manipulative field experiment in which we exposed Western Bluebird (*Sialia mexicana*) nests to either noise, light, noise and light (i.e., combination), or control treatments. We hypothesized that because anthropogenic noise and night lighting can affect animals through a variety of pathways (Kight and Swaddle 2011; Swaddle et al. 2015) and multiple stressors can often be additive or synergistic (Crain et al. 2008), nests exposed to the combined effects of noise and light pollution would experience lower reproductive success (measured in terms of nest success, clutch size, number of nestlings or fledglings and nestling morphology) than either treatment alone or the control. Additionally, based on previous work suggesting few impacts of noise exposure at the nest to Western Bluebirds (Mulholland et al. 2018) and research showing reduced growth of nestlings in response to two days of light exposure in another cavity-

nesting bird species, the Great Tit (*Parus major*) (Raap et al. 2016), we expected that light alone would be more detrimental to developing nestlings than noise alone. We therefore predicted that nests exposed to the combination treatment would have the fewest successful nests and the least developed nestlings, followed by the light-only treated nests, while noise-only and control nests would be equally successful and have equally developed nestlings.

## **2.2 MATERIALS AND METHODS**

### **2.2.1 Study area and species**

Cavity-nesting birds, such as Western Bluebirds, are ideal organisms to study the effects of noise and light pollution. Their nesting habits are conducive to performing manipulative field experiments, and previous research on noise and light pollution in cavity-nesting birds (e.g. Kleist et al. 2018; Raap et al. 2016; Schroeder et al. 2012), including in-box manipulations (e.g. Mulholland et al. 2018; Raap et al. 2016), serve as a foundation to compare our results to, as well as to develop future research questions and methods. Additionally, because responses to the photoperiod are highly conserved among vertebrates (O'Brien et al. 2012), our findings may have implications for a variety of species exposed to evolutionarily novel lighting conditions.

We conducted our study on California Polytechnic State University-owned land near San Luis Obispo, California during the 2017 and 2018 breeding seasons. The location was ideal for our noise and light manipulations because of its isolation from these and other anthropogenic stimuli. The nest box system included 200 nest boxes

placed on fence posts or trees in grasslands, riparian and oak woodlands. In 2017, all boxes were 30 x 19 x 18.5 cm, but in 2018 new smaller boxes (24.5 x 14 x 15.5 cm) replaced 30 of the original boxes that had broken.

### *2.2.2 Data collection and nest box monitoring*

Nest box monitoring began in March and continued until July. Early in the season, boxes were usually checked weekly for nest material or other signs of activity (e.g., a bluebird investigating the box). Once we discovered nesting material in a box, we typically monitored it every 1-3 days so that we could implement the sensory stimuli treatment upon clutch initiation (see below) and determine the clutch initiation date.

We continued to monitor active nests every 1-3 days until the attempt failed or nestlings fledged. Nests were considered successful if one or more chicks fledged, which was determined by visually observing the fledgling(s) or hearing begging calls around the box, observing parents carrying food and/or alarm calling, or observing an empty nest, especially if it was flattened and contained fecal matter (Martin and Geupel 1993) near the estimated fledge date without any signs of depredation or abandonment. Fledge dates were typically known within a 3-day period, but occasionally were known between a 1-4 day period. We estimated fledge dates as follows: for a 2-day period, the earlier date was used; for a 3-day period, the middle date was used; and for a 4-day period, the second date was used. If nestlings were known to have fledged on different days, we considered the estimated day that the final chick fledged as the fledge date for the whole nest.

Because noise and light pollution have the potential to disrupt incubation rhythms and nestling provisioning rates (reviewed in Swaddle et al. 2015), we calculated the duration

of the incubation and nestling stages from our monitoring efforts. The day the clutch was completed was considered the first day of incubation. The hatch date (Day 1) was considered the first day at least 1 egg hatched.

### *2.2.3 Experimental treatments*

Treatments were typically applied on the day the first egg was laid and always before the start of incubation and lasted for the entire nesting period. To control for differences in reproductive success due to clutch initiation date, treatments were applied in a randomized pre-determined order (e.g., light only, light + noise, control, noise only); however, 34 of 84 nests were discovered with > 1 egg. Because exposure to noise, light or both stimuli during egg laying could influence clutch size or other metrics (reviewed in Swaddle et al. 2015), if most of the clutch had already been laid at discovery (i.e., 4+ eggs,  $n = 5$ ) we assigned these nests to the control condition so that sensory conditions of subsequent nesting stages matched those during laying.

For the light treatments, we placed a Prodeli portable 150 lumen LED light inside the nest box. It was powered by a small solar panel (12 x 8 cm) mounted near the nest box in a south-facing location, which charged a 1600 mA internal battery. The light produced a cool white color, with a strong peak at 450 nm (i.e., blue wavelengths) and, to a lesser extent, between 500 and 600 nm (i.e., green, yellow and orange wavelengths; Figure S1). We placed the light in the box such that the bottom of the nest box received an average nightly light intensity of 3.3 lux, as measured from four trials with a Konica Minolta T-10A Illuminance Meter. However, light levels were higher at dusk than later in the night due to battery drawdown (Figure S2). Cool-color LED lighting was appropriate

for our study, as it is increasingly replacing other types of lighting in commercial and residential applications (Schubert and Kim 2005) and the high proportion of energy in the blue spectrum (400-500 nm) may be especially problematic for wildlife (Pawson and Bader 2014). Although manufacturer specifications suggest that lights used in our treatment can provide continuous lighting for 8-10 hrs and several tested units provided lighting for over 10 hrs, some fully-charged units that we tested provided lighting for 5-6 hrs, suggesting some variation in the duration of lighting within and among our light- and combination-treated nests. Thus, although some light- and combination-treated nests may have experienced lighting from dusk until dawn, others may have experienced lighting that elevated light levels for only over half of the night.

For the noise treatments, we followed the methods of Mulholland et al. (2018). We mounted waterproof STORMp3 speakers to the inside of the nest box lid using screwed-in adhesive mounts and zip ties. Each noise-treated nest was exposed to a randomly assigned playback file (n=24) of traffic noise from highways in and around San Luis Obispo recorded using Roland R05 recorders 10m from the road between October 2014 and May 2015 (see Mulholland et al. 2018 for details). Recordings that averaged  $201.5 \pm 7.3$  SE seconds were looped continuously. Each recording had a 5 second fade in/fade out period to avoid the potential for a startle response caused by abrupt onsets or cutoffs (reviewed in Francis & Barber 2013). Speakers broadcasted traffic noise at approximately 65 dB (A-weighting, Leq, fast response, re. 20  $\mu$ Pa) at 10 cm, and typically standardized using 2-minute measurements with a type 1 sound level meter (i.e., Larson-Davis 824 or 831). Occasionally, we standardized noise amplitude using measurements from a MicWi436 omnidirectional microphone paired with a smartphone

with the SPLnFFT app, which provides sound measurements equivalent to a type 2 sound level meter (Kardous and Shaw 2014). We did not measure sound levels in control nests because previous work in this system found that ambient sound levels in control nests were approximately 20 dB(A) lower than noise treatment boxes (Mulholland et al. 2018). Speaker batteries were changed every 2-3 days for noise- and combination-treated nests during nest checks to ensure continuous playback.

For the control nests, a wooden block (approx. 5.5 x 10 x 15 cm) covered with electrical tape was zip-tied to the lid to simulate the presence of a speaker, and a clear plastic cup was attached to the side of the nest box to simulate the presence of a light bulb. The wooden block was also placed in the light-only boxes, and the cup was also placed in the noise-only boxes.

#### *2.2.4 Morphological measurements and banding*

Nestlings were measured and banded with standard United States Geological Survey aluminum bands when they were 12 days old (considering hatch day of the oldest nestling as day 1) to avoid force-fledging and standardize measurements across nests. Tarsus length (mm), rectrix [tail feather] length (mm), and unflattened wing chord (mm) were measured to the nearest 0.5 mm using a standard wing ruler. Mass (g) was measured using a cloth bird bag and spring scale (Avinet, Pesola 50g) to the nearest 0.5 g. To avoid observer bias, the same person measured all nestlings. Because the apparent size of an individual as measured by these morphological measurements or mass alone can potentially differ from the condition of an individual, we also scaled body mass with wing chord length to create a body condition metric following Peig and Green's (2009)

method using standard major axis regression using the *lmodel2* function in the *lmodel2* 1.7-3 package (Legendre 2018) in R.

### 2.2.5 Data analysis

For nest-level analyses we initially used linear and generalized linear mixed effect models using the *lmer* and *glmer* functions in the *lme4* 1.1-21 package (Bates et al. 2015b) in R with a random intercept of nest box identity within year to account for multiple nests in the same nest box in a single breeding season. When the variance estimate of the random effect estimate was  $< 0.0001$ , we removed the random effect from the model (Bates et al. 2015a) and used linear regression or generalized linear models (GLM). Specifically, we confirmed clutch initiation did not differ among treatments using Gaussian error ( $n = 84$ ). We modeled nest success and depredation rates on all nests ( $n = 84$ ) using binomial error. For analyses of clutch size, we excluded nests that failed or had eggs broken before incubation started ( $n = 76$ ). Initial models with Poisson error using this subset of nests, as well as those restricted to only those nests where the treatment was installed on the clutch initiation date ( $n = 46$ ), were underdispersed. Therefore, we used Conway-Maxwell Poisson error using the *glm.cmp* function in the *mpcomp* 0.1.3 package (Fung et al. 2019) in R for all clutch size models. We also used Conway-Maxwell Poisson error for the analyses of brood size and considered all nests in the study except for two, which had eggs broken prior to hatching when measuring sound levels ( $n = 82$ ). We also separately considered a subset where we only considered nests that produced at least 1 nestling ( $n = 71$ ) using a model with Poisson error. For the analysis of incubation length, we used Gaussian error and only considered nests where the exact clutch initiation date was known and at least one egg hatched ( $n = 68$ ). We also

used Gaussian error for the analysis of nestling period length (i.e., the number of days from hatching until fledge) and only considered successful nests ( $n = 52$ ). We used binomial error for the analysis of hatching success (i.e., the proportion of eggs that hatched per nest) and only considered nests where at least 1 egg hatched and none were accidentally broken ( $n = 71$ ). We used Poisson error for models of the number of fledglings produced per nest by each treatment and considered all nests except for one that produced fledglings but had eggs accidentally broken ( $n = 83$ ). We also repeated this analysis with only those nests that produced at least 1 fledgling ( $n = 51$ ).

For nestling mass, body condition, wing chord, rectrices, and tarsus measurements, we used linear mixed effect models with a random intercept among nests within year to account for the measurement of multiple chicks within each nest. Two nests containing 4 nestlings each were excluded from the tarsus analysis due to incorrect measurements.

With the exception of our analysis to confirm that clutch initiation did not systematically differ among treatments, all other models included clutch initiation date as a predictor variable. Models explaining variation in hatch success, brood size and incubation period length included clutch size as a predictor. Models explaining variation in the nestling period length, number of fledglings and nestling morphological measurements included brood size as a predictor variable. In one model explaining variation in number of fledglings, clutch initiation date and brood size were centered and scaled to improve model convergence. Models were initially run with control as the reference state for treatment categories. To obtain all possible contrasts, we reran models with a different treatment as the reference state. We used a variety of model diagnostics



to verify model assumptions were met, including the examination of residual distributions with QQ plots from linear models and GLMs or the *simulateResiduals* function for mixed models using the DHARMA package (Hartig 2020) in R. We also examined histograms of residuals for models with Gaussian error. Finally, in an effort to embrace a more “nuanced” reporting of the size and confidence of parameter estimates than the dichotomous use of significance testing (reviewed in Hurlbert et al. 2019), we present effect sizes of apparent trends and considered a variable to have an influence on the response if the 85% CI did not overlap zero and a strong influence if the 95% CI did not overlap zero.

## 2.3 RESULTS

From 4 April to 2 July 2017, we monitored 43 nests in total ( $n_{\text{control}} = 12$ ,  $n_{\text{light}} = 10$ ,  $n_{\text{noise}} = 10$ ,  $n_{\text{combination}} = 11$ ). From 10 April to 7 July 2018, we monitored 41 nests in total ( $n_{\text{control}} = 11$ ,  $n_{\text{light}} = 11$ ,  $n_{\text{noise}} = 8$ ,  $n_{\text{combination}} = 11$ ). As expected from our protocol of rotating the assignment of different treatments to nests, we did not find any differences among treatments in clutch initiation date (Table A1).

### 2.3.1 Nest-level analyses

Nest success did not differ across most treatments; however, the probability of fledging at least 1 nestling from noise-treated nests was 60% higher than the probability of fledging at least 1 nestling from light-treated nests (Binomial GLMER,  $n = 84$ ,  $\beta_{\text{noise}} = 1.314$ , 85% CI 0.208, 2.420; Fig. A1, Table A2). This difference can largely be explained

by variation in nest predation, which was the main source of nest failure (56.25% of failed nests). Although the probability of nest failure among noise-treated nests was only  $0.109 \pm 0.073$  SE, the odds of depredation were over 4 times higher for control nests (Binomial GLMER,  $n = 84$ , ref. control  $\beta_{\text{noise}} = -1.467$ , 85% CI -2.863, -0.296; Fig. A2; Table A3). Similarly, combination-treated nests had 75% lower risk of failing to nest predation than control nests ( $\beta_{\text{combination}} = -1.702$ , 95% CI -3.697, -0.149) and 70% lower risk than light-treated nests ( $\beta_{\text{combination}} = -1.456$ , 85% CI -2.884, -0.237, Fig. A2, Table A3).

We did not find any differences in clutch size among treatments regardless of whether we considered all nests with valid clutch sizes or only nests where the treatment was installed on the clutch initiation date (Tables A4A and A4B). Because there were no differences among treatments in hatching success (Table A5), we also found no differences in the number of nestlings among treatments (Table A6). Although clutch size and brood size did not differ, we found weak evidence for changes in the duration of the incubation and nestling periods. Specifically, the incubation period for light-treated nests was about half a day longer than control nests (linear model,  $n = 68$ ,  $\beta_{\text{light}} = 0.597$ , 85% CI 0.027, 1.168, Fig. A3, Table A7) and combination-treated nests and noise-treated nests both had slightly longer nestling periods than control nests (linear model,  $n = 52$ ,  $\beta_{\text{combination}} = 1.027$ , 85% CI 0.124, 1.929;  $\beta_{\text{noise}} = 0.918$ , 85% CI 0.004, 1.833; Fig. 4, Table A8).

Finally, the average noise-treated nest produced at least one more fledgling than control nests (Poisson GLMER,  $n = 83$ , ref. control  $\beta_{\text{noise}} = 0.374$ , 85% CI 0.046, 0.715) and over double the number of fledglings than light-treated nests (ref. light  $\beta_{\text{noise}} = 0.653$ ,

95% CI 0.160, 1.166; Fig. A5, Table A9A). Combination-treated nests also produced an average of one more fledgling than light-treated nests (ref. light  $\beta_{\text{combination}} = 0.489$ , 85% CI 0.132, 0.857, Fig. A5, Table A9A). However, when only considering nests that produced at least 1 fledgling, we found no differences among treatments (Table A9B), suggesting that the absolute differences in number of fledglings produced in nests exposed to the different treatments reflect variation in predation and other sources of failure during the nestling stage.

### 2.3.2 Nestling-level analyses

Light, noise and combination-treated nestlings were over 1, 1.5 and almost 2 grams smaller than control nestlings, respectively (LMER,  $n = 258$ ,  $\beta_{\text{light}} = -1.28$ , 85% CI -2.314, -0.247;  $\beta_{\text{noise}} = -1.547$ , 95% CI -2.980, -0.113;  $\beta_{\text{combined}} = -1.872$ , 95% CI -3.271, -0.212; Fig. A6A, Table A10). However, when considering body condition by scaling mass by wing chord, only light-treated nestlings were in worse condition than control nestlings (LMER,  $n = 258$ ,  $\beta_{\text{light}} = -0.881$ , 85% CI -1.737, -0.024; Figure A6B, Table A11). Yet analyses of other morphological measurements suggest nestlings exposed to noise, light or the combination of the two were smaller than those in control nests. Wing chord length among nestlings in combination-treated nests was approximately 6% smaller than that for nestlings in control nests (LMER,  $n = 258$ ,  $\beta_{\text{combined}} = -2.520$ , 85% CI -4.462, -0.583; Figure A7A, Table A12). Nestlings in combination-treated nests also had rectrices that were 13% shorter than those in control nests (LMER,  $n = 258$ ,  $\beta_{\text{combined}} = -1.729$ , 95% CI -3.364, -0.095) and 7% shorter than those in light-treated nests ( $\beta_{\text{combined}} =$

-1.257, 85% CI -2.455, -0.060; Figure A7B, Table A13). Finally, combination-treated nestlings had smaller tarsi than nestlings in all other treatments (LMER,  $n = 250$ , ref. control  $\beta_{\text{combined}} = -1.044$ , 95% CI -1.641, -0.451; ref. light  $\beta_{\text{combined}} = -0.652$ , 95% CI -1.246, -0.064; ref. noise  $\beta_{\text{combined}} = -0.657$ , 95% CI -1.254, -0.065; Figure A7C, Table A14).

## **2.4 DISCUSSION**

Light and noise pollution are quickly growing (Barber et al. 2010; Kyba et al. 2017) and often co-occur across urban and rural areas (see Box 2 in Dominoni et al. 2020). Given the well-documented effects of either stimulus in isolation on birds and other organisms (reviewed in Swaddle et al. 2015; Dominoni et al. 2020), understanding their combined influence is paramount. To our knowledge, this study is the first to investigate the combined effects of noise and light pollution on avian reproduction. Our field-based manipulation of noise and light exposure in Western Bluebird nests revealed a variety of impacts from these sensory pollutants spanning changes in predation rates, overall success, the duration of incubation and nestling stages and the size and condition of nestlings. Not all influences of these stimuli were negative (see below), and although we found evidence of negative impacts on various reproductive metrics from noise or light pollution alone, our analyses of several nestling morphological features suggest that combined exposure may have more severe consequences for Western Bluebird nestling development, which has important implications for post-fledging survival (see below). Collectively, these results suggest that fully understanding the consequences of co-exposure to noise and light for avian reproduction may require careful quantification of

effects of each stimulus at different stages of the breeding process to account for potential additive, antagonistic and synergistic effects.

Previous studies of birds have documented reduced clutch sizes and number of fledglings (Halfwerk et al. 2011; Hayward et al. 2011), increased fecal cortisol (Blickley et al. 2012), and impaired parent-offspring communication (Lucass et al. 2016; Schroeder et al. 2012) in response to noise pollution; however, responses to noise pollution appear to vary among species. A previous study using experimental manipulations of noise at the nest did not find any consequences of noise alone on reproductive success in Western Bluebirds, but Ash-throated Flycatchers (*Myiarchus cinerascens*) exposed to noise experienced lower brood sizes relative to the control due to increased nest abandonment (Mulholland et al. 2018). Occupancy at noisy versus quiet sites has also been shown to vary among species (Kleist et al. 2017; Francis et al. 2011). Differing responses to noise pollution have also been observed within species. For example, Schroeder et al. (2012) found reduced survival and growth in House Sparrow (*Passer domesticus*) nestlings reared in noisy versus quiet conditions, but Angelier et al. (2016) found no such trend. Our work builds on previous work focused on the effects of sensory stimuli on Western Bluebirds (Kleist et al. 2017, 2018; Mulholland et al. 2018). Specifically, our results differ with those of Mulholland et al. (2018), who found no influence of noise alone on Western Bluebird reproductive success. Although we found nestlings in noise-treated nests to be smaller and take longer to fledge than those in control boxes, they were preyed upon less than those in control nests and were more likely to fledge than those in light-treated nests. Recent studies on Western and Mountain Bluebirds (*Sialia currucoides*) in New Mexico are suggestive of similar mixed effects of noise. In an

initial study, Kleist et al. (2017) found adult Western Bluebirds did not avoid noisy areas in their nest placement. However, a subsequent study focused on the effects of noise on success and individual condition revealed that adults and nestlings in noisy areas experienced reduced baseline corticosterone levels, a response associated with chronic stress. Moreover, elevated noise levels were associated with increased incidence of hatch failure (Kleist et al. 2018). Collectively, these studies suggest that noise exposure may have negative consequences, but responses may vary across populations and contexts (i.e., other environmental conditions). Additionally, these studies also illustrate that lack of a strong effect of noise on one response may not translate to other responses. Our present study adds reduced nestling size to the list of potential impacts of noise. Because lower mass is associated with reduced survival in fledglings (Naef-Daenzer, Widmer, and Nuber 2001), future work should investigate post-fledging survival among birds that emerge from noise-exposed nests. Finally, it is also worth noting that the smaller size of noise-treated and combination-treated nestlings may also explain why nestlings in these treatments took longer to fledge relative to nestlings in the control group.

Our finding that light-treated nestlings had lower mass and body condition relative to those in control nests mirrors Raap et al. 2016's findings that Great Tit (*Parus major*) nestlings exposed to light for 2 nights from days 13-15 after hatching ceased gaining mass, while untreated nestlings continued growing. Both Raap et al.'s (2016) and our results should be considered fairly conservative estimates of the potential effect of light on nestlings due to the short-term exposure in the Raap et al. study and because some of our lights may have supplied light for only half the night. Additionally, although depredation was the dominant cause of nest failures in our study, four of five nests that

failed due to unexplained causes (i.e., nestlings were intact but dead in the nest) had either a light or combination treatment. Although the causes of these nest failures are unknown, it is possible that stress or other physiological responses to light may have been a contributing factor. Future research should consider the effects of continuous light on the trajectory of nestling development throughout the nestling stage for a more comprehensive understanding of the potential consequence of exposure to this stimulus.

The reduced size of combination-treated nestlings relative to the control across multiple measurements (i.e., mass, tarsus, and rectrices) suggests that co-exposure to these sensory pollutants is capable of impairing development of Western Bluebirds more strongly than either one alone. One possibility is that either pollutant alone can be compensated for via allostatic processes (McEwen and Wingfield 2003), but the combined pollutants exceed this threshold. Importantly, the reduced size of nestlings may have detrimental impacts on post-fledging survival. Because newly-fledged birds face multiple new challenges simultaneously (e.g., foraging, navigating in the environment, avoiding predators, and more direct exposure to the elements), survival during the first week after fledging is lower than both the nestling stage and the later post-fledging stage in altricial birds, and larger fledglings are more likely to survive (reviewed in Naef-Daenzer and Gruebler 2016). Of course, exposure to noise and light pollution at the fledgling stage may also affect survival, rather than through a lag effect from the influence of these stimuli on their condition or size while in the nest. However, no studies have examined the influence of noise and light on this critical time period. Future studies should prioritize tracking the fate of fledgling in sensory-polluted areas and also seek to understand whether early-life exposure has consequences for individuals as adults.

Noise or light pollution alone may have detrimental effects on bluebirds not measured in our study, such as sleep quality (Sun et al. 2017; Rabat et al. 2004), immune response (Moore and Siopes 2000; Kight and Swaddle 2011), and stress (Ouyang et al. 2015; Kleist et al. 2018; Blickley et al. 2012). Additionally, either pollutant alone may reduce an individual's ability to compensate for other stressors such as inclement weather, disease, parasites, or limited food. Detrimental responses to combined stressors where there was no response to a single stressor were observed in sage thrashers (*Oreoscoptes montanus*), where blowfly infestation alone did not reduce nestling mortality, but infestation combined with inclement weather did (Howe 1992).

Our finding that combination-treated and noise-treated boxes experienced lower rates of depredation relative to the control should be interpreted with caution. Nest box-level treatments do not accurately reflect landscape-level noise and light pollution. However, when viewed in conjunction with the lower depredation rates in combination-treated nests relative to light-treated nests, these results provide some evidence that noise may function as a “predator shield” in certain contexts. For instance, when noise was present at the landscape level, Francis et al. (2009) found declines in nest predation with noise level and lower occupancy of Woodhouse's Scrub-Jay (*Aphelocoma woodhouseii*, formerly the Western Scrub-Jay), a common nest predator, relative to quiet sites. Although our in-box treatments would not be able to deter predators from the landscape surrounding the nest boxes, it is possible that the noise in our treatments masked nestlings' begging calls that predators use as cues to locate nests (Haff and Magrath 2011). Alternatively, common nest predators (e.g., snakes, weasels, and corvids) in our



system may show aversive responses to noise and thus may be less likely to enter a noise-exposed nest and prey upon the nestlings.

Our field-based manipulative experiment exposed brooding females, eggs, and nestlings to noise and light pollution at the nest. Despite the strengths of this approach, a major limitation is that our treatments were localized entirely within the nest boxes and did not extend throughout the surrounding environment, which does not encompass the landscape-level effects inherent to exposure to real noise and light pollution. For example, traffic noise playback in a roadless forest habitat is associated with reduced adult mass, and birds exposed to traffic noise in a laboratory setting reduced their foraging efficiency relative to the control (Ware et al. 2015). Such effects could potentially affect developing nestlings indirectly by reducing their parents' fitness and/or provisioning efficiency. Another limitation stems from the variability in our light treatments, such that some may have only exposed birds to light for approximately six hours per night. Many real-world sources of light pollution (streetlights, commercial buildings, etc.) emit light throughout the entire night; therefore, combined with the limited scale of exposure (i.e., at the nest box), our results may underestimate the potential effects of light pollution on nestling development. Finally, because treatments were only installed after clutch initiation, it is possible that the adult bluebirds only remained at the nest due to the time and resources already invested in the nesting attempt, but would have avoided a site with pre-existing noise or light pollution altogether. Indeed, the literature is replete with examples of noise avoidance by breeding birds (e.g., Bayne et al. 2008; Francis 2015), although Western Bluebirds in New Mexico were not deterred from nesting at sites with landscape-level noise pollution despite physiological

and reproductive costs (Kleist et al. 2017, 2018). Notwithstanding our inability to capture these and other territory-level effects, our approach with in-box treatments explores the direct effects of noise and light pollution on free-living nestlings isolated from other confounding habitat factors typically associated with these pollutants. Because we found influences of these stimuli alone and in combination with this limited spatial exposure, we might expect the consequences of noise and light exposure to be more severe in real landscapes where these stimuli can affect other aspects of the breeding process, such as mate attraction, and the lives of wild organisms (i.e., foraging, sleep, predator detection).

Noise and light pollution often co-occur and this study is the first to demonstrate that the combination of these stimuli negatively influences the development of wild birds, even in isolation from other anthropogenic habitat factors that typically accompany these sensory pollutants. Future research should prioritize using landscape-scale experiments and explicitly consider the post-fledging stage to develop a more comprehensive understanding of how these stimuli affect birds in real landscapes and through which pathways. Because both light and noise pollution represent widespread, evolutionarily novel changes to the world's landscapes, these and other experiments will be critical for understanding the costs of living in a brighter and noisier world.

### 3 THE PHANTOM CHORUS: BIRDSONG BOOSTS HUMAN WELL-BEING IN PROTECTED AREAS

#### ***3.1 INTRODUCTION***

Humans in developed countries spend much of their time indoors and in urban landscapes that bear little resemblance to the environment in which our species evolved. This disconnection from nature has negative consequences for environmental conservation (Pauly 1995, Kals et al. 1999, Miller 2005, Nisbet et al. 2009, Cardoso et al. 2011, Rosa et al. 2018) and can deprive individuals from the health and well-being benefits that nature provides (Capaldi et al. 2014).

Nature supplies a variety of beneficial ecosystem services that contribute to human well-being, including psychological (Fuller et al. 2007, Morita et al. 2007), cognitive (Berman et al. 2008, Shin et al. 2011), and physical health benefits (Ulrich 1984, Rook 2013). Although many studies have identified various benefits humans obtain from interacting with nature, few studies have explored why humans benefit from nature. For example, Fuller et al. (2007) found a positive relationship between greenspace biodiversity (measured by the species richness of plants, butterflies, and birds) and self-reported well-being among greenspace visitors. Dallimer et al. (2012), using similar methods as Fuller et al. (2007) but with an expanded survey, determined that greenspace visitors' self-reported well-being was more strongly associated with their perceptions of biodiversity (i.e., level of biodiversity a visitor thought was present) than actual levels of biodiversity. Instead, tree cover, rather than true biodiversity levels, was more strongly linked with visitors' biodiversity estimates (Dallimer et al. 2012). Another study conducted in public gardens found that regular visitors were unable to detect

experimentally increased levels of plant, bird and butterfly biodiversity, yet nevertheless indicated a preference for higher species richness in the gardens (Shwartz et al. 2014). Although these limited studies show mixed outcomes about the role of actual versus perceived biodiversity, it is clear that biodiversity plays a role in human well-being.

In addition to the sights and smells of nature, natural sounds are a key factor of human experiences in nature (Pilcher et al. 2009, Marin et al. 2011, Miller et al. 2018) and may contribute to perceptions of biodiversity. Natural sounds enhance the quality of nature-based experiences (Newman et al. 2013) by adding to overall satisfaction (Pilcher et al. 2009, Marin et al. 2011, Newman et al. 2013), enhancing perceptions of natural landscapes (Weinzimmer et al. 2014), and improving mood (Benfield et al. 2014). In particular, birdsong is regarded by most people as enjoyable (Carles et al. 1992, Viollon et al. 2002, Pilcher et al. 2009, Miller et al. 2014, 2018), perhaps owing to its ubiquity throughout human evolution (Senter 2008, Francis et al. 2017) or its association with forthcoming or current pleasant weather (i.e., spring and summer, respectively). Hedblom et al. (2014) also found that more diverse birdsong was appreciated more than less diverse birdsong, and enhanced participants' perceptions of photos of urban landscapes. Additionally, survey in unnatural settings and lab-based studies suggest birdsong can improve stress recovery (Alvarsson et al. 2010, Ratcliffe et al. 2013) and cognitive function (Abbott et al. 2016) in lab studies. However, whether birdsong influences perceptions of biodiversity and well-being among people in real natural settings has not yet been explored.

Here, we investigated how an experimental increase in birdsong influenced self-reported perceptions of biodiversity and concepts of well-being among natural area

visitors. To do so we implemented a “phantom chorus” in week-long “on” and “off” (i.e., ambient conditions) blocks by experimentally increasing bird acoustic biodiversity on hiking trails via playback through speakers. We used intercept surveys at the end of our experimental trail sections to record self-reported well-being by hikers. Based on previous studies suggesting that actual and perceived biodiversity are correlated (Fuller et al. 2007), we predicted that an experimental increase in birdsong would lead to an increase in perceived bird biodiversity by hikers. Other studies conducted in non-natural settings have linked birdsong to psychological benefits (Alvarsson et al. 2010, Ratcliffe et al. 2013, Abbott et al. 2016). If hikers in nature exposed to acoustic stimuli reflective of high bird diversity also experience greater well-being, hikers exposed to the phantom chorus will self-report higher scores for well-being concepts than those that did not experience the phantom chorus. Finally, based on the notion that perceptions of biodiversity are linked to well-being (Dallimer et al. 2012), we also expected a positive association between people’s self-reported perceptions of bird biodiversity and concepts of well-being.

## ***3.2 MATERIALS AND METHODS***

### ***3.2.1 Experiment overview***

Data collection occurred from July 15-September 4, 2017 in Boulder Open Space and Mountain Parks, Colorado. These dates were selected because they minimized potential disruption of breeding birds’ behaviors caused by playback (Kleist et al. 2016) while maximizing the number of surveys and enhancing the effect of the phantom chorus treatment (i.e., birds are less vocal after the breeding season; Hyman (2005) Yahner and

Ross (1995)). We applied the phantom chorus treatment (see below) in weekly intervals at each trail, alternating with a “quiet” week of no broadcast, allowing each trail to serve as its own control and ensuring the treatment was not correlated with other seasonal aspects of biodiversity, such as flower abundance or weather patterns. Treatment broadcasts also alternated across trails so that when the playback was “on” along one trail, it was “off” along the other.

### *3.2.2 Phantom chorus treatment*

During treatment weeks, 10 hidden, evenly-spaced Eco Extreme waterproof speakers (Grace Digital, Inc.) were placed approximately 15-30 meters away from the trail in 500-meter stretches of the Upper McClintock (McClintock) and Lower Gregory Canyon (Gregory Canyon) trails (Figure B1). Each of the 10 speakers broadcast a different looping 5-minute file containing songs and calls from one common native species, with the exception of one file that contained two species (Figure B2), using Olympus LS-P2 devices (Olympus Corporation). We broadcast recordings from 9:00-15:00 five days a week, including weekends. We set broadcast amplitude at 80 A-weighted decibels (maximum sound level [LAFmax], fast response, re. 20  $\mu$ Pa) using a MicWi436 omnidirectional microphone and the SPLnFFT smartphone application, which serves as a type 2 sound level meter (Kardous and Shaw 2014). This amplitude is typical of songbird playback because it falls within the range of natural sounds (reviewed in Luther et al. 2017). Phantom chorus files were created with edited song and call recordings using recordings taken as close to our study trails as possible to account for regional variation in song. We also selected songs with higher signal-to-noise ratios. The files were edited using Audacity 2.1.3 software (audacityteam.org) to remove background noise and

vocalizations from other species. We also standardized amplitude among all files using Raven Pro 1.5 (ravensoundsoftware.com). Speakers were placed in realistic microhabitat for each species. For example, the speaker broadcasting Spotted Towhee (*Pipilo maculatus*) was placed near the ground in shrubs where this species is often found. The same suite of species was used at both trails, but the order of species differed due to variations in habitat.

### *3.2.3 Point counts*

To quantify actual avian species richness along the study trails, we conducted weekly point counts at 3 locations at each trail between August 3 and September 3, 2017 (Figure B1). We recorded the number of individuals of all species of birds seen or heard within a 5-minute period at each location. Bird activity is often highest at dawn (e.g., Aschoff 1966) and surveys typically take advantage of this increased activity (Ralph et al. 1993). However, our visitor surveys did not begin until 9:00 AM, thus we timed our point counts to better measure bird activity perceptible to visitors later in the morning by starting them approximately an hour after sunrise and finishing them shortly before our visitor surveying started at 9:00 AM.

### *3.2.4 Ambient sound levels*

To determine whether sound levels systematically varied between trails or between time intervals with and without playback, on each trail we set up five Olympus LS-P2 recorders (Olympus Corporation), each spaced approximately halfway between

successive speakers and no more than 5 meters from the trail to record hourly ambient sound levels (see below; Figure B1). Recording started just before surveying began at 9:00 AM each day and stopped after surveying was completed for the day. We positioned each recorder approximately 1.5 meters off the ground and surrounded by a custom windscreen, which also served as camouflage.

### *3.2.5 Survey administration*

We intercepted hikers from approximately 09:00-15:00, 5 days a week for the duration of the study. In an attempt to maximize our sample size and obtain surveys from a diverse population, each week we always surveyed hikers Friday through Sunday when visitation rates were higher and were known to include more non-local hikers (Boulder Open Space and Mountain Parks Staff, personal communication). To ensure that each participant experienced the full treatment, only hikers walking uphill on each trail were intercepted. This was possible because the trail sections used for our experiment were not connected to other trails. We administered surveys approximately 50 meters beyond the last speaker location. We gave each participant a laminated copy of the survey to follow along with the verbal instructions given by a researcher, who entered responses into the iSURVEY program ([harvestyourdata.com](http://harvestyourdata.com)) on an iPad. We did not ask hikers who were running or wearing headphones to participate.



### *3.2.6 Data instrument*

We collected responses from visitors using a questionnaire (see Appendix C). The instrument contained two main sections relevant to this study: perceived biodiversity and self-reported well-being. To operationalize these concepts, perceived biodiversity was measured as perceived bird species diversity and self-reported well-being was measured as perceived psychological restoration (Kaplan and Kaplan 1989, Kaplan 1995, Payne 2013). We also collected demographic information for descriptive purposes.

### *3.2.7 Perceived bird species diversity*

To measure hikers' perceptions of bird species diversity, we asked respondents "Based on your experience on the trail today, about how many different types or species of birds would you say are in the last quarter mile or last seven minutes of your walk on the trail?" Responses were recorded on a 5-point scale, where 1= 0-3 different types of birds, 2= 4-7 different types of birds, 3= 8-11 different types of birds, 4= 12-15 different types of birds, and 5= more than 15 different types of birds.

### *3.2.8 Perceived psychological restoration*

We derived measures of perceived psychological restoration from Payne (2013), Kaplan and Kaplan (1989), and Kaplan (1995). This includes 5 concepts: Fascination, Being-Away-To, Being-Away-From, Compatibility, and Extent (Table B1). "Fascination" refers to the ability of a stimulus to hold an individual's attention in such a way that it does not inhibit their ability to focus on other stimuli or cause attentional fatigue (Kaplan 1995).

An example from the survey included: “Sounds on the trail today make me wonder about things”. “Being-away-to” refers to the ability of the soundscape to contribute to the restorative qualities of the destination not typically found in the one’s daily life. An example question from our survey was: “The trail’s acoustic environment is different from what I usually hear in my daily life”. “Being-away-from” refers to the soundscape’s ability to serve as a refuge from the stress of one’s daily life. An example question from our survey is: “Hearing sounds on the trail today made me feel free from work, routine, and responsibilities”. “Compatibility” refers to how compatible the trail’s soundscape is with one’s personal preferences and motivations for visiting. An example question from our survey was: “The trail’s acoustic environment fits with my personal preferences”. “Extent” refers to the environment’s ability to be “rich and coherent enough to constitute another world” and engage the mind with few distractions (Kaplan 1995). An example question from our survey was: “All the sounds merge to form a coherent acoustic environment.” Hikers were asked, “Based on your experience from the last quarter mile of trail or seven minutes of your hike today, how much do you agree with each of these statements?” Responses were recorded on a 7-point scale, where 0=not at all and 6=completely (Table B1).

### *3.2.9 Data Analysis*

We used RStudio (RStudio Team 2016) to analyze whether the phantom chorus increased the number of potential species detected (i.e., avian species richness) along trails. First, for each point count week, we calculated the sum of unique species observed during point count surveys from all point count locations per trail plus the number of additional

species represented in the phantom chorus that had not been detected on point count surveys (i.e., the sum of unique species from point counts and the phantom chorus). We then compared this combined total of real and simulated bird species to the total species from just the point counts on a trail using linear models with the `lm` function in program R 3.6.1. In an initial analysis we considered the influence of week of observation, trail and count method (i.e., the number of species detected in point counts vs. that number plus additional unique species added by the phantom chorus), plus an interaction between trail and measurement, but found the interaction and week of observation did not improve model performance (not shown). Thus, the final model included only the influence of trail and count method.

Analyses of ambient noise recordings were completed using the National Park Service's Acoustic Toolbox software (National Park Service 2008). We used L50 A-weighted decibels (dB) to characterize sound levels along the trails. L50 represents a median of fluctuating sound levels such that sound levels exceed this value 50% of the time. We used linear mixed effect models (LMER) with the *lmer* function in the lme4 R package (Bates et al. 2012) to model hourly sound levels. For fixed effects, we included a variable denoting whether the phantom chorus was on or off. Because general sound levels could differ between trails for other reasons and sound levels can also fluctuate seasonally, we also included trail and pseudo-date (where July 15 = 1) as fixed effects and considered an interaction between treatment and trail. Given the hierarchical structure of sound collection, we also included hour within recording location as nested random effects.

**\*The following text from here until the start of the Results was written by Dr. Zach Miller.**

We used the Statistical Package for the Social Sciences (SPSS®) and Amos® to perform statistical analyses with the survey data. Three different methods were used in analysis. This included a principal component analysis (PCA), confirmatory factor analysis (CFA), and structural equation modeling (SEM). Maximum likelihood estimation was used in all CFA and SEM procedures. Data screening showed that some variables had one or two missing data points. Because the maximum likelihood estimation model we used requires no missing data, we deleted cases with missing data points to be as conservative as possible. This left a final sample size of  $n=665$ . We did not assume multivariate normality, and thus applied bootstrapping to correct for this using bias-corrected confidence intervals (95%) for all CFA and SEM procedures.

A PCA was used to examine the underlying structure of the perceived psychological restoration scale in preparation for the CFA. We used this exploratory process first because this scale has achieved mixed results in different settings (Payne 2013) and we wanted to keep the CFA in the “spirit” of a confirmatory process. For the PCA, we checked assumptions about the appropriateness of the method using the Kaiser-Meyer-Olkin (KMO) statistics ( $KMO > 0.50$ ) and Bartlett’s test of sphericity ( $p < 0.05$ ). Only components with an eigenvalue  $> 1$  were extracted from the data. Varimax rotation was applied to help interpret the results. Using guidance from prior research (Payne 2013), loadings with absolute value  $> 0.40$  were interpreted as belonging to a particular axis (Kline 1994). Any cross-loading items were also removed. The reliability of items

measuring a component was examined using Cronbach's alpha, with  $\alpha > 0.65$  being sufficient (Vaske 2008).

A CFA was used to test an *a priori* specified structure that represents the relationships among variables. Based on past research (Payne 2013), we conceptualized perceived soundscape restoration as a second-order factor composed of several first-order factors. The first-order factors were informed through the PCA. Similar to the PCA, a CFA model should generally have factor loadings  $> 0.40$ , with values greater than 0.60 considered high (Kline 1994). We also used Cronbach's alpha to establish factor reliability in the CFA.

In addition to the criteria above, Goodness-of-fit (GOF) statistics allow researchers to evaluate how well the data match the specified model. Here, we provide several commonly used GOF statistics, including both relative and absolute fit statistics. This includes  $\chi^2$ ,  $BS_{boot}$  (a  $\chi^2$  that accounts for the bootstrapping procedure), the comparative fit index (CFI), the Tucker-Lewis index (TLI), the root mean square error of approximation (RMSEA), and the standardized root mean square residual (SRMR).

Interpretation of the GOF statistics varies. Both the  $\chi^2$  and  $BS_{boot}$  are likely to be rejected with larger samples ( $n \geq 200$ ), and results of  $p < 0.05$  are largely ignored in CFA and SEM procedures. Instead, other fit statistics are preferred. For CFI and TLI, values should be  $\geq 0.90$ , with  $\geq 0.95$  indicative of an excellent fit (Hu and Bentler 1998). For SRMR, values  $\leq 0.08$  are acceptable, with values closer to 0 indicative of a better fit (Hu and Bentler 1999). RMSEA values  $\leq 0.10$  are considered sufficient, with values  $\leq 0.05$  considered excellent (Browne and Cudeck 1992, Kline 2011). Collectively, these GOF

statistics indicate whether the theoretical model accurately represents the relationships among the data.

The last step in the analysis was building SEMs to represent the relationships among the phantom chorus treatment, perceived bird species diversity (“Perceived biodiversity” in Figures B4 and B5), and perceived psychological restoration. Phantom chorus treatment was dummy coded in the models, with 0 = control (phantom chorus off) and 1 = treatment (phantom chorus on). Like the CFA, bootstrapping was applied in the SEMs and GOF statistics are reported. Lastly, standardized path coefficients and their statistical significance are reported using the bias-corrected confidence intervals (95%). Trails (e.g. McClintock and Gregory Canyon) were analyzed using separate SEMs.

### **3.3 RESULTS**

#### **3.3.1 Phantom chorus treatment**

Point counts showed that the phantom chorus increased acoustic bird species richness by approximately 6 species ( $t = 6.797$ ,  $p < 0.001$ ) and that Gregory Canyon tended to have higher bird species richness than McClintock ( $t = -2.650$ ,  $p = 0.017$ ; Table B3). Sound levels were significantly higher during phantom chorus playback weeks than during non-playback weeks on McClintock (LMER,  $t = 5.932$ ,  $p < 0.001$ ), but were significantly lower during playback weeks than non-playback weeks on Gregory Canyon (LMER,  $t = -2.048$ ,  $p < 0.001$ ). However, the differences were  $< 1$  dB in both contrasts. Sound levels also increased across the season (LMER,  $t = 2.639$ ,  $p = 0.008$ ; Figure B3).

### *3.3.2 Sample characteristics*

Table B2 contains descriptive information about the sample characteristics. Overall, the samples at Gregory Canyon and McClintock appeared different. Respondents at McClintock were older and contained more females when compared to Gregory Canyon respondents. To evaluate for non-response bias, qualitative comparisons were made between respondents in this study and respondents in a recent study conducted in the same area (VanderWoude and Kellogg 2018; Table B2). Differences existed when comparing the overall sample in this study to that conducted from VanderWoude and Kellogg (2018). The sample within this study appeared to be younger, out-of-state residents hiking in larger groups. This indicates that there may be some characteristic differences between the respondents in this current study and the general visitor to Boulder Open Space and Mountain Parks (OSMP), so caution should be used in generalizing the results from this study to all visitors at OSMP.

**\*The following text from here until the Discussion was written by Dr. Zach Miller.**

### *3.3.3 Principal component analysis of perceived restoration measures*

KMO (0.916) and Bartlett's test of sphericity ( $p < 0.001$ ) indicated PCA was an appropriate method to apply. Although the PCA succeeded in extracting four components, several items cross-loaded (perceived restoration, "PR" axes 1 and 11), and others had low loadings ( $< 0.40$ ; PR15). We removed the cross-loaded and low loading items and reran the PCA analysis. This PCA analysis also met the assumptions for the analysis (KMO = 0.904; Bartlett's test of sphericity,  $p < 0.001$ ) and extracted four

components that explained 69.70% of the variance in the data (see Table B1). Reliability for three of the components was sufficient ( $\alpha > 0.65$ ) and ranged from 0.85 to 0.90. However, the items of one component failed to display acceptable reliability ( $\alpha = 0.492$ ), and thus the component and items were removed from further analyses. This left three useable components to inform future analyses. We named these components according to Payne's (2013) previous research: sound fascination, sound compatibility, and sound coherence (Table B1).

### *3.3.4 Second order confirmatory factor analysis for perceived restoration measures*

Using the results of the PCA, we constructed a second-order CFA (Figure B4). In this CFA, perceived psychological restoration was a second-order factor consisting of three first-order factors: sound fascination, sound compatibility, and sound coherence. Variable codes from Figure B3 can be found in Table B1 (e.g., PR2, PR3, etc.). Although both the  $\chi^2$  ( $\chi^2 = 279.419$ ,  $df = 62$ ,  $p < 0.001$ ) and  $BS_{boot}$  ( $p = 0.002$ ) were significant, the rest of the GOF statistics supported the model (RMSEA = 0.073; SRMR = 0.049; CFI = 0.958; TLI = 0.947). Additionally, all factor loadings were  $\geq 0.60$  and statistically significant. Reliability for first order factors was already examined in the PCA (Table B1), and reliability for the second-order factor of perceived psychological restoration was  $\alpha = 0.77$ .



### *3.3.5 Structural equation model of the phantom chorus, perceived bird species diversity, and perceived psychological restoration*

#### *McClintock Trail*

The  $\chi^2$  ( $\chi^2 = 151.262$ ,  $df = 86$ ,  $p < 0.001$ ) for the SEM was significant, but the rest of the GOF statistics supported the model ( $BS_{boot}$ ,  $p = 0.088$ ;  $RMSEA = 0.049$ ;  $SRMR = 0.0427$ ;  $CFI = 0.975$ ;  $TLI = 0.970$ ). Overall, the model explained about 6% of the variance in perceived restoration (Figure B5). The model identified a significantly positive, but small ( $p = 0.003$ ) direct effect from the phantom chorus on perceived bird species diversity (“Perceived biodiversity” in Figure B5) (Cohen 1988). There was also a small but significant ( $p = 0.008$ ) direct effect from perceived bird species diversity on perceived psychological restoration (Cohen 1988). However, there was not a significant direct effect between the phantom chorus and perceived psychological restoration ( $p = 0.20$ ). A further look at the indirect effect between the phantom chorus and perceived psychological restoration through perceived bird species diversity revealed a small but significant positive indirect effect (standardized indirect effect = 0.073;  $p = 0.003$ ). The lack of a direct effect between the phantom chorus treatment and perceived psychological restoration in conjunction with the presence of an indirect effect indicates that perceived bird species biodiversity mediates the relationship between the phantom chorus treatment and perceived psychological restoration.

#### *Gregory Canyon Trail*

The  $\chi^2$  ( $\chi^2 = 242.601$ ,  $df = 86$ ,  $p < 0.001$ ) and  $BS_{boot}$  ( $p = 0.002$ ) for the SEM were significant, but the rest of the GOF statistics supported the model ( $RMSEA = 0.072$ ;

SRMR = 0.056; CFI = 0.939; TLI = 0.925). Overall, the model explained about 2% of the variance in perceived psychological restoration (Figure B6). The model showed the only significant effect ( $p = 0.028$ ) was a positive but small direct effect from the phantom chorus on perceived psychological restoration (Figure B6) (Cohen 1988). The indirect effect between the phantom chorus and perceived psychological restoration through perceived bird species diversity was not significant ( $p = 0.478$ ).

### **3.4 DISCUSSION**

We showed that the experimental addition of a phantom bird chorus increased perceived psychological restoration of hikers on both the McClintock and Gregory Canyon trails. Our results add to a growing body of evidence linking improvements in mental health to nature experiences (Bratman et al. 2019). Additionally, our study is the first to our knowledge to use a field-based experimental approach to understand whether specific sensory modalities are involved in acquiring psychological benefits from nature. In general, our results provide support to prior work linking biodiversity to human well-being (Fuller et al. 2007, Dallimer et al. 2012, Shwartz et al. 2014), and also reveal interesting differences between our two study trails. At the McClintock trail, the SEM supported previous research demonstrating people perceive increases in biodiversity and that it positively impacts their sense of well-being (Dallimer et al. 2012). Additionally, the model suggests that the change in perceived psychological restoration in response to the phantom chorus was mediated by visitor perceptions of bird diversity. In other words, increases in visitor perceptions of bird species diversity may be necessary to achieve higher levels of perceived psychological restoration and the perceptions of bird species

diversity were positively influenced by the phantom chorus. Recent research has connected increased birdsong to human well-being through concepts like attention restoration (Ratcliffe et al. 2013, Abbott et al. 2016). The evidence from the McClintock trail SEM builds on this connection by indicating that perceived biodiversity may play a key role in the relationship between nature exposure and perceived human health and well-being outcomes. Although some research has explored this area (Dallimer et al. 2012), future inquiries should continue to refine this relationship between perceived biodiversity and human health and well-being, and also explore how forms of natural history-based recreation and nature study (e.g., hunting, fishing, rock hounding, botanical sketching, insect collecting, mushroom foraging, etc.) are related to perceived biodiversity and human health and well-being.

In contrast to the results described above, the SEM explaining results from the experiment at Gregory Canyon was in line with the findings of Schwartz et al. (2014) that show that people do not perceive increases in biodiversity when it is elevated experimentally, and yet exposure to birdsong still improved hikers' perceived psychological restoration. Although these results are quite different than the results at McClintock, both SEMs demonstrated that the phantom chorus had a positive impact on perceived psychological restoration, either directly (at Gregory Canyon) or indirectly (at McClintock) through perceived bird species diversity. Thus our results are mixed in terms of support for perceptions of biodiversity serving to mediate perceived psychological restoration, yet the end product is clear: hearing increased bird species diversity improves perceived psychological restoration (Figure B7).

Why the results differed between Gregory Canyon and McClintock is unclear. One possibility is that the different terrain at each trail affected hikers' abilities to perceive bird species diversity. Gregory Canyon is much steeper and rockier than McClintock, and it is possible that these conditions demanded increased focus and attention to footing and movements at the expense of a conscious or subconscious awareness of sounds. Differences in the characteristics of the samples at Gregory Canyon and McClintock could also have affected the results; particularly notable are the differences in ages and proportion of out-of-state hikers at each trail (Table B2). Additionally, unlike the increase in sound levels during phantom playback on McClintock trail, there were lower ambient sound levels during playback vs. control days at Gregory Canyon (Figure B3). There are no obvious explanations for this difference. However, an intriguing prospect for future research is the possibility that audible birdsong and time spent talking among visitors negatively covary. That is, the slightly higher sound levels on control weeks could reflect more time spent talking among visitors than during weeks with the phantom chorus. Use of wearable, ambulatory recording devices on hikers, similar to on-animal recorders used in animal behavior studies (Lynch et al. 2013), could provide a powerful approach for testing these possibilities.

Our results also provide insights into the utility of perceived psychological restoration in psychological ecosystem service research. Our analyses supported perceived psychological restoration as a second-order concept composed of three first-order concepts: sound fascination, sound compatibility, and sound coherence. When compared to previous research (Payne 2013), our model displayed a different structure.

For instance, several items failed to display acceptable scale development qualities, such as reliability and sufficient factor loadings (Table B1). Future research should focus on continuing to refine valid and reliable tools for measuring the perceived psychological restoration scale, including configural and metric invariance tests in diverse and cross-cultural populations.

The finding that acoustic bird species diversity improves visitors' perceived psychological restoration has implications beyond this study. For example, observing wildlife is a key motivation to visit parks and protected areas (Manfredo 2008), yet human presence can reduce the abundance of wildlife or displace them away from human activity, which makes them more difficult to observe (Karp and Guevara 2011). Recent research shows educational signs instructing visitors to reduce their noise significantly reduced noise levels, increased bird biodiversity, increased visitor perceptions of bird biodiversity, and improved visitor experiences at Muir Woods National Monument (Levenhagen et al. n.d., Pilcher et al. 2009). This simple, cost-effective measure could help mitigate noise pollution and improve visitors' experiences and well-being in protected areas without restricting the number of visitors.

Because an emotional affinity towards nature has been shown to motivate conservation-oriented behaviors (Kals et al. 1999, Halpenny 2010, Soga and Gaston 2016), managing noise in parks has the potential to create a feedback loop where increased biodiversity improves visitors' experiences, improves their well-being, and increases their emotional affinity towards nature, thereby motivating actions that will further benefit biodiversity (reviewed in Francis et al. 2017). Further supporting this idea, Larson et al. (2018) found that birdwatching is linked to pro-environmental behaviors

(recycling, donating to environmental causes, etc.) both directly and indirectly by strengthening participants' attachment to a place. Place attachment, or the positive emotional connection that a person has with a particular environment, is influenced by a variety of factors, which in a natural setting can include things such as scenery, peacefulness, or wildlife (Stedman 2003). Our study demonstrates the importance of natural sounds to having positive experiences in nature, which may further motivate pro-conservation behaviors. As the world's population grows and natural areas become increasingly fragmented and impacted by noise, preserving acoustic resources will be important for both biodiversity and human well-being.

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## Appendices

### Appendix A. Tables

**Table A1. Linear mixed effect model parameter estimates for differences in clutch initiation among treatments.** Reference state listed after "ref." ( $n = 84$ ). Variance and standard deviation estimates of random intercept of nest box within year also provided.

Variable	Estimate	SE	lower	upper	CI level
light ref. control	-2.569	3.836	-7.991	2.853	85%
noise ref. control	0.889	3.950	-4.693	6.471	85%
combined ref. control	1.227	3.743	-4.063	6.517	85%
noise ref. light	3.458	4.077	-2.303	9.219	85%
combined ref. light	3.796	3.877	-1.682	9.275	85%
combined ref. noise	0.338	3.989	-5.299	5.976	85%
(1 year:box_no)	variance = 149.523		SD = 12.232		

**Table A2. Binomial generalized linear mixed effect model parameter estimates explaining variation in nest success among treatments and in response to clutch initiation date.** Reference state listed after "ref." ( $n = 84$ ). Variance and standard deviation estimates of random intercept of nest box within year also provided. Parameters with 85% CIs that do not overlap zero are bolded and those with 95% CIs that do not overlap zero are bolded and italicized.

Variable	Estimate	SE	lower	upper	CI level*
light ref. control	-0.309	0.629	-1.214	0.597	85%
noise ref. control	1.005	0.745	-0.068	2.078	85%
combined ref. control	0.499	0.646	-0.431	1.429	85%
<b>noise ref. light</b>	<b>1.314</b>	<b>0.768</b>	<b>0.208</b>	<b>2.420</b>	<b>85%</b>
combined ref. light	0.807	0.667	-0.153	1.768	85%
combined ref. noise	-0.506	0.762	-1.589	0.576	85%
clutch initiation date	0.018	0.020	-0.010	0.046	85%
(1 year:box_no)	variance = 0.014		SD = 0.322		

\*CIs calculated with "Wald" method

**Table A3. Binomial generalized linear model parameter estimates explaining variation in nest depredation among treatments and in response to clutch initiation date.** Reference state listed after "ref." ( $n = 84$ ). Parameters with 85% CIs that do not overlap zero are bolded and those with 95% CIs that do not overlap zero are bolded and italicized.

Variable	Estimate	SE	lower	upper	CI level
light ref. control	-0.246	0.657	-1.208	0.697	85%
<b>noise ref. control</b>	<b>-1.467</b>	<b>0.870</b>	<b>-2.863</b>	<b>-0.296</b>	<b>85%</b>
<b><i>combined ref. control</i></b>	<b><i>-1.702</i></b>	<b><i>0.866</i></b>	<b><i>-3.697</i></b>	<b><i>-0.149</i></b>	<b><i>95%</i></b>
noise ref. light	-1.221	0.900	-2.649	0.004	85%
<b>combined ref. light</b>	<b>-1.456</b>	<b>0.897</b>	<b>-2.884</b>	<b>-0.237</b>	<b>85%</b>
combined ref. noise	-0.235	1.057	-1.811	1.340	85%
clutch initiation date	0.013	0.024	-0.020	0.048	85%

**Table A4A. Conway-Maxwell Poisson generalized linear model parameter estimates explaining variation in clutch size among treatments and in response to clutch initiation date.** Reference state listed after "ref." ( $n = 76$ ). Nests that failed or had eggs broken before incubation started were excluded. Parameters with 85% CIs that do not overlap zero are bolded and those with 95% CIs that do not overlap zero are bolded and italicized.

Variable	Estimate	SE	lower	upper	CI level*
light ref. control	-0.020	0.048	-0.090	0.049	85%
noise ref. control	0.020	0.049	-0.051	0.090	85%
combined ref. control	0.021	0.046	-0.045	0.086	85%
noise ref. light	0.040	0.052	-0.034	0.114	85%
combined ref. light	0.041	0.048	-0.028	0.110	85%
combined ref. noise	0.001	0.049	-0.070	0.072	85%
clutch initiation date	-0.003	0.001	-0.005	0.000	85%

\*85 and 95% CIs calculated based on Estimate  $\pm$  (standard error x 1.44 OR 1.96)

**Table A4B. Conway-Maxwell Poisson generalized linear model parameter estimates explaining variation in clutch size among treatments and in response to clutch initiation date.** Reference state listed after "ref." ( $n = 46$ ). For this analysis, we only included nests where treatment was installed on the exact CID. Parameters with 85% CIs that do not overlap zero are bolded.

Variable	Estimate	SE	lower	upper	CI level*
light ref. control	-0.054	0.065	-0.147	0.040	85%
noise ref. control	-0.003	0.064	-0.095	0.089	85%
combined ref. control	-0.015	0.065	-0.108	0.078	85%
noise ref. light	0.050	0.057	-0.032	0.132	85%
combined ref. light	0.039	0.058	-0.044	0.122	85%
combined ref. noise	-0.012	0.057	-0.094	0.071	85%
<b>clutch initiation date</b>	<b>-0.004</b>	<b>0.002</b>	<b>-0.006</b>	<b>-0.001</b>	<b>85%</b>

\*85 and 95% CIs calculated based on Estimate  $\pm$  (standard error x 1.44 OR 1.96)

**Table A5. Binomial generalized linear mixed model parameter estimates explaining variation in hatch success among treatments and in response to clutch size, clutch initiation date, and box number within year.** Reference state listed after "ref." ( $n = 71$ ). For this analysis, we only considered nests where at least 1 egg hatched and none were broken during incubation. All parameters had 85% CIs which overlapped zero. Variance and standard deviation estimates of random intercept of nest box within year also provided.

Variable	Estimate	SE	lower	upper	CI level
light ref. control	-0.090	0.664	-1.045	0.866	85%
noise ref. control	-0.040	0.697	-1.044	0.963	85%
combined ref. control	-0.419	0.628	-1.323	0.484	85%
noise ref. light	0.049	0.700	-0.953	1.051	85%
combined ref. light	-0.330	0.625	-1.230	0.570	85%
combined ref. noise	-0.379	0.663	-1.330	0.575	85%
clutch size	0.059	0.356	-0.454	0.572	85%
clutch initiation date	0.025	0.020	-0.003	0.054	85%
(1 year:box_no)	variance = 0.863	SD = 0.929			

**Table A6. Conway-Maxwell Poisson generalized linear model parameter estimates explaining variation in brood size among treatments and in response to clutch initiation date and clutch size.** Reference state listed after "ref." ( $n = 82$ ). We excluded 2 nests that produced nestlings but had eggs broken during incubation. Parameters with 95% CIs that did not overlap zero are bolded and italicized.

Variable	Estimate	SE	lower	upper	CI level*
light ref. control	0.047	0.139	-0.153	0.247	85%
noise ref. control	0.055	0.144	-0.152	0.262	85%
combined ref. control	-0.021	0.137	-0.218	0.177	85%
noise ref. light	0.008	0.147	-0.204	0.220	85%
combined ref. light	-0.068	0.141	-0.271	0.134	85%
combined ref. noise	-0.076	0.145	-0.285	0.133	85%
clutch initiation date	0.001	0.004	-0.005	0.007	85%
<i>clutch size</i>	<b><i>0.306</i></b>	<b><i>0.075</i></b>	<b><i>0.159</i></b>	<b><i>0.453</i></b>	<b><i>95%</i></b>

\*85 and 95% CIs calculated based on Estimate  $\pm$  (standard error x 1.44 OR 1.96)

**Table A7. Linear model parameter estimates explaining variation in incubation length among treatments and in response to clutch initiation date and clutch size.** Reference state listed after "ref." ( $n = 68$ ). For this analysis, we only considered nests where the exact CID is known and at least 1 egg hatched. Parameter estimates with 85% CIs that do not overlap zero are bolded, and those with 95% CIs that do not overlap zero are bolded and italicized.

Variable	Estimate	SE	lower	upper	CI level
<b>light ref. control</b>	<b>0.597</b>	<b>0.391</b>	<b>0.027</b>	<b>1.168</b>	<b>85%</b>
noise ref. control	0.075	0.402	-0.512	0.661	85%
combined ref. control	0.486	0.387	-0.077	1.049	85%
noise ref. light	-0.523	0.387	-1.086	0.041	85%
combined ref. light	-0.111	0.370	-0.651	0.428	85%
combined ref. noise	0.411	0.379	-0.142	0.964	85%
<i>clutch initiation date</i>	<b><i>-0.035</i></b>	<b><i>0.012</i></b>	<b><i>-0.059</i></b>	<b><i>-0.011</i></b>	<b><i>95%</i></b>
<i>clutch size</i>	<b><i>-0.399</i></b>	<b><i>0.195</i></b>	<b><i>-0.789</i></b>	<b><i>-0.010</i></b>	<b><i>95%</i></b>

**Table A8. Linear model parameter estimates explaining variation in nestling period length among treatments and in response to clutch initiation date and clutch size.**

Reference state listed after "ref." ( $n = 52$ ). For this analysis, we only considered nests that produced at least 1 fledgling. Parameters with 85% CIs that do not overlap zero are bolded, and those with 95% CIs that do not overlap zero are bolded and italicized.

Variable	Estimate	SE	lower	upper	CI level
light ref. control	0.489	0.692	-0.524	1.501	85%
<b>noise ref. control</b>	<b>0.918</b>	<b>0.625</b>	<b>0.004</b>	<b>1.833</b>	<b>85%</b>
<b>combined ref. control</b>	<b>1.027</b>	<b>0.617</b>	<b>0.124</b>	<b>1.929</b>	<b>85%</b>
noise ref. light	0.430	0.683	-0.571	1.430	85%
combined ref. light	0.538	0.665	-0.436	1.512	85%
combined ref. noise	0.108	0.606	-0.779	0.995	85%
<i><b>clutch initiation date</b></i>	<i><b>-0.041</b></i>	<i><b>0.018</b></i>	<i><b>-0.078</b></i>	<i><b>-0.005</b></i>	<i><b>95%</b></i>
chicks	0.242	0.246	-0.117	0.602	85%

**Table A9A. Poisson generalized linear mixed model estimates explaining variation in number of fledglings among treatments and in response to scaled clutch initiation date, scaled brood size, and box number within year.** Reference state listed after "ref." ( $n = 83$ ). For this analysis, we excluded one nest that produced fledglings but had eggs broken during incubation. Parameters with 85% CIs that did not overlap zero are bolded, and those with 95% CIs that did not overlap zero are bolded and italicized. Variance and standard deviation estimates of random intercept of nest box within year also provided.

Variable	Estimate	SE	lower	upper	CI level
light ref. control	-0.279	0.255	-0.650	0.093	85%
<b>noise ref. control</b>	<b>0.374</b>	<b>0.255</b>	<b>0.046</b>	<b>0.715</b>	<b>85%</b>
combined ref. control	0.211	0.227	-0.115	0.548	85%
<i><b>noise ref. light</b></i>	<i><b>0.653</b></i>	<i><b>0.250</b></i>	<i><b>0.160</b></i>	<i><b>1.166</b></i>	<i><b>95%</b></i>
<i><b>combined ref. light</b></i>	<i><b>0.489</b></i>	<i><b>0.249</b></i>	<i><b>0.000</b></i>	<i><b>0.996</b></i>	<i><b>95%</b></i>
combined ref. noise	-0.163	0.221	-0.487	0.160	85%
<b>scale(clutch initiation date)</b>	<b>0.166</b>	<b>0.087</b>	<b>0.041</b>	<b>0.295</b>	<b>85%</b>
<i><b>scale(chicks)</b></i>	<i><b>0.627</b></i>	<i><b>0.126</b></i>	<i><b>0.395</b></i>	<i><b>0.896</b></i>	<i><b>95%</b></i>
(1 year:box_no)	variance = 0.112		SD = 0.335		

**Table A9B. Poisson generalized linear model parameter estimate explaining variation in number of fledglings among treatments and in response to clutch initiation date and brood size.** Reference state listed after "ref." ( $n = 51$ ). For this analysis, only nests with at least 1 fledgling were considered, and we excluded one nest that produced fledglings but had eggs broken during incubation. Parameters with 95% CIs that overlapped zero were bolded and italicized.

Variable	Estimate	SE	lower	upper	CI level
light ref. control	-0.068	0.229	-0.402	0.259	85%
noise ref. control	0.048	0.195	-0.233	0.330	85%
combined ref. control	0.008	0.199	-0.278	0.295	85%
noise ref. light	0.115	0.221	-0.198	0.438	85%
combined ref. light	0.075	0.220	-0.237	0.397	85%
combined ref. noise	-0.040	0.189	-0.313	0.232	85%
clutch initiation date	0.006	0.006	-0.003	0.014	85%
<i>chicks</i>	<b><i>0.244</i></b>	<b><i>0.086</i></b>	<b><i>0.078</i></b>	<b><i>0.416</i></b>	<b><i>95%</i></b>

**Table A10. Linear mixed effect model parameter estimates explaining variation in nestling mass among treatments and in response to clutch initiation date, brood size, and box number within year.** Reference state listed after "ref." ( $n = 258$ ). Parameter estimates with 85% CIs that do not overlap zero are bolded, and those with 95% CIs that do not overlap zero are bolded and italicized. Variance and standard deviation estimates of random intercept of nest box within year also provided.

Variable	Estimate	SE	lower	upper	CI level
<b>light ref. control</b>	<b>-1.281</b>	<b>0.712</b>	<b>-2.314</b>	<b>-0.247</b>	<b>85%</b>
<b><i>noise ref. control</i></b>	<b><i>-1.547</i></b>	<b><i>0.720</i></b>	<b><i>-2.980</i></b>	<b><i>-0.113</i></b>	<b><i>95%</i></b>
<b><i>combined ref. control</i></b>	<b><i>-1.872</i></b>	<b><i>0.700</i></b>	<b><i>-3.271</i></b>	<b><i>-0.212</i></b>	<b><i>95%</i></b>
noise ref. light	-0.267	0.722	-1.315	0.782	85%
combined ref. light	-0.591	0.704	-1.616	0.428	85%
combined ref. noise	-0.325	0.712	-1.361	0.707	85%
<b><i>clutch initiation date</i></b>	<b><i>0.046</i></b>	<b><i>0.020</i></b>	<b><i>0.006</i></b>	<b><i>0.086</i></b>	<b><i>95%</i></b>
<b><i>chicks</i></b>	<b><i>-0.762</i></b>	<b><i>0.277</i></b>	<b><i>-1.313</i></b>	<b><i>-0.212</i></b>	<b><i>95%</i></b>
(1 year:box_no)	variance = 3.36	SD = 1.833			



**Table A11. Linear mixed effect model parameter estimates explaining variation in nestling body condition (mass scaled by wing chord) among treatments and in response to clutch initiation date, brood size, and box number within year.** Reference state listed after "ref." ( $n = 258$ ). Parameter estimates with 85% CIs that do not overlap zero are bolded. Variance and standard deviation estimates of random intercept of nest box within year also provided.

Variable	Estimate	SE	lower	upper	CI level
<b>light ref. control</b>	<b>-0.881</b>	<b>0.590</b>	<b>-1.737</b>	<b>-0.024</b>	<b>85%</b>
noise ref. control	-0.861	0.596	-1.726	0.004	85%
combined ref. control	-0.430	0.581	-1.273	0.412	85%
noise ref. light	0.020	0.598	-0.849	0.887	85%
combined ref. light	0.451	0.584	-0.398	1.297	85%
combined ref. noise	0.431	0.590	-0.426	1.286	85%
clutch initiation date	-0.009	0.017	-0.033	0.015	85%
chicks	-0.012	0.231	-0.347	0.323	85%
(1 year:box_no)	variance = 2.144	SD = 1.464			

**Table A12. Linear mixed effect model parameter estimates explaining variation in nestling wing chord length among treatments and in response to clutch initiation date, brood size, and box number within year.** Reference state listed after "ref." ( $n = 258$ ). Parameter estimates with 85% CIs that do not overlap zero are bolded, and those with 95% CIs that do not overlap zero are bolded and italicized. Variance and standard deviation estimates of random intercept of nest box within year also provided.

Variable	Estimate	SE	lower	upper	CI level
light ref. control	-0.703	1.358	-2.675	1.267	85%
noise ref. control	-1.065	1.375	-3.061	0.932	85%
<b>combined ref. control</b>	<b>-2.520</b>	<b>1.336</b>	<b>-4.462</b>	<b>-0.583</b>	<b>85%</b>
noise ref. light	-0.362	1.379	-2.363	1.641	85%
combined ref. light	-1.817	1.342	-3.766	0.128	85%
combined ref. noise	-1.455	1.360	-3.431	0.515	85%
<b><i>clutch initiation date</i></b>	<b><i>0.100</i></b>	<b><i>0.039</i></b>	<b><i>0.023</i></b>	<b><i>0.177</i></b>	<b>95%</b>
<b><i>chicks</i></b>	<b><i>-1.298</i></b>	<b><i>0.525</i></b>	<b><i>-2.344</i></b>	<b><i>-0.254</i></b>	<b>95%</b>
(1 year:box_no)	variance = 12.884	SD = 3.589			

**Table A13. Linear mixed effect model parameter estimates explaining variation in nestling rectrice length among treatments and in response to clutch initiation date, brood size and box number within year.** Reference state listed after "ref." ( $n = 258$ ). Parameter estimates with 85% CIs that do not overlap zero are bolded, and those with 95% CIs that do not overlap zero are bolded and italicized. Variance and standard deviation estimates of random intercept of nest box within year also provided.

Variable	Estimate	SE	lower	upper	CI level
light ref. control	-0.471	0.835	-1.683	0.740	85%
noise ref. control	-0.652	0.845	-1.877	0.575	85%
<i>combined ref. control</i>	<b><i>-1.729</i></b>	<b><i>0.822</i></b>	<b><i>-3.364</i></b>	<b><i>-0.095</i></b>	<b><i>95%</i></b>
noise ref. light	-0.181	0.848	-1.410	1.050	85%
<b>combined ref. light</b>	<b>-1.257</b>	<b>0.825</b>	<b>-2.455</b>	<b>-0.060</b>	<b>85%</b>
combined ref. noise	-1.077	0.835	-2.291	0.134	85%
<i>clutch initiation date</i>	<b><i>0.106</i></b>	<b><i>0.024</i></b>	<b><i>0.059</i></b>	<b><i>0.153</i></b>	<b><i>95%</i></b>
<b>chicks</b>	<b>-0.569</b>	<b>0.324</b>	<b>-1.040</b>	<b>-0.099</b>	<b>85%</b>
(1 year:box_no)	variance = 4.701		SD = 2.168		

**Table A14. Linear mixed effect model parameter estimates explaining variation in nestling tarsus length among treatments and in response to clutch initiation date, brood size, and box number within year.** Reference state listed after "ref." ( $n = 250$ ). Eight nestlings from two nests were excluded due to incorrect measurements. Parameter estimates with 85% CIs that do not overlap zero are bolded, and those with 95% CIs that do not overlap zero are bolded and italicized. Variance and standard deviation estimates of random intercept of nest box within year also provided.

Variable	Estimate	SE	lower	upper	CI level
light ref. control	-0.392	0.301	-0.827	0.044	85%
noise ref. control	-0.387	0.302	-0.825	0.051	85%
<i>combined ref. control</i>	<b><i>-1.044</i></b>	<b><i>0.299</i></b>	<b><i>-1.641</i></b>	<b><i>-0.451</i></b>	<b><i>95%</i></b>
noise ref. light	0.005	0.298	-0.429	0.438	85%
<i>combined ref. light</i>	<b><i>-0.652</i></b>	<b><i>0.296</i></b>	<b><i>-1.246</i></b>	<b><i>-0.064</i></b>	<b><i>95%</i></b>
<i>combined ref. noise</i>	<b><i>-0.657</i></b>	<b><i>0.298</i></b>	<b><i>-1.254</i></b>	<b><i>-0.065</i></b>	<b><i>95%</i></b>
<i>clutch initiation date</i>	<b><i>0.018</i></b>	<b><i>0.009</i></b>	<b><i>0.000</i></b>	<b><i>0.036</i></b>	<b><i>95%</i></b>
<b>chicks</b>	<b>-0.214</b>	<b>0.115</b>	<b>-0.381</b>	<b>-0.048</b>	<b>85%</b>
(1 year:box_no)	variance = 0.554		SD = 0.744		

**Table B1. Principal components analysis for perceived soundscape restorativeness scale measures.<sup>1</sup>**

Component	Variable	Loading	Mean (SD) <sup>2</sup>
<b>Sound fascination</b>			
		--	--
$\alpha = 0.89$	PR2: My attention is drawn to interesting sounds on the trail	0.781	5.1 (1.42)
	PR3: Sounds on the trail make me want to linger	0.806	4.4 (1.63)
	PR4: Sounds on the trail make me wonder about things	0.824	4.5 (1.66)
	PR5: I am engrossed by the sounds I heard today	0.854	4.0 (1.68)
<b>Sound compatibility</b>			
		--	--
$\alpha = 0.82$	PR9: The trail's acoustic environment is a refuge from unwanted distractions	0.657	5.4 (1.41)
	PR10: Hearing sounds from the trail today made me feel free from work, routine, and responsibilities	0.632	5.6 (1.38)
	PR12: Sounds on the trail today relate to activities I like to do	0.698	5.4 (1.38)
	PR13: The trail's acoustic environment fits with my personal preferences	0.723	5.6 (1.18)
	PR14: I rapidly get used to hearing the trail's acoustic environment	0.651	5.3 (1.31)
<b>Sound coherence</b>			
		--	--
$\alpha = 0.88$	PR16: All the sounds I heard on the trail today belong here	0.780	5.0 (1.56)
	PR17: All the sounds merge to form a coherent acoustic environment	0.791	5.1 (1.48)
	PR18: The sounds I heard seem to fit together quite naturally with this area	0.795	5.3 (1.44)
	PR19: The acoustic environment suggests the size of this area is limitless	0.453	4.8 (1.65)
<b>Items removed from further analyses</b>			
	The sounds I heard on the trail today are appealing	--	5.4 (1.27)
	I hear sounds I heard on the trail when I am doing something different than what I usually do	--	4.7 (1.67)
	Listening to sounds on the trail today gave me a break from my day-to-day listening experiences	--	5.4 (1.41)
	Hearings sounds heard on the trail today hinders what I would want to do in this place*	--	4.2 (1.60)

The trail's acoustic environment is different from what I usually hear in my daily life	--	5.7 (1.46)
--	----	------------

---

<sup>1</sup>KMO = .916 , Bartlett's test of sphericity  $p < 0.001$ ; <sup>2</sup>Items were measured on a 7-point scale, where 1=not at all and 7=completely; \*Item was reverse coded

**Table B2. Sample characteristics.<sup>1</sup>**

Variable	Categories	Gregory Canyon <sup>2</sup>	McClintock <sup>3</sup>	Both trails combined <sup>4</sup>	OSMP summer <sup>5</sup>
<b>Age</b> (in years of age)	16-19*	3%	2%	2%	3%
	20-29	37%	20%	29%	15%
	30-39	24%	26%	20%	15%
	40-49	15%	22%	18%	20%
	50-59	14%	21%	17%	21%
	60-69	6%	13%	9%	16%
	70+	2%	7%	4%	6%
	Median age	32	46	39	47
<b>Gender identity</b>	Female	49%	61%	55%	49%
	Male	51%	38%	45%	50%
	Other	1%	1%	1%	1%
<b>Education<sup>6</sup></b>	Some high school	<1%	1%	<1%	3%
	High school diploma	2%	2%	2%	4%
	Some college	11%	10%	11%	9%
	Associate	5%	4%	5%	4%
	Bachelors	36%	30%	36%	33%
	Graduate/professional	39%	45%	39%	36%
	Ph.D.	8%	8%	8%	11%
<b>Primary residence</b>	Boulder city limits	31%	27%	29%	50%
	Other Boulder County city	14%	11%	12%	29%
	Metro Denver	21%	14%	18%	9%
	Other Colorado	5%	4%	5%	4%
	Other US State	25%	41%	32%	7%
	Other country	3%	5%	4%	2%
<b>Group size</b>	1	28%	18%	23%	49%
	2	53%	52%	53%	39%
	3 to 4	18%	21%	19%	8%
	5+	2%	9%	5%	5%

<sup>1</sup>All percentages are rounded; <sup>2</sup> $n = 354$ ; <sup>3</sup> $n = 311$ ; <sup>4</sup>Represents all respondents intercepted in this study,  $n = 665$ ; <sup>5</sup>Data from VanderWoude and Kellogg (2018),  $n = 624$ ; <sup>6</sup>High level of education achieved; \*Only people 18 years of age and older were included in Gregory and McClintock samples.

**Table B3. Linear model output for species richness added by phantom chorus.**

Linear model: Richness ~ Measure + Trail

<b>Fixed effects</b>	<b>Estimate</b>	<b>SE</b>	<b>t</b>	<b>P</b>
Intercept	12.550	0.752	16.694	< 0.001
Measure*	5.900	0.868	6.797	< 0.001
Trail (McClintock)	-2.300	0.868	-2.650	0.017

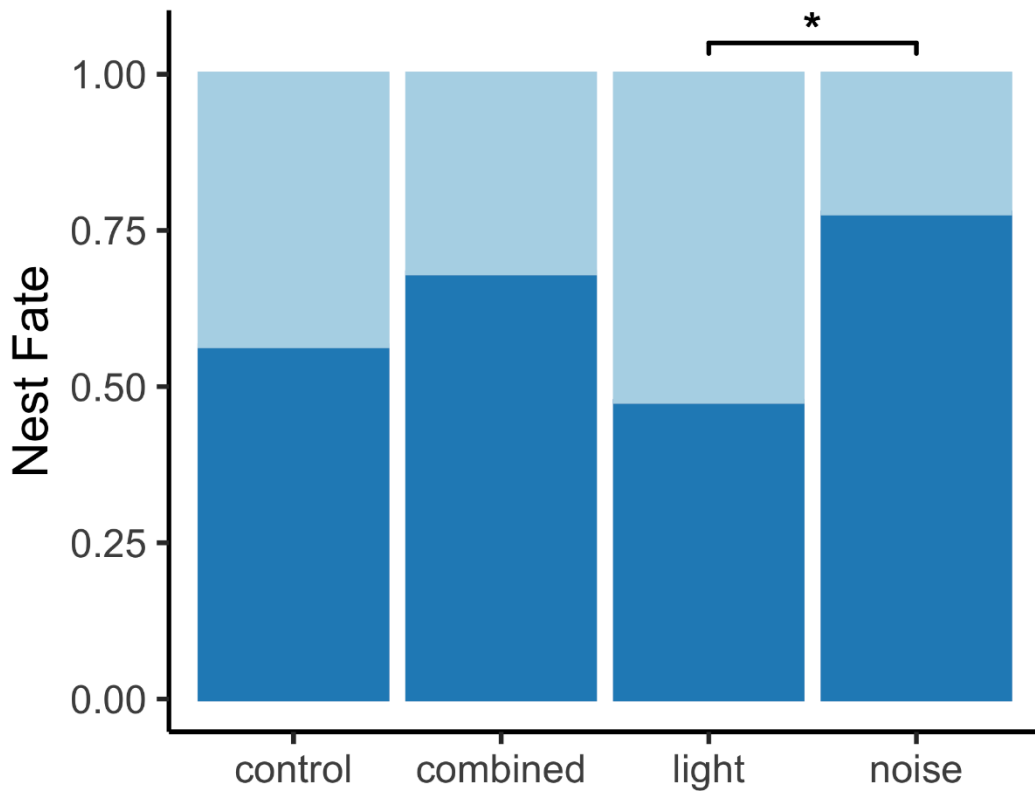
\* Detected species vs. detected species plus additional unique species from playback

**Table B4. Linear mixed model output for ambient sound levels.**

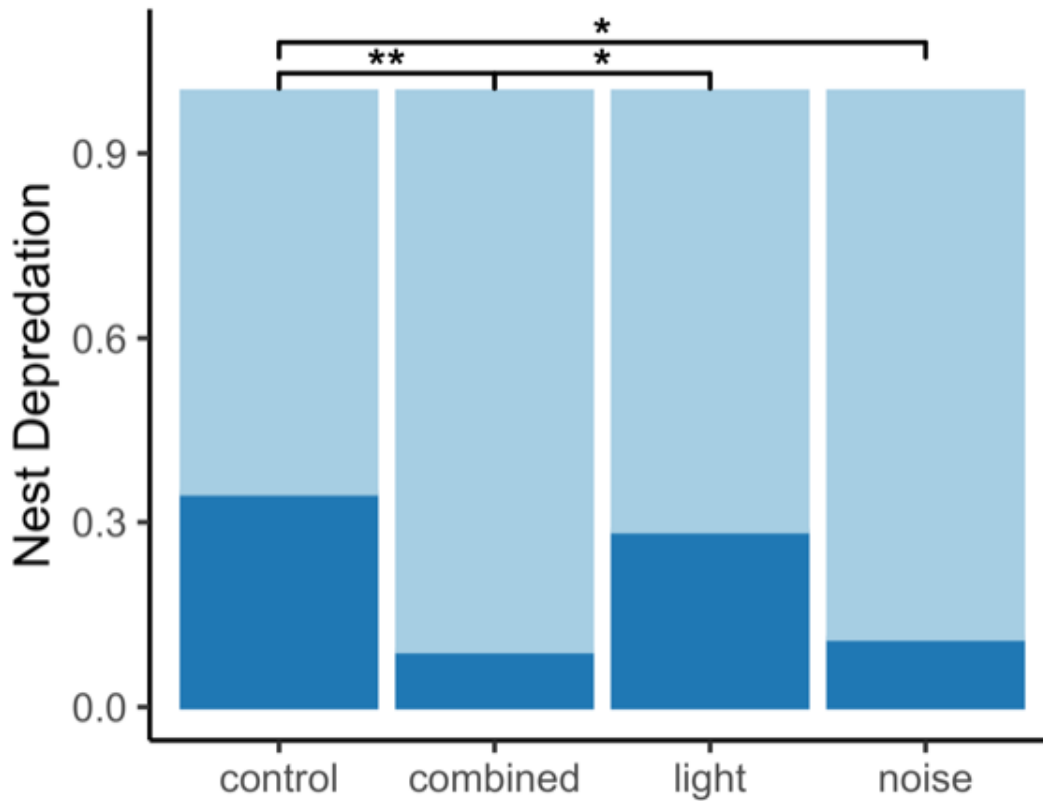
Linear mixed model: dbAL050 ~ Treatment \* Trail + Trail + Date + (1 | Recorder location / Hour of day)

<b>Fixed effects</b>	<b>Estimate</b>	<b>SE</b>	<b>t</b>	<b>P</b>
Intercept	32.900	0.358	89.892	< 0.001
Treatment (On)	0.699	0.118	5.932	< 0.001
Trail (Gregory)	-0.750	0.501	-1.498	0.164
Date	0.008	0.003	2.639	0.008
Treatment:Trail	-0.965	0.177	-5.449	< 0.001

## Appendix B. Figures.



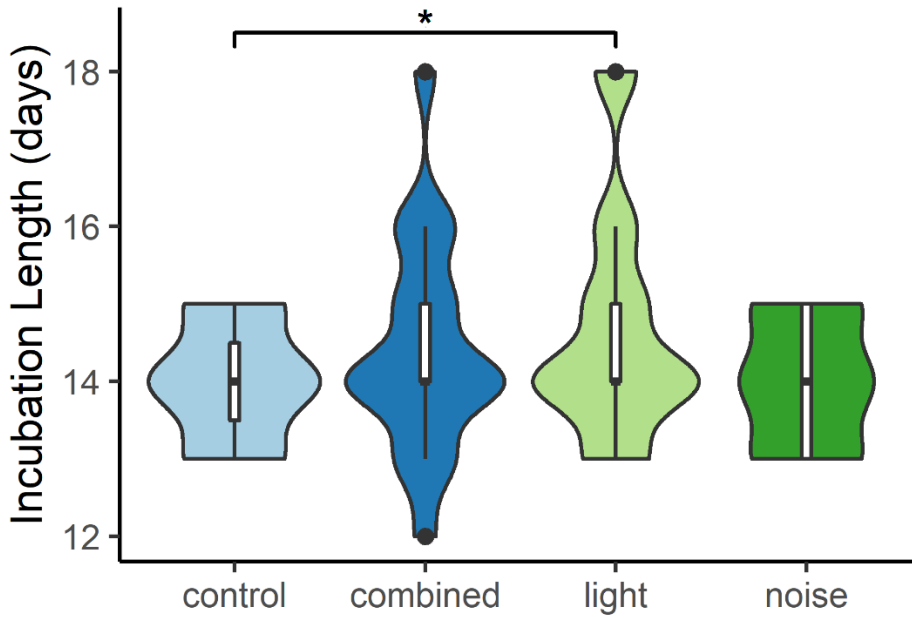
**Figure A1. Proportions of successful and failed nests for each treatment.** Successful nests are dark blue and failed nests are light blue. Single asterisk above brackets denote differences between treatments based on 85% confidence intervals that did not overlap zero.



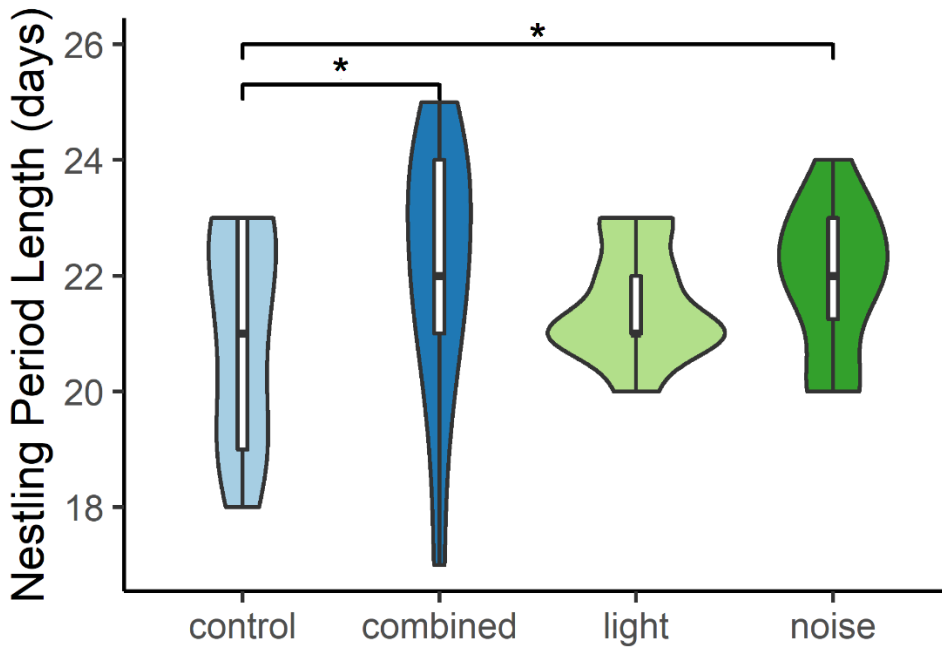
**Figure A2. Proportions of depredated and non-depredated nests for each treatment.**

Depredated nests are dark blue, non-depredated nests are light blue. Single and double asterisks above brackets denote differences between treatments based on 85 and 95% confidence intervals that did not overlap zero, respectively.

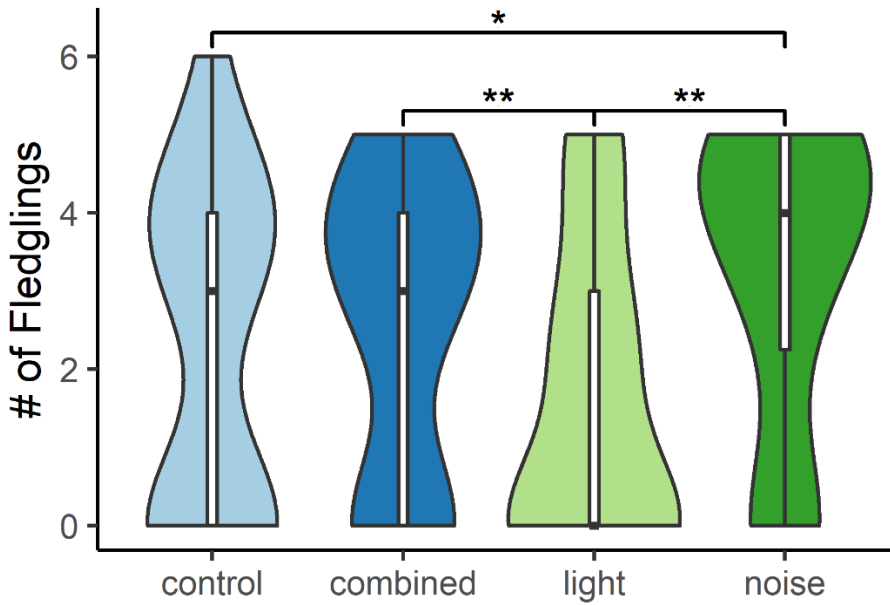




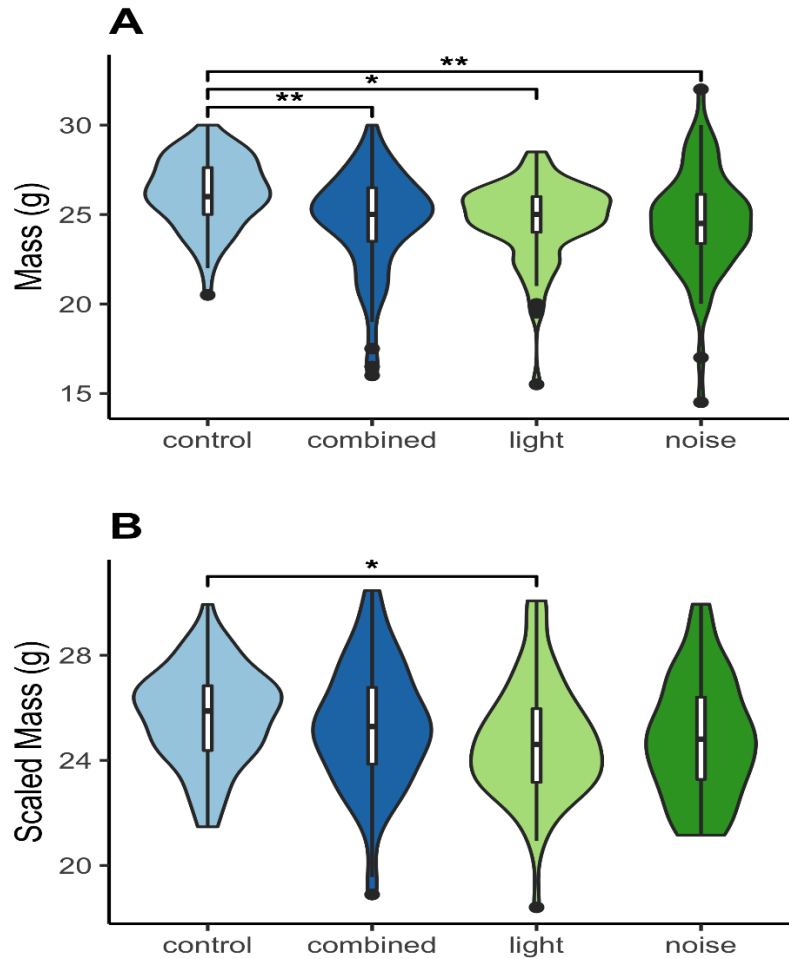
**Figure A3. Incubation lengths for each treatment.** Light-treated nests had longer incubation periods than control nests. Violin outlines illustrate kernel probability density. Boxplots show the median and quartiles and whiskers denote 1.5 times the interquartile range. Single asterisk above brackets denote differences between treatments based on 85% confidence intervals that did not overlap zero.



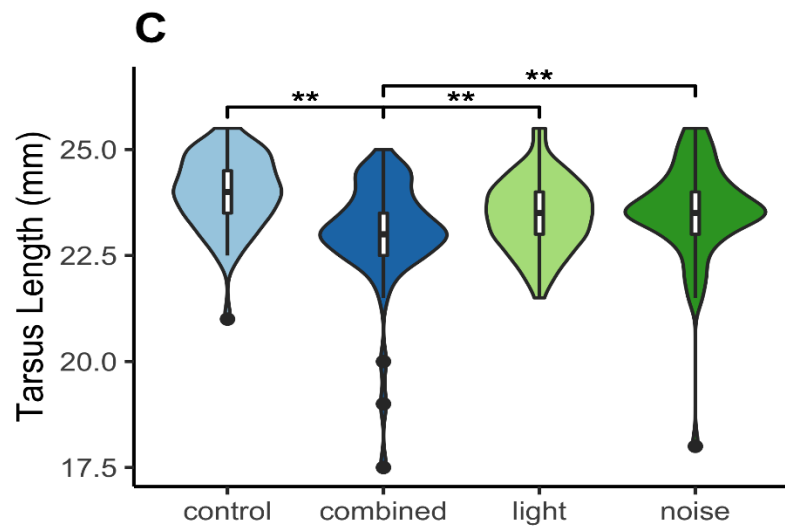
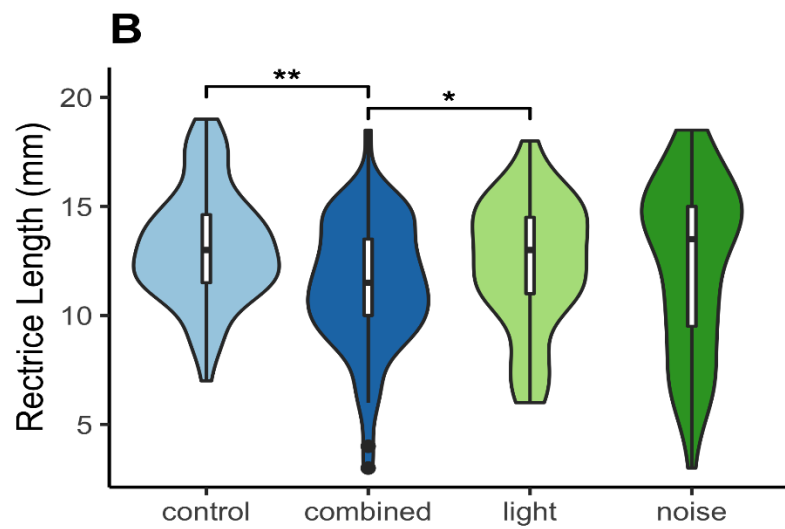
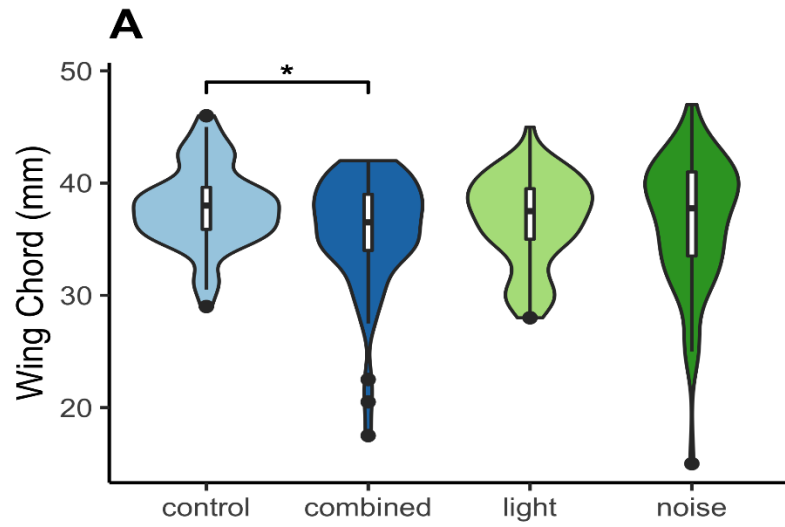
**Figure A4. Nestling period lengths for each treatment.** Combination-treated nests and noise-treated nests both had longer nestling periods than control nests. Violin outlines illustrate kernel probability density. Boxplots show the median and quartiles and whiskers denote 1.5 times the interquartile range. Single asterisk above brackets denote differences between treatments based on 85% confidence intervals that did not overlap zero.



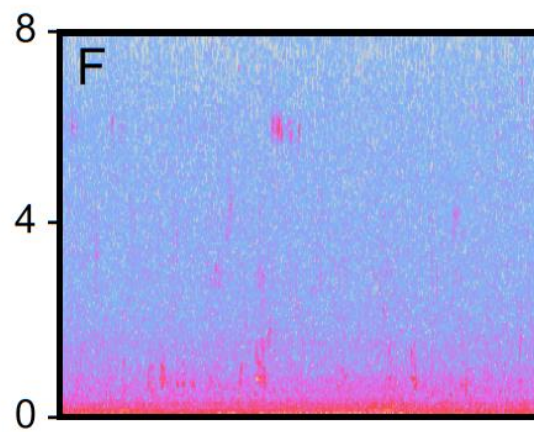
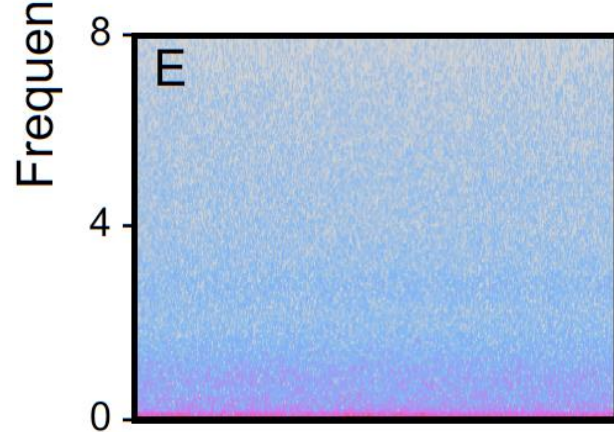
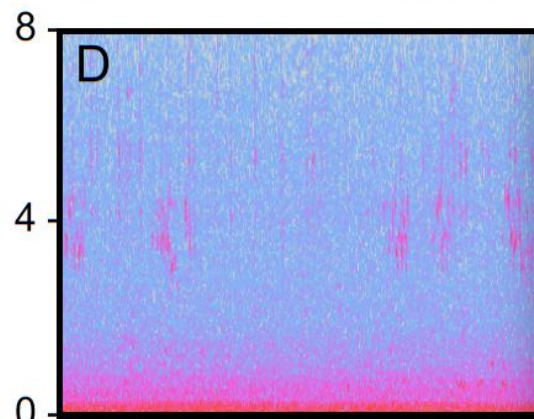
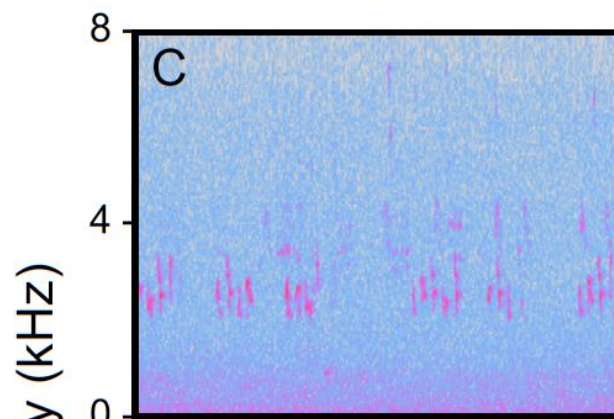
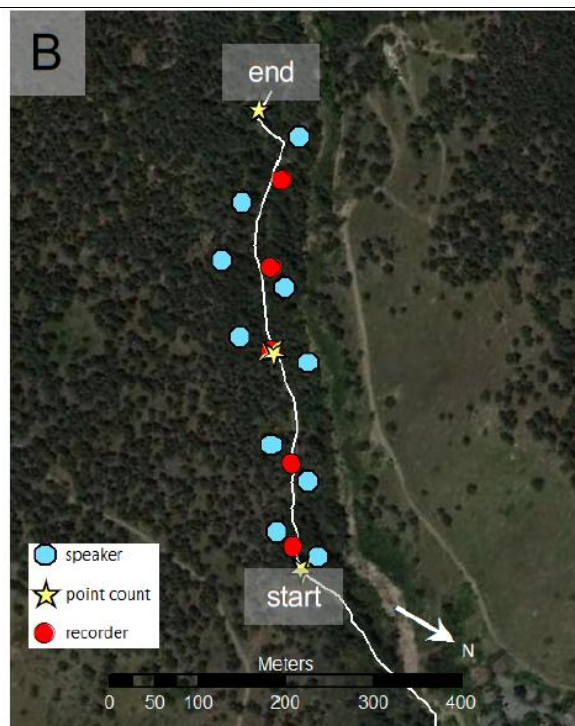
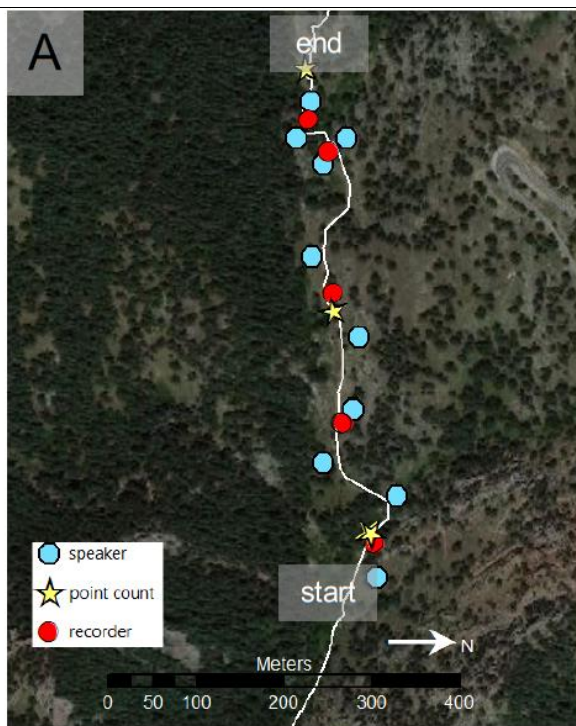
**Figure A5. Number of fledglings for each treatment (including nests that produced no fledglings).** Noise-treated nests produced more fledglings than control and light-treated nests, and combination-treated nests produced more fledglings than light-treated nests. Violin outlines illustrate kernel probability density. Boxplots show the median and quartiles and whiskers denote 1.5 times the interquartile range. Single and double asterisks above brackets denote differences between treatments based on 85 and 95% confidence intervals that did not overlap zero, respectively.



**Figure A6. Nestling mass and mass scaled by wing chord.** A) Control nestlings were heavier than nestlings in combination-treated, light-treated, and noise-treated nests. B) When considering mass scaled by wing chord, control nestlings were only heavier than nestlings in light-treated nests. Violin outlines illustrate kernel probability density. Boxplots show the median and quartiles and whiskers denote 1.5 times the interquartile range. Single and double asterisks above brackets denote differences between treatments based on 85 and 95% confidence intervals that did not overlap zero, respectively.



**Figure A7. Nestling wing chord, rectrice length, and tarsus length.** A) Control nestlings had longer wing chords than combination-treated nestlings. B) Control nestlings and light-treated nestlings both had longer wing chords than combination-treated nestlings. C) Control, light-treated, and noise-treated nestlings all had longer tarsus lengths than combination-treated nestlings. Violin outlines illustrate kernel probability density. Boxplots show the median and quartiles and whiskers denote 1.5 times the interquartile range. Single and double asterisks above brackets denote differences between treatments based on 85 and 95% confidence intervals that did not overlap zero, respectively.



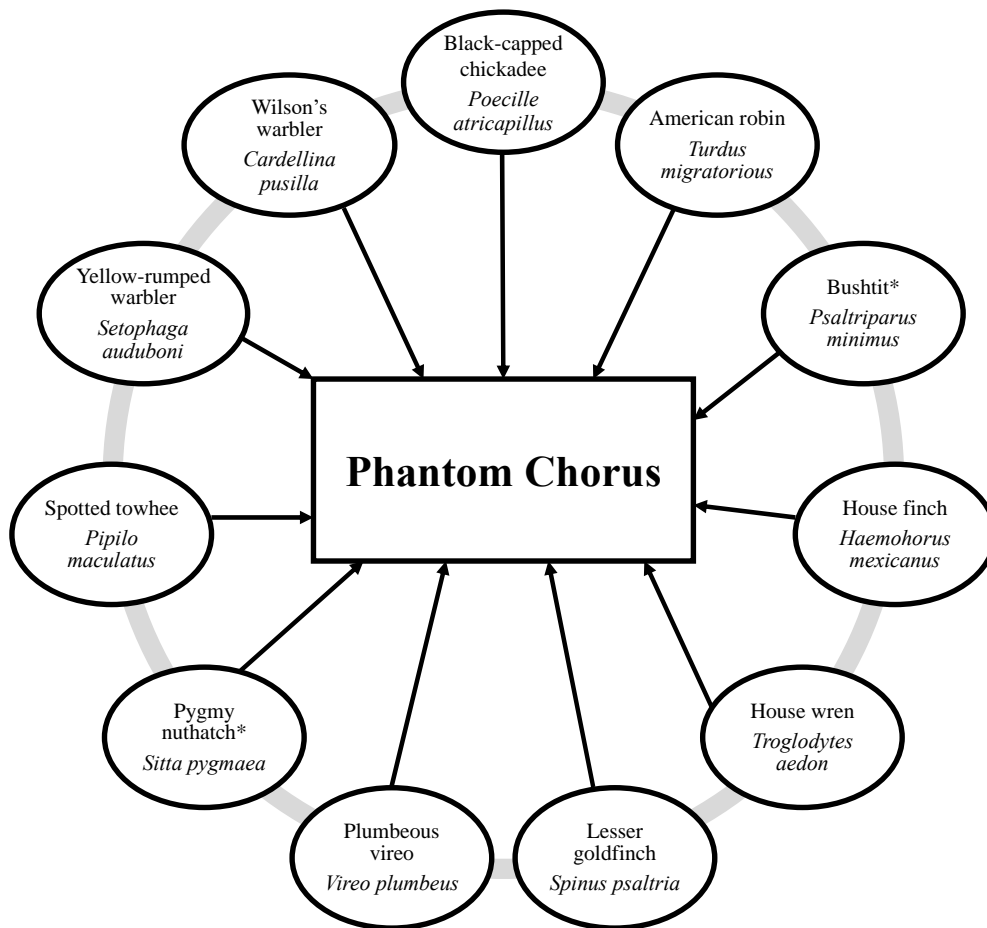
Time

Time

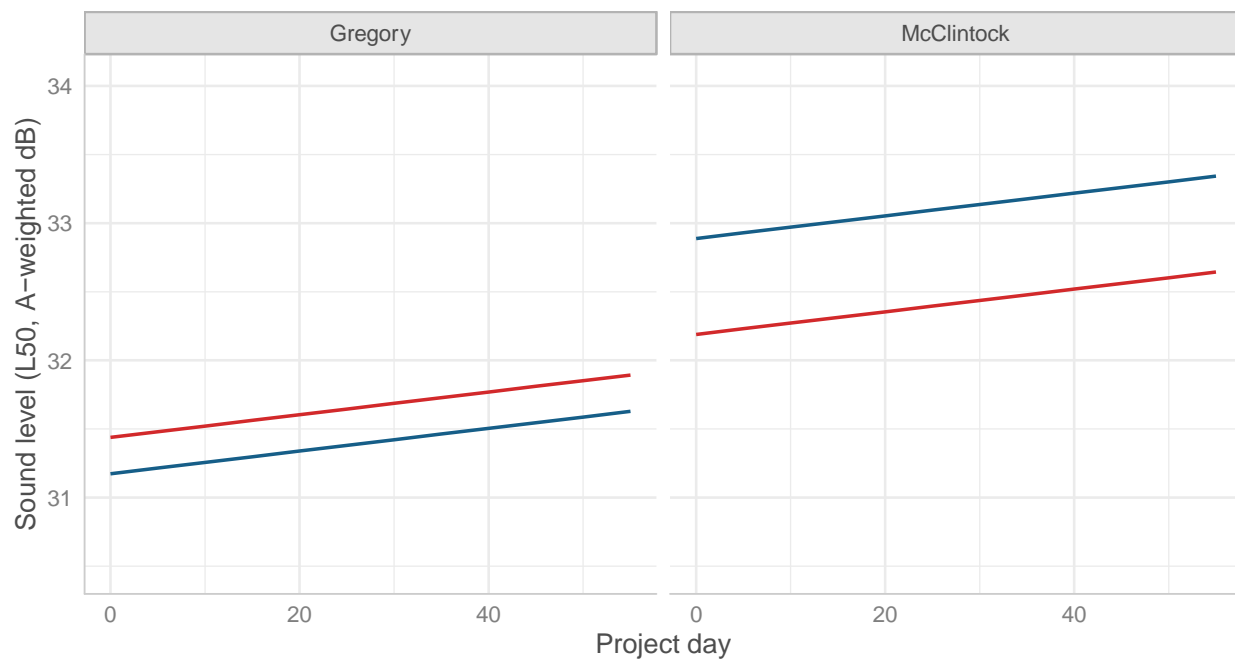
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**Figure B1. Speaker, recorder, and point count locations at (A) Gregory Canyon and (B) McClintock.** (C) and (D) denote spectrograms of 30-second clips of audio recordings taken during the phantom chorus treatment at Gregory Canyon and McClintock, respectively; (E) and (F) were taken on control days at each site (i.e., the phantom chorus treatment was off). Control conditions were not necessarily quiet; for example, (F) illustrates sounds produced by a hummingbird flying and a human talking at McClintock.

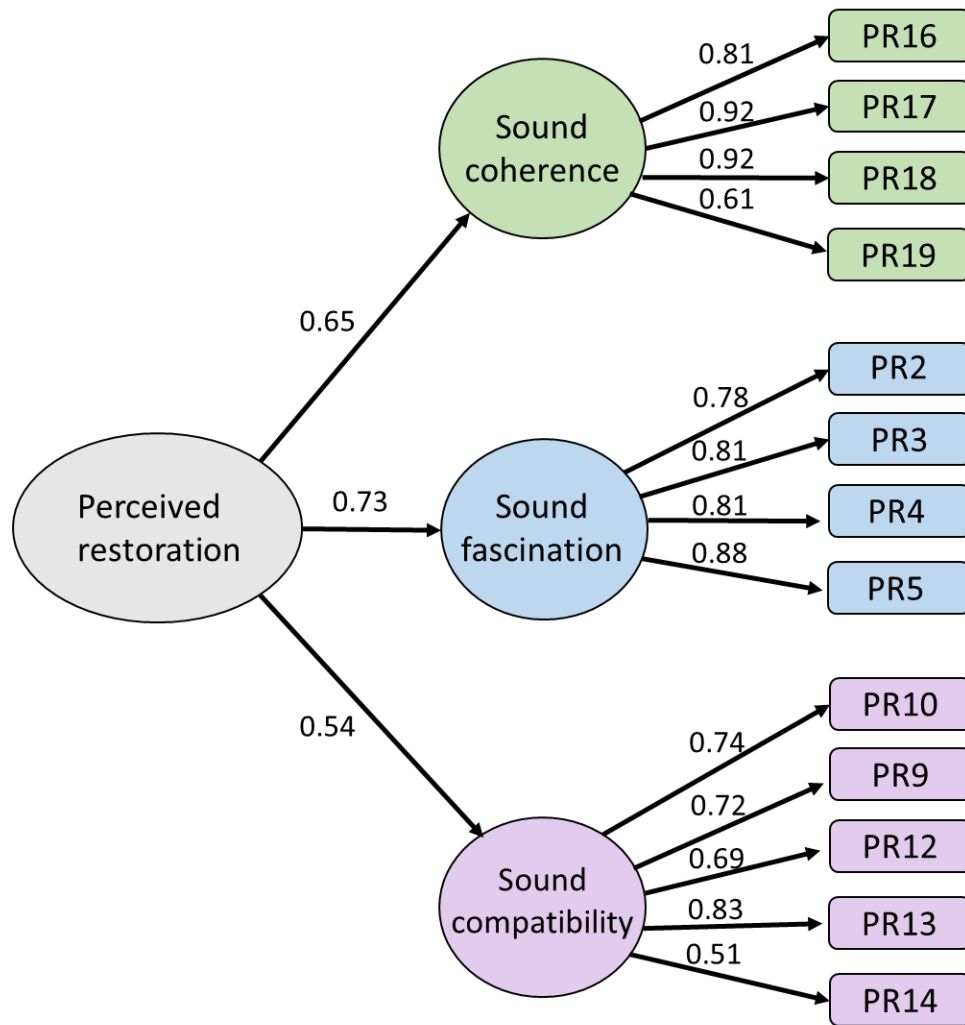




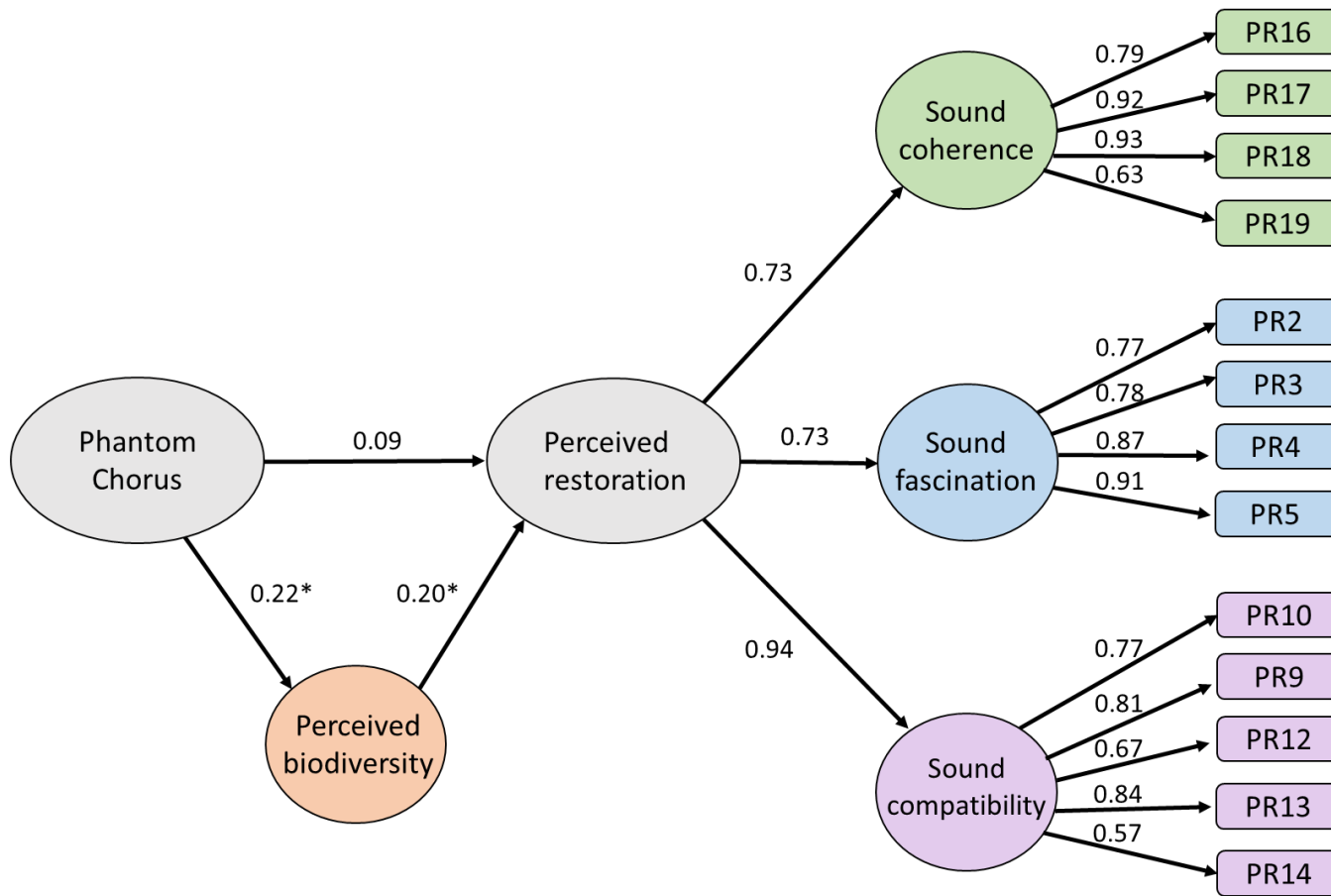
**Figure B2. Species composition of the phantom chorus.** \*Pygmy nuthatch and Bushtit sounds were combined into a single file.



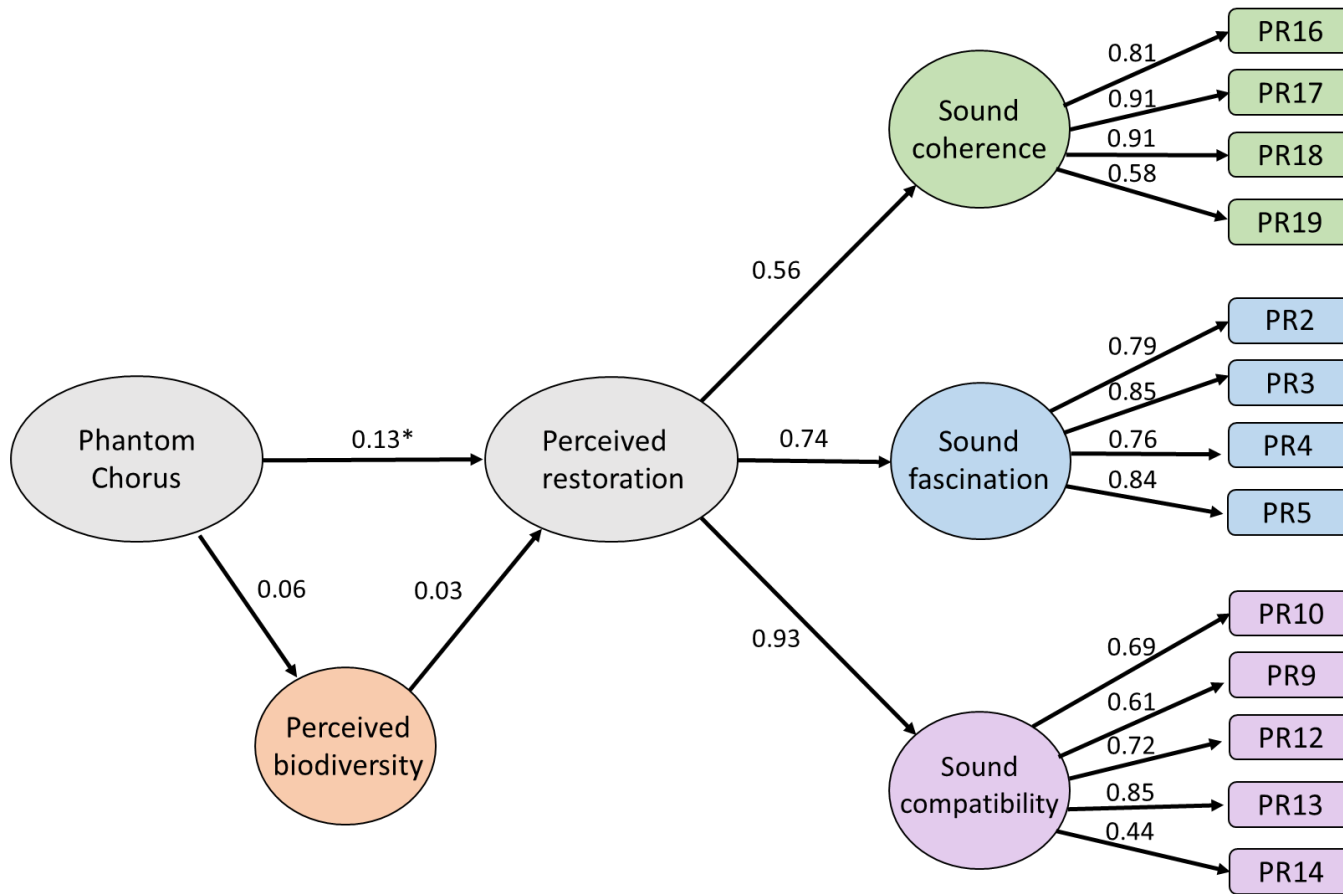
**Figure B3. Ambient sound levels on trails during treatment (blue) and control (red) days.** Sound levels as measured by L50 were significantly higher at McClintock, and significantly lower on Gregory Canyon on treatment days than control days. Project dates ranged from 15 July 2017 to 4 September 2017.



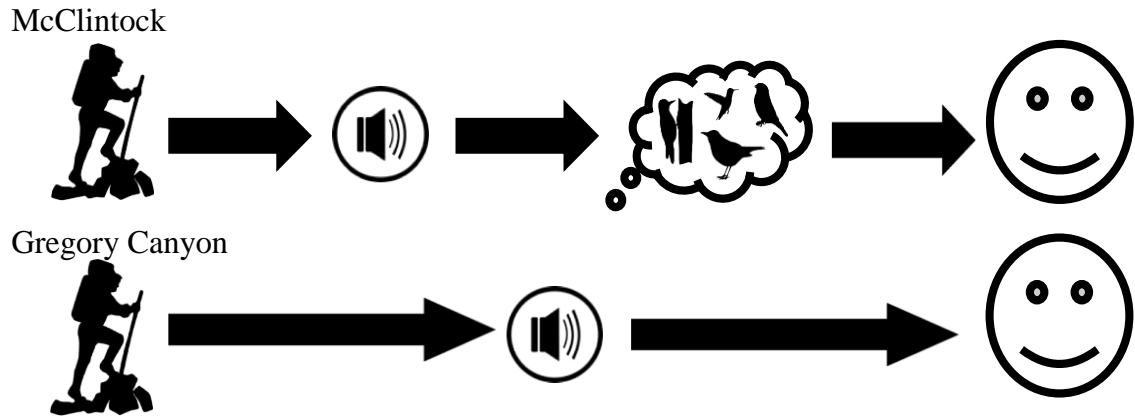
**Figure B4. Second order CFA of perceived psychological restoration scale.** Model fit:  $\chi^2 = 279.419$ ,  $df = 62$ ,  $p < 0.001$ ;  $BS_{boot}$ ,  $p = 0.002$ ; RMSEA = 0.073; SRMR = 0.0491; CFI = 0.958; TLI=0.947.



**Figure B5. Structural equation model for the relationships between the phantom chorus treatment, perceived bird species diversity, and perceived psychological restoration at the McClintock trail.** Model fit:  $\chi^2=151.262$ ,  $df = 86$ ,  $p < 0.001$ ;  $BS_{boot}$ ,  $p = 0.088$ ;  $RMSEA = 0.049$ ;  $SRMR = 0.0427$ ;  $CFI = 0.975$ ;  $TLI = 0.970$ . Structural paths marked with \* denote  $p < 0.05$ . All factor loadings are statistically significant ( $p < 0.05$ ).



**Figure B6. Structural equation model for the relationships between the phantom chorus treatment, perceived bird species diversity, and perceived psychological restoration at the Gregory Canyon trail.** Model fit:  $\chi^2 = 242.601$ ,  $df = 86$ ,  $p < 0.001$ ;  $BS_{boot}$ ,  $p = 0.002$ ;  $RMSEA = 0.072$ ;  $SRMR = 0.0557$ ;  $CFI = 0.939$ ;  $TLI = 0.925$ . Structural paths marked with \* denote  $p < 0.05$ . All factor loadings are statistically significant ( $p < 0.05$ ).



**Figure B7. Conceptual figure showing the effect of the phantom chorus treatment.** At the McClintock trail, only hikers who perceived higher levels of bird species diversity experienced perceived psychological benefits from the phantom chorus. At the Gregory Canyon trail, hikers experienced perceived psychological benefits from the phantom chorus regardless of their perceived levels of bird species diversity.

## **Appendix C. Phantom Chorus visitor survey.**

### **Intro/Consent Screen**

The focus of this study is to better understand visitor experiences in Boulder Open Space and Mountain Parks.

Your participation in the study is voluntary. There are no penalties for not answering some or all questions, but because each participant will represent many others who will not be included in the study, your input is extremely important. The answers you provide will remain anonymous. Our results will be summarized so that the answers you provide cannot be associated with you or anyone in your group or household.

### **Finish Screen text**

Thank you for completing the survey

### **Pre-responder questions (filled out by us)**

#### **Q1. (X1) Trail**

1. McClintock
2. Gregory Canyon

#### **Q2. (X2) Direction**

1. Up
2. Down

*\*\*The only answer should be "up" - if down, correct it*

#### **Q3. (X3) Treatment**

1. Treatment
2. Control

*\*\*Make sure that answers from the same place and date have all the same treatments*

### **Grid Questions**

**Q4. (Energy) Please place an 'X' in the grid that best represents how you feel at the moment.  
(Energy)**

1. -5
2. -4
3. -3
4. -2
5. -1
6. 0
7. 1
8. 2
9. 3
10. 4
11. 5

**Q5. (Pleasantness) Please place an 'X' in the grid that best represents how you feel at the moment.**  
**(Pleasantness)**

1. -5
2. -4
3. -3
4. -2
5. -1
6. 0
7. 1
8. 2
9. 3
10. 4
11. 5

### **Motivations**

**Q6. (M1) (Motivations)**

**Visitors have different reasons for visiting OSMP. Please rate the importance of each of the following reasons for your visit today. Please mark only one response for each item.**

**To experience a sense of connection with nature**

1. Not relevant (1)
2. Not at all important (2)
3. Slightly important (3)
4. Moderately important (4)
5. Very important (5)
6. Extremely important (6)

**Q7. (M2) To experience the diversity of the natural world**

1. Not relevant (1)
2. Not at all important (2)
3. Slightly important (3)
4. Moderately important (4)
5. Very important (5)
6. Extremely important (6)

**Q8. (M3) To enjoy the natural quiet and sounds of nature**

1. Not relevant (1)
2. Not at all important (2)



- 3. Slightly important (3)
- 4. Moderately important (4)
- 5. Very important (5)
- 6. Extremely important (6)

**Q9. (M4) To give my mind a rest**

- 1. Not relevant (1)
- 2. Not at all important (2)
- 3. Slightly important (3)
- 4. Moderately important (4)
- 5. Very important (5)
- 6. Extremely important (6)

**Q10. (M5) To get away from the usual demands of life**

- 1. Not relevant (1)
- 2. Not at all important (2)
- 3. Slightly important (3)
- 4. Moderately important (4)
- 5. Very important (5)
- 6. Extremely important (6)

**Q11. (M6) To get away from the noise back home**

- 1. Not relevant (1)
- 2. Not at all important (2)
- 3. Slightly important (3)
- 4. Moderately important (4)
- 5. Very important (5)
- 6. Extremely important (6)

**Q12. (M7) To develop your skills and abilities**

- 1. Not relevant (1)
- 2. Not at all important (2)
- 3. Slightly important (3)
- 4. Moderately important (4)
- 5. Very important (5)
- 6. Extremely important (6)

**Q13. (M8) To do something with your family**

- 1. Not relevant (1)
- 2. Not at all important (2)

- 3. Slightly important (3)
- 4. Moderately important (4)
- 5. Very important (5)
- 6. Extremely important (6)

**Q14. (M9) To be with friends**

- 1. Not relevant (1)
- 2. Not at all important (2)
- 3. Slightly important (3)
- 4. Moderately important (4)
- 5. Very important (5)
- 6. Extremely important (6)

**Q15. (M10) To experience wildlife in nature**

- 1. Not relevant (1)
- 2. Not at all important (2)
- 3. Slightly important (3)
- 4. Moderately important (4)
- 5. Very important (5)
- 6. Extremely important (6)

**Q16. (M11) To photograph wildlife**

- 1. Not relevant (1)
- 2. Not at all important (2)
- 3. Slightly important (3)
- 4. Moderately important (4)
- 5. Very important (5)
- 6. Extremely important (6)

**Q17. (M12) Appreciating the scenic beauty**

- 1. Not relevant (1)
- 2. Not at all important (2)
- 3. Slightly important (3)
- 4. Moderately important (4)
- 5. Very important (5)
- 6. Extremely important (6)

**Q18. (M13) Experiencing solitude**

- 1. Not relevant (1)
- 2. Not at all important (2)

- 3. Slightly important (3)
- 4. Moderately important (4)
- 5. Very important (5)
- 6. Extremely important (6)

**Q19. (M14) Getting some exercise**

- 1. Not relevant (1)
- 2. Not at all important (2)
- 3. Slightly important (3)
- 4. Moderately important (4)
- 5. Very important (5)
- 6. Extremely important (6)

**Q20. (M15) Learning about nature**

- 1. Not relevant (1)
- 2. Not at all important (2)
- 3. Slightly important (3)
- 4. Moderately important (4)
- 5. Very important (5)
- 6. Extremely important (6)

**Q21. (M16) Being with my dog(s)**

- 1. Not relevant (1)
- 2. Not at all important (2)
- 3. Slightly important (3)
- 4. Moderately important (4)
- 5. Very important (5)
- 6. Extremely important (6)

**Q22. (M17) Enjoying the peace and quiet**

- 1. Not relevant (1)
- 2. Not at all important (2)
- 3. Slightly important (3)
- 4. Moderately important (4)
- 5. Very important (5)
- 6. Extremely important (6)

**Q22. (M17) Enjoying the peace and quiet**

- 1. Not relevant (1)
- 2. Not at all important (2)

3. Slightly important (3)
4. Moderately important (4)
5. Very important (5)
6. Extremely important (6)

### **Diversity/Richness**

#### **Q23. (DR1) (Diversity/Richness)**

**Based on your experience on the trail today, about how many different types or species of birds would you say are in the last quarter mile or last seven minutes of your walk on the trail? Please mark one response.**

1. 0-3 different types of birds
2. 4-7 different types of birds
3. 8-11 different types of birds
4. 12-15 different types of birds
5. More than 15 different types of birds

**Q24. (DR2) If you heard bird song today along the trail, how would you rate the diversity of the bird song chorus? Please mark one response.**

1. Not at all diverse
2. A little diverse
3. Moderately diverse
4. Highly diverse
5. Extremely diverse
6. I did not hear bird song

**Q25. (DR3) Visitors hear a lot of sounds, including natural sounds and human-made sounds. Based on your experience today on the trail, how would you rate the pleasantness of the soundscape?**

1. Very unpleasant
2. Unpleasant
3. Slightly unpleasant
4. Slightly pleasant
5. Pleasant
6. Very pleasant

**Q26. (DR4) Based on your experience today on the trail, how well were you able to hear natural (non-human) sounds?**

1. Almost always clearly without interference from human-made sound
2. Usually clearly without interference from human-made sound
3. Sometimes clearly without interference from human-made sound
4. Usually with interference from human-made sound

5. Almost always with interference from human-made sound

### **Perceived Restoration**

#### **Q27. (PR1-Fascination) (Perceived Restoration)**

**Based on your experience from the last quarter mile of trail or seven minutes of your hike today, how much do you agree with each of these statements?**

**The sounds I heard on the trail today are appealing**

1. Not at all (0)
2. Very little (1)
3. A little (2)
4. Somewhat (3)
5. A fair bit (4)
6. Very much (5)
7. Completely (6)

#### **Q28. (PR2-Fascination) My attention is drawn to interesting sounds on the trail**

1. Not at all (0)
2. Very little (1)
3. A little (2)
4. Somewhat (3)
5. A fair bit (4)
6. Very much (5)
7. Completely (6)

#### **Q29. (PR3-Fascination) Sounds on the trail today make me want to linger**

1. Not at all (0)
2. Very little (1)
3. A little (2)
4. Somewhat (3)
5. A fair bit (4)
6. Very much (5)
7. Completely (6)

#### **Q30. (PR4-Fascination) Sounds on the trail today make me wonder about things**

1. Not at all (0)
2. Very little (1)
3. A little (2)
4. Somewhat (3)

- 5. A fair bit (4)
- 6. Very much (5)
- 7. Completely (6)

**Q31. (PR5-Fascination) I am engrossed by the sounds I heard today**

- 1. Not at all (0)
- 2. Very little (1)
- 3. A little (2)
- 4. Somewhat (3)
- 5. A fair bit (4)
- 6. Very much (5)
- 7. Completely (6)

**Q32. (PR6-BeingAwayTo) I hear sounds I heard on the trail when I am doing something different than what I usually do**

- 1. Not at all (0)
- 2. Very little (1)
- 3. A little (2)
- 4. Somewhat (3)
- 5. A fair bit (4)
- 6. Very much (5)
- 7. Completely (6)

**Q33. (PR7-BeingAwayTo) The trail's acoustic environment is different from what I usually hear in my daily life**

- 1. Not at all (0)
- 2. Very little (1)
- 3. A little (2)
- 4. Somewhat (3)
- 5. A fair bit (4)
- 6. Very much (5)
- 7. Completely (6)

**Q34. (PR8-BeingAwayTo) I heard sounds on the trail today that I usually hear in my daily life**

- 1. Not at all (0)
- 2. Very little (1)
- 3. A little (2)
- 4. Somewhat (3)
- 5. A fair bit (4)

6. Very much (5)

7. Completely (6)

**Q35. (PR9-BeingAwayFrm) The trail's acoustic environment is a refuge from unwanted distractions**

1. Not at all (0)

2. Very little (1)

3. A little (2)

4. Somewhat (3)

5. A fair bit (4)

6. Very much (5)

7. Completely (6)

**Q36. (PR10BeingAwayFrm) Hearing sounds from the trail today made me feel free from work, routine and responsibilities**

1. Not at all (0)

2. Very little (1)

3. A little (2)

4. Somewhat (3)

5. A fair bit (4)

6. Very much (5)

7. Completely (6)

**Q37. (PR11BeingAwayFrm) Listening to sounds on the trail today gave me a break from my day-to-day listening experiences**

1. Not at all (0)

2. Very little (1)

3. A little (2)

4. Somewhat (3)

5. A fair bit (4)

6. Very much (5)

7. Completely (6)

**Q38. (PR12-Compatibility) Sounds on the trail today relate to activities I like to do**

1. Not at all (0)

2. Very little (1)

3. A little (2)

4. Somewhat (3)

5. A fair bit (4)

6. Very much (5)

7. Completely (6)

**Q39. (PR13-Compatibility) The trail's acoustic environment fits with my personal preferences**

1. Not at all (0)

2. Very little (1)

3. A little (2)

4. Somewhat (3)

5. A fair bit (4)

6. Very much (5)

7. Completely (6)

**Q40. (PR14-Compatibility) I rapidly get used to hearing the trail's acoustic environment**

1. Not at all (0)

2. Very little (1)

3. A little (2)

4. Somewhat (3)

5. A fair bit (4)

6. Very much (5)

7. Completely (6)

**Q41. (PR15-Compatibility) Hearing sounds heard on the trail today hinders what I would want to do in this place**

1. Not at all (0)

2. Very little (1)

3. A little (2)

4. Somewhat (3)

5. A fair bit (4)

6. Very much (5)

7. Completely (6)

**Q42. (PR16-ExtCoherence) All the sounds I heard on the trail today belong here**

1. Not at all (0)

2. Very little (1)

3. A little (2)

4. Somewhat (3)

5. A fair bit (4)

6. Very much (5)

7. Completely (6)

**Q43. (PR17-ExtCoherence) All the sounds merge to form a coherent acoustic environment**



1. Not at all (0)
2. Very little (1)
3. A little (2)
4. Somewhat (3)
5. A fair bit (4)
6. Very much (5)
7. Completely (6)

**Q44. (PR18-ExtCoherence) The sounds I heard seem to fit together quite naturally with this area**

1. Not at all (0)
2. Very little (1)
3. A little (2)
4. Somewhat (3)
5. A fair bit (4)
6. Very much (5)
7. Completely (6)

**Q45. (PR19-ExtScope) The acoustic environment suggests the size of this area is limitless**

1. Not at all (0)
2. Very little (1)
3. A little (2)
4. Somewhat (3)
5. A fair bit (4)
6. Very much (5)
7. Completely (6)

**Assessment of birding background**

**Q46. (BB1) (Assessment of birding background- the following question will use skip logic. If a visitor replies "yes" we will ask the other questions.)**

**Do you participate in birding?**

1. Yes
2. No

**Q47. (BB2) If you participate in birding, which best describes you?**

**(Definitions as described by Scott et al. (2005) will be provided should a visitor ask for clarification.)**

1. Casual
2. Active
3. Committed

**Q48. (BB3) In the past 12 months, how many trips away from home did you expressly take to bird?**

1. 0-1
2. 2-3
3. 4-7
4. 8+

**Q49. (BB4) In the past 12 months, how many days did you bird in total?**

1. 1-5
2. 6-18
3. 19-53
4. 54+

**Q50. (BB5) How do you compare your ability to identify birds by sound to that of other birders, in general?**

1. Less skilled
2. Equally skilled
3. More skilled

**Q51. (BB6) Are you a member of any local, state, national, or international birding or conservation organizations?**

1. Yes
2. No

### **Demographic Information**

**Q52. (D1) (Demographic information)**

**Including this visit, how many times have you visited Boulder Open Space and Mountain Parks in the past 12 months? (approximate)**

(answer should be a non-decimal number >0)

**Q53. (D2) Approximately how many hours did you spend in Boulder Open Space and Mountain Parks TODAY?**

(answer is a non-decimal number)

**Q54. (D3a) How many adults and how many children were in your personal group (spouse, family, friends) during your visit to Boulder Open Space and Mountain Parks today? Please provide a number.**

**Adults (18 or older):**

(answer is a non-decimal number)

**Q55. (D3b) How many adults and how many children were in your personal group (spouse, family, friends) during your visit to Boulder Open Space and Mountain Parks today? Please provide a number.**

**Children (17 or younger):**

(answer is a non-decimal number)

**Q56. (D4) How would you describe your group?**

1. Alone
2. Family
3. Friends
4. Family and Friends
5. Organized group (e.g. club, educational group)
6. Commercial tour group

**Q57. (D5) What is your gender?**

1. Male
2. Female
3. Other

**Q58. (D6) In what year were you born?**

Should be a 4-digit year; change to 4 digits if not

**Q59. (D7) Where is your primary residence?**

1. Boulder (within city limits)
2. Louisville
3. Lafayette
4. Superior
5. Longmont
6. Unincorporated Boulder County
7. Other city in Boulder County
8. Metro Denver
9. Other area in Colorado
10. Other US state
11. Other country

**Q60. (D8) What is the highest degree or level of education you have completed?**

1. Some high school
2. High school graduate (or equivalency)
3. Some college, no degree

4. Associate's degree
5. Bachelor's degree
6. Graduate or professional degree
7. PhD