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The effects of anthropogenic noise on animals: a meta-analysis

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Anthropogenic noise has become a major global pollutant and studies have shown that noise can affect animals. However, such single studies cannot provide holistic quantitative assessments on the potential effects of noise across species. Using a multi-level phylogenetically controlled meta-analysis, we provide the first holistic quantitative analysis on the effects of anthropogenic noise. We found that noise affects many species of amphibians, arthropods, birds, fish mammals, molluscs, and reptilians. Interestingly, phylogeny contributes only little to the variation in response to noise. Thus, the effects of anthropogenic noise can be explained by the majority of species responding to noise rather than a few species being particularly sensitive to noise. Consequently, anthropogenic noise must be considered as a serious form of environmental change and pollution as it affects both aquatic and terrestrial species. Our analyses provides the quantitative evidence necessary for legislative bodies to regulate this environmental stressor more effectively.

1. Introduction

Many species are currently experiencing anthropogenically driven environmental changes, which can negatively affect the persistence of populations or species [1, 2]. One form of anthropogenically driven environmental change is the change in the acoustic environment through anthropogenic noise pollution. According to the World Health Organisation, noise is one of the most hazardous forms of pollution and has become omnipresent in aquatic and terrestrial ecosystems [3]. Historically, noise has been viewed as a major problem for humans, because it can lead to a wide range of health issues [3].

Only relatively recently has it been realized that noise may also affect wildlife, which led to a number of excellent experimental studies (reviewed in e.g. [4-6]). For example, noise may affect communication, distribution, foraging, or homeostasis of organisms. However, such single studies cannot provide holistic quantitative assessments on the potential effects of noise across species. Consequently, only a formal empirical quantification, providing global estimates will allow us to get a holistic understanding of the effects of noise. Understanding the global effects of human-induced environmental changes such as noise is crucial, because it allows directed conservation efforts. At the same time these estimates provide a window into how evolutionary ecology contributes to the susceptibility of species to human-induced environmental changes.

Meta-analyses provide such global estimates, enabling us to quantify the effects of anthropogenic noise on wildlife. Therefore, we conducted a phylogenetically controlled meta-analysis on the effects of noise on more than 100 species, including amphibians, arthropods, birds, fish, mammals, molluscs, and reptilians. As only carefully controlled experimental manipulations allow establishing cause and effect relationships [7], we focused on experimental studies to assess the effects of noise without ambiguity. We extracted 487 effect sizes from 108 experimental studies of 109 species. Effect sizes were calculated from response variables that span from genes to ecosystems (for the specific response variables see table S1). Specifically, we tested whether anthropogenic noise causes significant responses across taxonomic groups. Furthermore, we also tested whether species within taxonomic groups vary in their responses to noise.

2. Methods

Here we provide a short description of our methodological approach, a detailed description can be found in the electronic supplementary material. We conducted a systematic literature search in Scopus and Web of Science, searching for studies that reported effects of noise pollution. To be included in our meta-analysis the studies had to fulfil four criteria: (i) effect sizes must be obtained from noise exposure experiments, (ii) the reported details on sample size, measure of central tendency and spread had to be accessible in the text or figures, (iii) the type of stimuli used in noise exposure experiments had to mimic the characteristics of anthropogenic noise, and (iv) the response to the treatment had to be unambiguously elicited by anthropogenic noise (for details see electronic supplementary material).

Meta-analysis usually summarises the effects of an experimental treatment on a single response variable [8], which not only allows to test whether there is an effect, but also to quantify the direction of an effect. However, the current state of the anthropogenic noise literature does not permit such detailed analysis [4].The main reason being that different studies use a plethora of different response variables, i.e. not enough effect sizes of single response variables are available (table S1). These different response variables differ in the direction of the scale, i.e. some response variables increase with noise whilst other decrease.

Therefore, when analysing the global effect of noise in one analysis we have to ensure that all the scales point in the same direction [9]. We used the standardized mean difference, because it standardizes the response variables to a uniform scale [9] and it is also considered a good fit for experimental studies [10]. However, the standardized mean difference approach does not correct for differences in the direction of response variables [9], and thus to ensure that all response variables point in the same direction we used the absolute values [9].

All statistical analyses were performed in R version 3.5.2 [11] and R studio 1.1.463. To control for phylogeny, we created a phylogenetic tree of species using the Open Tree of Life [12]. Meta-models were built using the rma.mv function in the package METAFOR [13]. We used the option “standardized mean effect difference with heteroscedastic population variances in two groups (SMDH)” [13-15]. To test whether noise elicits a significant response we first ran an overall model on 464 effect sizes. This model allows us to test whether noise has an effect across all taxonomic groups (amphibians, arthropods, birds, fish, mammals, molluscs, reptiles) and how much phylogeny contributes to the inconsistency in effect sizes in our data (see below). To analyse whether species within taxonomic groups differ in their response to noise we ran a model for each taxonomic group separately.

Meta-analysis also allows us to quantify heterogeneity I^2_{total}, which can be interpreted as an indicator of inconsistency in effect sizes among studies [16, 17]. In ecology and evolution, this inconsistency is often caused by differences among effect sizes, studies, and/ or species investigated. High values of I^2 would suggest that there may be differences in responses to noise, which can have ecologically important implications [18]. Multi-level meta-analytic models allow~~s~~ us to quantify single partitions of I^2_{total} among random effects [19]. These partitions identify the extent to which inconsistencies among effect sizes are attributable to particular sources of variance (e.g. effect size, study, species). Here, $I^2_{\text{effect size}}$ reflects inconsistencies in within-study variation, I^2_{study} reflects inconsistencies among studies, $I^2_{\text{phylogeny}}$ inconsistencies due to phylogenetic relatedness, I^2_{species} inconsistencies due to differences among species, and I^2_{total} is the sum of these values combined.

Our analysis comprised two sections: Firstly, to test whether noise elicits a significant response we ran an overall model, including taxonomic group as a moderator and study, effect size, and phylogeny as random factors. This model allows us to test whether noise has an effect, whether there is a difference in response to noise among taxonomic groups and how much the phylogenetic information contributes to the inconsistency in our data. Secondly, we ran separate analyses for several taxonomic groups, including study, effect size, and species as random factors. We could not include phylogeny in the second analyses because the number of species within some taxonomic groups was too small. Therefore, in contrast to the first analysis where we report $I^2_{\text{phylogeny}}$, we report I^2_{species} in the second analysis instead. For analysis of publication and time-lag bias see supplementary material.

3. Results

We found that anthropogenic noise causes significant responses but taxonomic groups did not differ in their response to noise (table 1a). When analysing each taxonomic group separately, we found that each group showed a significant response to noise (figure 1, table 1b). In both the overall model and in the separate models for each taxonomic group, heterogeneities I^2_{total} stem mostly from inconsistencies among effect sizes ($I^2_{\text{effect size}}$) and studies (I^2_{study}) (table 1, figure 2). We found no evidence for publication bias nor time-lag bias (for details see electronic supplementary material).

4. Discussion

We found clear evidence that anthropogenic noise affects a wide range of species from a variety of different taxonomic groups. The overall model revealed that noise causes significant responses, but taxonomic groups did not differ in their response to noise. In all models, phylogeny contributed only little to the inconsistencies among effect sizes, as $I^2_{\text{phylogeny}}$ and I^2_{species} contributed little to the total heterogeneity (I^2_{total}). Thus, the significant response to noise can be explained by most species responding to noise rather than a few species being particularly sensitive to noise.

Although we found a statistically significant effect of noise in each analysis, it is likely that we underestimate the effect of noise. Usually, studies looking at responses to noise not only report the results of statistically significant variables, but also report a suit of statistically non-significant variables as well. In a meta-analysis that includes all response variables in one single analysis, this leads to SMDs values that are closer to 0 and thus underestimating the effect of noise. Therefore, it is very likely that the real effects of noise exceed those effects shown in our models.

It is important to note that our analysis quantifies whether there is an effect of noise, but it does not imply that all changes caused by anthropogenic noise have to be biologically negative per se. Whether an effect may be negative or positive in a biological sense may depend on the species or a given context, and such complexities cannot be unravelled in such a large scale analysis. For example, anthropogenic noise decreases hunting efficiency of bats [20]. Thus, increasing noise levels affect the predator negatively, which in turn may be associated with a reduced predation pressure on potential prey, i.e. potential prey may benefit indirectly from anthropogenic noise. Therefore, to quantify the direction of effects more data from standardised noise exposure experiments measuring the same response variables are needed. This will allow a more fine-scaled analysis of the potential effects of noise between species.

From an evolutionary point of view, we would expect that taxonomic groups differ in their response to a novel selection pressure such as noise, because groups differ in many traits. However, neither did taxonomic groups differ in the overall model nor did the partitions of phylogeny ($I^2_{\mathrm{phylogeny}}$ or $I^2_{species}$) suggest that species show much inconsistency in response to noise. Thus, responses to noise are found across a wide range of species, which is particularly notable as our sample spans a wide range of taxonomic groups. More comparative studies across species focusing on the same response variables and the same experimental protocol are needed to unravel the underlying mechanisms of responses to noise.

What is the evolutionary underlying mechanism of these responses to anthropogenic noise? Adjustments to changing environmental conditions can occur either through phenotypic plasticity or microevolutionary response to natural selection [21]. Phenotypic plasticity allows individuals to adjust immediately to changes in the environment, whereas microevolutionary responses result from selection [22]. Until now, most of the phenotypic changes observed in response to other human induced environmental changes are found to be based on phenotypic plasticity [23]. The fact that our effect sizes stem from short-term experimental noise exposures, makes phenotypic plasticity currently the most parsimonious explanation for the observed changes to anthropogenic noise.

In conclusion, we show that anthropogenic noise affects species of all taxonomic groups. Therefore, our study provides the first comprehensive quantitative empirical evidence that noise affects many aquatic and terrestrial species. Since we included exclusively effect sizes obtained from experimental studies there is little ambiguity about the effects of anthropogenic noise. These clear-cut effects of noise are particularly important from a conservation point of view, because it shows that noise affects not only a few species that we need to pay attention to but many species that inhabit very different ecosystems. Thus, to fully understand how noise affects ecosystems and species living therein also potential interactions between noise and both abiotic and biotic factors have to be considered. Ecosystems differ in a variety of key traits such as their structural complexity and/or vegetation. For example, in terrestrial ecosystems the effects of noise might be mitigated depending on attenuation of noise caused by vegetation whereas pelagic zones of aquatic systems may have less capacity to attenuate noise. Furthermore, these effects are likely to be amplified because human induced environmental changes often occur in concert rather than in isolation [24].

Our results show that anthropogenic noise must be considered as a serious form of environmental change and pollution. Although data availability does not allow to account for the direction of effects in a holistic meta-analysis yet, i.e. whether noise has a positive or a negative biological effect, we show that anthropogenic noise causes change; such changes among a wide group of species indicate *per se* that noise affects wildlife. Our results give legislative bodies the much needed empirical evidence to develop a robust legal framework to protect species from increasing anthropogenic noise effectively.

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Figure 1. Effects of anthropogenic noise on taxonomic groups. Shown are the standardized mean differences (SMDH) and 95% confidence intervals from random-effects models. The dashed line at zero indicates no effect of anthropogenic noise; an effect of noise occurs if the 95% confidence interval of the SMDH does not overlap zero (for forest plots of each species see figure S2; for sample sizes of effect sizes, studies, and species see table 1b).

Figure 2. Heterogeneities (I^2) calculated from phylogenetically controlled meta-analyses for the overall model (top bar) and six separate models for the taxonomic groups. Black bars denote $I^2_{\text{efffect size}}$, reflecting inconsistencies within study variation. Grey bars denote I^2_{study}, reflecting inconsistencies among studies. White bars reflects in the top bar $I^2_{\text{phylogeny}}$ and in the bars below I^2_{species}. $I^2_{\text{phylogeny}}$ are inconsistencies due to phylogenetic relatedness and I^2_{species} are inconsistencies due to differences among species. All graphs combined within each analysis is I^2_{total}.

Table 1. Effect of anthropogenic noise on wildlife. (a) Effect of noise on taxonomic groups. (b) Effect of noise on species of a taxonomic group. Estimates and 95% confidence intervals (CI) calculated from a phylogenetically controlled meta-analysis. All effect sizes (ES) are derived from experimental noise exposure studies.

Insert Table here

Note: For the overall model out of the 108 studies the species of six studies had to be excluded, because the Open Tree of Life did not return the phylogenetic information. For the individual taxonomic group analyses the sum of studies is 107 as the reptiles have not been analysed separately, because the effect sizes were obtained from only one study (for details see electronic supplementary material).

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