Response of Freshwater Zooplankton Communities to Chronic Anthropogenic Noise

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Abstract

Man-made sounds are now recognized as a pervasive pollutant, and impacts on wildlife have been researched for many years. However, less knowledge is available on certain species, particularly small freshwater invertebrates, which are abundant, highly diversified, and occupy key positions in food webs. Also, it is not clear whether the responses to noise observed at the level of individuals have consequences on communities. A mesocosm investigation was performed to assess the response of a freshwater planktonic community to chronic motorboat noise. Noise was expected to disturb trophic links within the community and particularly the consumption of cladocerans by dipteran larvae. To test this hypothesis, the functional response of *Chaoborus* larvae feeding on *Daphnia* was derived, and their behavior during the foraging process was recorded in microcosms (aquariums). Although noise did not induce obvious alteration in the community composition, a significant increase in the abundance of cladocerans was found that was not supported by the results of the microcosm investigation, showing no difference in *Chaoborus* functional response or behavior between the noisy and noiseless conditions. The results of this chapter suggest that the composition of freshwater zooplankton and particularly cladocerans is likely to be altered by chronic noise, with further investigations needed to understand the mechanisms. They also illustrate how scaling up the effects of noise from individual responses to community remains difficult.

Keywords

Freshwater zooplankton · Motorboat noise · Functional response · Trophic links · Daphnids · *Chaoborus* larvae

Introduction

Threats to freshwaters include habitat degradation, flow modification, over-exploitation, invasive species, and disease (Dudgeon et al. 2006; Williams-Subiza and Epele 2021), and result in a decline in biodiversity at rates that exceed what is reported in most terrestrial and marine habitats (McRae et al. 2017). Anthropic pressures on freshwaters are not expected to ease given the growing human needs and also because people seek to reconnect with nature, a need reinforced by the recent crises like the Covid-19 pandemic. Managers of freshwater socio-ecological systems worry about the rise of recreational motorized activities and their associated noise emissions (Reid et al. 2019) that can disturb the various populations of users as well as wildlife.

Noise pollution has recently been categorized as an emergent threat to freshwaters (Reid et al. 2019), with motorized boats as the most widespread source of noise. Impacts of noise on fishes are well documented with physiological stress responses and alterations in communication, reproduction, mobility, foraging, and predator

avoidance (reviewed by Mickle and Higgs 2018; Popper 2003; Slabbekoorn et al. 2010). Although invertebrates are highly diverse, widespread, and possess statocysts or external sensory hairs that allow them to perceive sounds through particle motion (Popper and Hawkins 2018), interest in their response to noise pollution came later compared to vertebrate species, and 77% of the impact studies on invertebrates are less than 10 years (Wale et al. 2021). While cephalopods, large crustaceans (crabs, lobsters, and shrimps), and bivalves are among the most common model species studied (Fernández Robledo et al. 2019; Smith et al. 2018), little is known about small zooplankton despite its pivotal role in the functioning of aquatic food webs, maintaining energy flow between primary producers and higher trophic levels (Turner 2004; Vargas et al. 2010).

Available evidence on zooplankton shows a diversity of effects. While very loud emissions from seismic surveys have been found to cause mortality in both larval and adult stages of marine zooplankton (McCauley et al. 2017), vessel noise can act as a positive cue for larval settlement in the blue mussel *Mytilus edulis* (Jolivet et al. 2016). Exposure to low (30 Hz) and high (20 KHz) frequencies seems to promote grazing in the marine copepod *Acartia tonsa* (Yiwei and Berggren 2018). The water flea *Daphnia magna* (Cladocera) shows no alteration in mobility when exposed to either continuous or intermittent 300–1500 Hz band-pass filtered white noise (Sabet et al. 2016). More recently, it was found that larvae of the phantom midge *Chaoborus* (Diptera) made more body rotations in response to motorboat noise (Rojas et al. 2021).

In addition to the imbalance between vertebrates and invertebrates in the very rich literature on the impacts of noise pollution, there is also a discrepancy between the biological integration levels with a lack of research on ecosystems compared to behavioral and physiological outcomes (Sordello et al. 2020). Although a few empirical evidences from terrestrial systems illustrate how noise-induced changes in behavior can propagate through nested ecological interactions (Francis and Barber 2013; Phillips et al. 2021), scaling up the effects of noise from individuals to populations and communities without any experimental validation might overestimate impacts.

In this chapter, the effect of chronic motorboat noise on the dynamics of a freshwater zooplankton community was investigated, bringing together cladocerans, copepods, ostracods, and dipterans. Noise was expected to alter the structure of the community through changes in abundance and/or changes in the activity of the predators. To test this hypothesis, the response of the community was evaluated in mesocosms over 6 weeks, and, as a second part, it was assessed how the *per capita* predation rate of *Chaoborus* larvae (dipterans) varied with cladoceran density (the functional response) under control and noisy conditions. *Chaoborus* larvae are a relevant dominant predator of large filter-feeder zooplankton (cladoceran species) known to be a main structuring force within the community (Castilho-Noll and Arcifa 2007; Vanni and Findlay 1990). *Chaoborus* larvae have been found to make more body rotations in response to motorboat noise (Rojas et al. 2021), which could be associated with reduced foraging. Noise might therefore alter community dynamics through the modulation of the trophic pressure by *Chaoborus* larvae.

Materials and Methods

Mesocosm Experimental Design

The mesocosm experiment lasted 6 weeks from September to October 2021 and was carried out on the PLANAQUA platform of the CEREEP-Ecotron Ile-de-France research station (48° 16′10.92 N, 2° 43′50.879 E, Seine et Marne, France). Two acoustic conditions (with or without boat noise, see section "Playback Tracks") were applied in 16 outdoor plastic enclosures (diameter: 1.40 m, depth: 1 m, volume: 1 m^3, n = 8 replicates *per* condition) positioned in two lines and distributed in a systematic way to balance the effect of spatial distribution between the two conditions. All mesocosms included a 15-cm layer of Loire sand and were filled 2 months before the experiment with water from the littoral zone of one of the two storage lakes from the PLANAQUA platform, to reach a 70-cm water column. An underwater loudspeaker (Electrovoice UW30, 0.1–10 kHz) was fixed 10 cm below the water surface in the middle of each mesocosm. It was connected to an amplifier (Dynavox CS-PA 1MK), itself connected to an audio player (Handy's H4n zoom), both placed inside a waterproof electric box next to the mesocosm. One week before starting the experiment, temperature loggers attached to a ballast were positioned in the sunniest part of each mesocosm. The water temperature was 24 °C at the beginning of the experiment and decreased with some small fluctuations over time to reach 18 °C at the end of the experiment.

Zooplankton Dynamics

At day 0, +10, +26, and +42, 8 L of water were sampled with a 2-L sampling bottle at four different positions and depths in each mesocosm. Water was filtered with a 50-μm mesh size nylon filter to collect zooplankton species, which were immediately fixed in 15 mL of 90% ethanol. Species identification and classification on day 0 and day +42 were performed by the engineering office © 2021 SAGE Environment (Annecy, France). To save costs, accurate classification was done for all the mesocosms at day +42, while the data *per* noise condition at day 0 was pooled. At day +10 and day +26, only the numbers of cladocerans and *Chaoborus flavicans* larvae were quantified, as they were the most structuring trophic links expected in the communities. At the end of the experiment, a multiparameter probe (YSI ExO-2) was used to assess the main physicochemical parameters (temperature, pH, conductivity, turbidity, and chlorophyll).

Functional Response and Behavior of *Chaoborus* Larvae

The functional response (FR) of *Chaoborus* larvae feeding on five densities (3, 6, 12, 24, and 48) of *Daphnia* sp. coming from the storage lake has been derived with four replicates *per* density and *per* noise condition. To account for potential

habituation to the noise condition and better explain what happened in the mesocosms, larvae from the control and noisy mesocosms were collected and exposed to the same noise condition (see section "Playback Tracks") during the FR tests. The experiment took place in two 90-L rectangular tank (75 × 60 × 20 cm, one *per* noise condition) filled with filtered (50-μm mesh size) water from the storage lake. A UW30 underwater loudspeaker was positioned in the center of each tank 20 cm above the bottom. A single larva was presented to the water fleas at one of the five densities (3–48) for 8 h in a 150-mL glass beaker (height = 7.2 cm, diameter = 7 cm) covered with a 0.03 mm mesh allowing water flow only. A total of 20 beakers *per* mesocosm were used and placed at 10 cm all around the loudspeaker. At the end of the experiment, each larva was removed and put into 90 °C alcohol to be measured under a binocular loop and using a rule. The number of remaining prey was counted to determine the number of prey eaten.

The behavior of the *Chaoborus* larvae was studied in a 50-L aquarium (length×width×height: 60 × 25 × 35 cm) filled with filtered water from the mesocosms and equipped with an UW30 underwater loudspeaker in the center and 20 cm above the bottom. A 150-mL glass beaker containing 20 larvae and covered with a mesh allowing water flow only was positioned inside the aquarium at 10 cm of the loudspeaker. The number of body rotations performed by each larva was counted over a 20-min period of ambient noise (recorded in one of the mesocosm) or ambient noise supplemented with motorboat noise (see section "Playback Tracks").

Playback Tracks

An Aquarian Audio H2A-XLR hydrophone (frequency response from 10 Hz to 100 kHz) connected to a ZOOM H4next Handy recorder was used for all the recordings and a UW30 underwater loudspeaker (Electrovoice) connected to a Dynavox CS-PA 1MK amplifier itself connected to a ZOOM H4next Handy player for all the playbacks.

Natural background noise did not differ between the mesocosms and was around 90 dB re 1 μPa. In the control mesocosms, a 1-h audio track of silence was looped continuously. To make the audio tracks of the noisy mesocosms, 25 sounds from commercial vessels and recreational boats were recorded from the river Seine after the lock of Champagne sur Seine (48°22′1.348 N, 2°29′37.401 E) at 1 m depth. The 25 original sounds were duplicated, changing a bit the intensity between the two replicates, and the resulting 50 sounds were distributed over 14 consecutive 1-h audio tracks of silence so as to mimic the mean daily activity of the Champagne sur Seine lock (Table 1). The boat sound audio tracks were broadcasted from 6 a.m. to 8 p.m. and silence the rest of the time. The intensity of each boat sound was modified with the Audacity 2.2.1 software to obtain realistic signal-to-noise ratios (SNR) ranging from 25 to 30 dB (Fig. 1a), calculated after re-recordings in the mesocosms and using the *SNR* function of *Seewave* R package (Sueur et al. 2008) with:

Table 1 Composition of the 14-h playback track broadcasting silence supplemented with motorboat sounds during the mesocosm experiment

Hour	Number of boat sounds	Boat ID	Duration in min	Start position in the 1-h track
6 h	3	17	07′00	5′00″
		31	05′35	47′00″
		45	06′10	51′00″
7 h	1	29	06′00	23′50″
8 h	2	44	04′20	13′50″
		20	01′25	40′30″
9 h	4	8	01′40	0′00″
		46	07′15	14′30″
		47	03′02	32′25″
		2	04′37	36′15″
10 h	6	11	06′05	2′55″
		10	02′20	13′35″
		42	02′30	16′25″
		50	03′30	19′30″
		41	02′00	18′40″
		33	02′35	54′10″
11 h	4	48	03′02	16′45″
		42	02′30	33′15″
		30	05′00	35′50″
		30	05′00	53′05″
12 h	2	2	04′37	8′25″
		27	07′00	18′45″
13 h	4	6	05′00	01′45″
		38	04′00	17′40″
		50	03′30	22′00″
		46	07′15	40′50″
14 h	6	40	04′15	01′45″
		17	02′00	05′30″
		24	03′02	07′45″
		20	01′25	29′15″
		25	06′30	35′10″
		10	02′20	42′05″
15 h	8	42	02′30	00′35″
		15	01′30	07′00″
		50	03′30	03′35″
		2	04′37	14′21″
		9	02′35	21′54″
		12	08′00	26′45″
		12	08′00	44′16″
		18	05′05	54′55″
16 h	4	20	01′25	00′00″
		44	04′00	06′05″
		23	07′15	20′52″
		35	06′05	32′19″
17 h	2	45	06′10	39′17″
		46	07′15	46′22″
18 h	1	13	03′30	27′07″

(continued)

Table 1 (continued)

Hour	Number of boat sounds	Boat ID	Duration in min	Start position in the 1-h track
19 h	3	31	05′35	24′03″
		30	05′00	30′43″
		42	02′30	49′29″

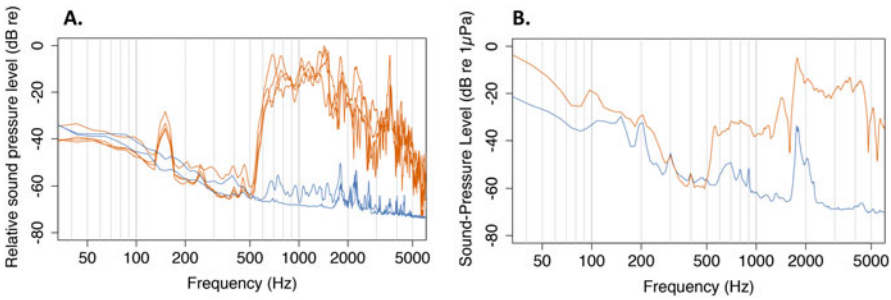

Fig. 1 Sound spectra of the two noise conditions (ambient noise in blue and boat noise in red) in: (**a**) the mesocosms used for the community investigation (each orange line corresponds to a recording of the same boat noise made in four noisy mesocosms and each blue line corresponds to a recording of 3 min of ambient noise made in two control mesocosms) and (**b**) the aquariums (50-L rectangular tanks) used for functional response derivation

$$\mathrm{SNR} = 20 \log_{10}(\mathrm{RMS}_{\text{boat sound}}/\mathrm{RMS}_{\text{ambient noise}})$$

where RMS corresponds to the root-mean-square sound pressure level.

For the control condition of the FR experiment, an 8-h (playlist 1) audio track of natural background noise previously recorded in one of the mesocosm and whose level was adjusted to match that in the mesocosm around 90 dB re 1 μPa (Fig. 1a) was broadcasted. For the boat noise treatment, an 8-h recording (playlist 2) from a noisy mesocosm (Fig. 1a) was broadcasted using the same process than for control condition.

Concerning the behavior of the *Chaoborus* larvae, a 20-min period of playlist 1 was randomly selected to be used for the control condition and a 20-min sequence of playlist 2 corresponding to the period with the largest number of boat sounds was used for the noisy condition (Fig. 1b).

Data Analyses

The R software version 4.0.3 (R Core Team 2018) was used for all the statistics with a significance level of 5%. A chi-square test of independence was performed to assess the homogeneity of taxa at day +0 between both noise treatments. A generalized linear mixed models with a quasi-Poisson distribution (GLMMTMB) was performed to explain the dynamic of cladocerans as a function of three fixed factors and their interactions: the noise condition (ambient or motorboat noise), the

abundance of *Chaoborus flavicans* larvae, the sampling date, and considering the tank identity as random factor to account for repetitive measures. A quasi-Poisson (or quasi-likelihood) distribution was used because it is recommended to consider the overdispersion (variance exceeding the mean) often found in count data (Ver Hoef and Boveng 2007). A Wilcoxon test was used to test for significance the difference in physiochemical parameters between the two noise conditions at day +42.

For the FR experiment, a one-way ANOVA test was performed to detect heterogeneity in the size of *Chaoborus* larvae between the two noise conditions as the data met the normality and homoscedasticity assumptions. FR analysis was done with the *Frair* R package (Pritchard et al. 2017). The three main categorical FR types (linear type I, Rogers' type II, and Hassel's type III) were modeled by maximum likelihood estimation (Bolker 2008) with the *frair_fit* function, and the fits were compared using the second-order Akaike information criterion (AIC). This allowed to exclude the types II and III whose AIC values were always the highest (ΔAIC >2 with the type I). A type I FR is characterized by a linear increase of consumption rate as a function of prey density (Holling 1959). Both FRs being of type I, the delta method implemented by the *frair_compare* function was used to perform pairwise FR comparison from parameter estimates with the null hypothesis that the difference in attack rates (D*a*) between the two FRs does not differ from zero (Pritchard et al. 2017). In addition, the overlaps of the 95% confidence intervals (BCa CIs) which correct for bias and skewness in the distribution of bootstrap estimates (*a* and *h* parameters) were inspected using the *frair_boots* function (bootstrapping method, n = 2000) (Pritchard et al. 2017).

Concerning the behavior of the *Chaoborus* larvae, the total number of body rotations was compared between the two noise conditions using a generalized linear mixed model with a negative binomial distribution with the noise condition (ambient or motorboat noise), the sampling date as predictors, and the tank where they came as a random factor to account for repetitive measures.

Results

At day +0, communities between ambient noise and ambient + motorboat noise did not differ in taxa density (chi-square test = 63.333, df = 56, p-value = 0.2336). At day +42, no significant differences in the physicochemical parameters between the two noise conditions (Tables 2 and 3) were found.

The zooplankton communities of the noisy and noiseless mesocosms included cladocerans (*Daphnia* sp., *Bosmina* sp., *Chydorus* sp., and *Ceriodaphnia* sp.), copepods (especially Calanoïda and Cyclopoïda), ostracods, and dipterans (especially *Chaoborus* larvae). Cladocerans species and more particularly *Daphnia* sp. were the most abundant at the beginning and at the end of the experiment in the control mesocosms (57.31% and on average 52.11%, respectively), whereas in

Table 2 Physicochemical parameters (mean ± SD) in the control (ambient noise) and noisy mesocosms (boat noise) at the end of the experiment, with the results of the Wilcoxon tests performed to test the difference between the two noise treatments

Parameters	Ambient noise (mean ± SD)	Boat noise (mean ± SD)	W	p-value
pH	7.60 ± 0.59	7.70 ± 0.37	266.5	0.665
Temperature °C	15.66 ± 0.08	15.66 ± 0.13	257.5	0.536
[Chlorophyll] µg/L	1.49 ± 0.87	1.71 ± 1.68	331	0.38
ODO mg/L	9.64 ± 0.32	9.62 ± 0.33	277.5	0.836
Conductivity uS/cm	165.32 ± 8.11	167.66 ± 5.74	212.5	0.121

the noisy mesocosms, copepods and cladocerans were more abundant at day +0 (48.25% and 39.84% respectively) but cladocerans increased to reach 71.24% of the whole community at the end of the experiment (Table 4, Fig. 2).

The abundance of cladocerans was significantly increased by noise (p-value = 0.044, Table 5, Fig. 3a) but was not influenced by the abundance of *Chaoborus*, the date, and the interactions between predictors. The abundance of *Chaoborus* larvae did not differ between the two noise conditions (GLMMs, Estimate = 0.026, Std. Error = 0.501, z-value = 0.050, p-value = 0.960, Fig. 3b).

Concerning the FR experiment, there was no difference in the size of the *Chaoborus* larvae between the two noise conditions (one-way ANOVA: $F_{1,18}$ = 0.269, p-value = 0.61). Irrespectively of the noise condition, the FR was a type I (linear increase of *per capita* consumption rate in function of prey density). No significant difference in attack rate (fixing the slope) was found between the two noise conditions (Estimate = 0.087, Std.Error = 0.108, z-value = 0.817, p-value = 0.413) supported by a strong overlap of the 95% BCa CIs, suggesting similar FRs (Fig. 4a).

No significant difference in the number of body rotations was found between the two noise conditions (noise: Estimates = 0.2957, Std.Error = 0.4268, z-value = 0.693, p-value = 0.488, Fig. 4b). However, interindividual variability in both FR and behavior was greater with boat noise than for controls.

Discussion

In this chapter, a mesocosm investigation was conducted to assess the effect of chronic motorboat noise on the dynamics of freshwater zooplankton. Predation tests were also performed in microcosms through the functional response (FR) derivation to test the prediction that in case of a noise-induced alteration in community dynamics, this would be linked with a change in the foraging behavior of invertebrate predators, focusing on *Chaoborus flavicans* as the main predator within the zooplanktonic community.

No marked effect of chronic motorboat noise on the zooplankton community was found except for water fleas (*Daphnia* sp.), which represented the most abundant

Table 3 Physicochemical parameters obtained at Day+0 and at Day+42 for all outdoor mesocosm

Tank	Noise condition	Temperature (°C)	pH	Conductivity (μs/cm)	Green algae (μg/L)	Cyanobacteria (μg/L)	Diatoms (μg/L)	Chlorophyll concentration (μg/L)	Turbidity (FNU)
1	Ambient	15.57	9.2	159.33	6.14	2.02	0.48	0.85	1.44
2	Boat	15.79	9.71	180.33	6.81	0	0.33	0.75	0.97
3	Ambient	15.68	9.76	172.9	7.55	0.92	0.3	0.88	1.15
4	Boat	15.73	9.55	165.63	7.58	1.65	0.87	0.45	1.1
5	Ambient	15.69	9.56	165.87	7.69	0.22	0.34	1.17	1.36
6	Boat	15.62	9.22	171.4	7.73	0.62	0.18	0.87	1.32
7	Ambient	15.71	9.37	181.07	7.76	0.25	0.24	1.05	1.18
8	Boat	15.59	9.96	166.23	7.95	1.08	0.43	0.96	0.99
9	Boat	15.39	9.86	161.8	7.91	6.21	0	5	6.04
10	Ambient	15.72	9.37	154.33	7.82	3.88	0.37	3.65	3.65
11	Boat	15.77	9.43	161.7	7.8	1.13	0.41	0.98	1.14
12	Ambient	15.73	9.92	161	7.92	0.76	0.16	1.36	1.26
13	Boat	15.65	9.32	167.5	7.9	0	0.21	0.79	0.86
14	Ambient	15.63	9.72	160.97	7.89	0.07	0.14	0.97	0.93
15	Boat	15.7	9.93	166.7	7.93	0.55	0.19	0.83	1.29
16	Ambient	15.53	10.21	167.17	8.05	0.26	0.07	0.66	0.95

Table 4 Count of taxa at Day+0 and at Day+42 for all outdoor mesocosms (n = 16) in both noise conditions (ambient noise, n = 8; boat noise, n = 8)

Order	taxa	Day+0 ambient noise (total, n = 8)	Day+0 boat noise (total, n = 8)	Day+42 ambient noise (total, n = 8)	Day+42 boat noise (total, n = 8)	Day+42 ambient noise (mean ± SD per mesocosm)	Day+42 boat noise (mean per mesocosm)
Copepods	**Cyclopoïds**	79	73	177	131	22.13 ± 28.2	16.38 ± 14.86
Copepods	**Calanoïds**	158	162	162	183	20.25 ± 23.06	22.88 ± 24.47
Cladocerans	***Bosmina* sp.**	0	0	25	0	3.13 ± 8.84	0
Cladocerans	***Ceriodaphnia* sp.**	2	0	25	2	3.13 ± 8.84	0.25 ± 0.71
Cladocerans	***Chydorus* sp.**	10	5	33	53	4.13 ± 6.33	6.63 ± 9.65
Cladocerans	***Daphnia* sp.**	439	189	567	1226	70.88 ± 44.32	153.25 ± 113.55
Crustacean	**Ostracods**	76	25	74	106	9.25 ± 12.08	13.25 ± 9.84
Insect	**Ephemeroptera**	11	0	4	9	0.5 ± 1.07	1.13 ± 2.10
Insect	***Chaoborus flavicans***	7	16	11	7	1.38 ± 1.77	0.88 ± 0.83
Insect	**Hydracarina**	2	1	6	2	0.75 ± 0.89	0.25 ± 0.71

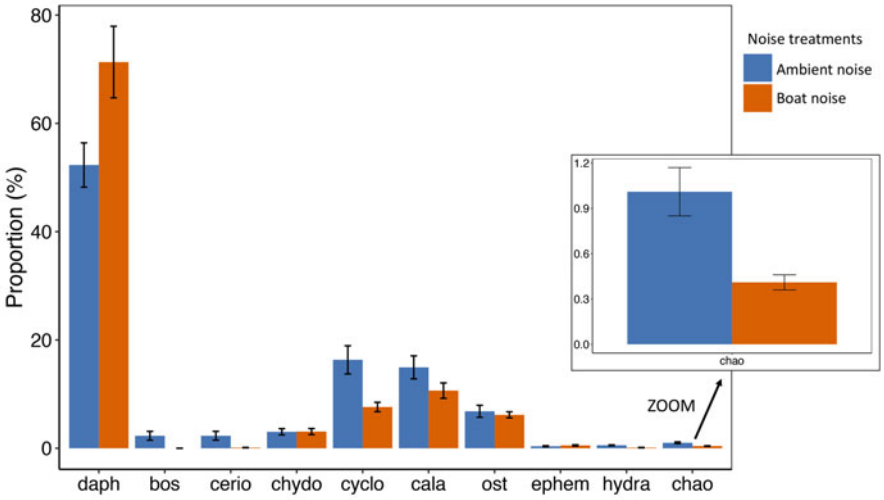

Fig. 2 Frequency distribution (mean ± SD) of the zooplankton taxa founds in the control (blue) and noisy (orange) mesocosms at the end of the experiment with a focus on *Chaoborus flavicans* larvae, the main predator (daph: *Daphnia* sp., bos: *Bosmina* sp., cerio: *Ceriodaphnia* sp., chido: *Chidorus* sp., cyclo: Cyclopoids, cala: Calanoïds, ost: Ostracods, ephem: Ephemeroptera, hydra: Hydracarina and chao: *Chaoborus* larvae (Diptera)

Table 5 Model-averaging coefficient estimates for the predictors included in the model used to explain the variation in cladoceran abundance. Predictors correspond to the noise condition broadcasted in mesocosm (silence or chronic motorboat noise), the presence of *Chaoborus* larvae, the date, and the interactions between all predictors. Significant p-values are in bold

	Estimate	Std. error	Z value	P-value
Intercept	4.35259	0.19096	22.793	**<0.001**
Noise	0.49052	0.24385	2.012	**0.0443**
Chaoborus	−0.06774	0.15784	−0.429	0.6678
Date	0.06991	0.13999	0.499	0.6175
Noise*_Chaoborus_ larvae	0.20685	0.19719	1.049	0.2942
Noise*date	0.19450	0.21705	0.896	0.3702
Chaoborus larvae*date	−0.18475	0.17620	−1.049	0.2944
Noise*_Chaoborus_ larvae*date	0.41613	0.41402	1.005	0.3148

taxon and were significantly more numerous in the noisy mesocosms. This apparent positive effect could be indirect, considering that noise has no or a very limited direct negative effect on water fleas but negatively influences their natural enemies. Although no investigation on the response of water fleas to noise was made, the absence of direct effect is partially supported by the little literature available. Sabet et al. (2016) did not find any alteration in mobility in *Daphnia magna* exposed to either continuous or intermittent 300–1500 Hz band-pass filtered white noise, a result that was also obtained working on motorboat noise (Rojas et al. unpublished

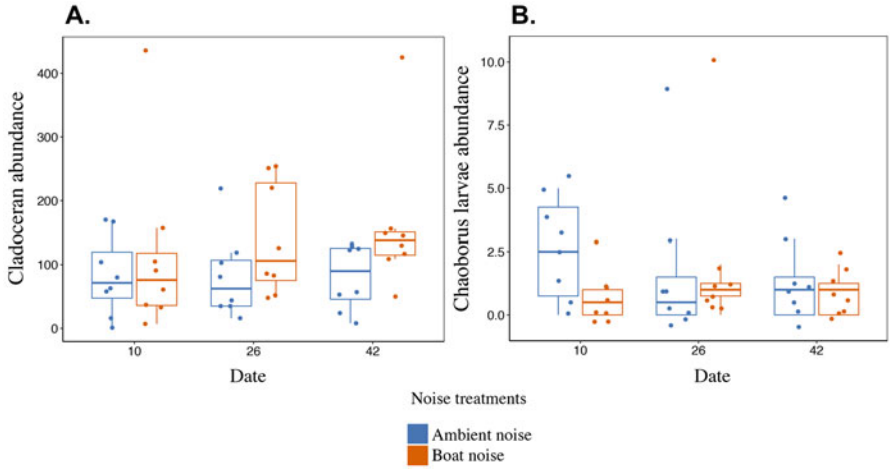

Fig. 3 Variation in the abundances (median and interquartile range) of Cladocerans (**a**) and *Chaoborus* larvae (**b**) in the control (ambient noise, blue) and noisy mesocosms (ambient noise supplemented with boat noise, orange) at days 10, 26, and 42

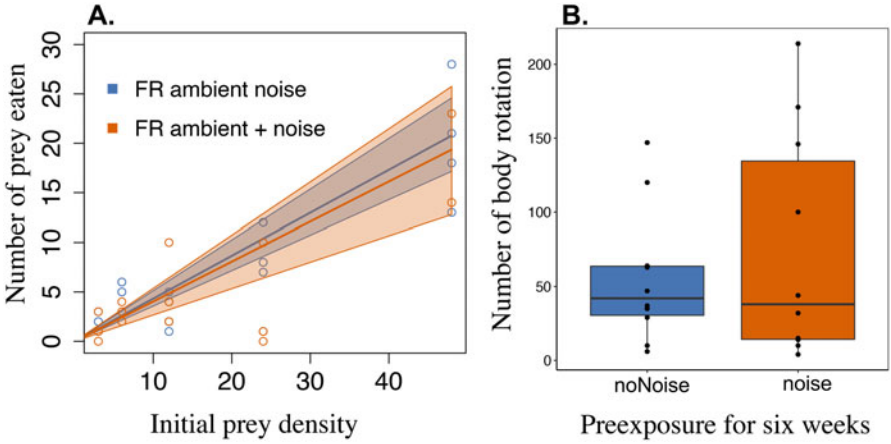

Fig. 4 (**a**) Number of water fleas eaten by single *Chaoborus* larvae as a function of initial water flea density (functional response) under ambient noise (blue) or chronic motorboat noise (red). Dots indicate the raw data and shaded areas the confidence intervals. (**b**) Number of body rotations (median and interquartile ranges) made by the *Chaoborus* larvae exposed to recordings of ambient noise (blue) or chronic motorboat noise (red)

data). More recently, Yağcılar and Yardımcı (2021) found that exposure to 432 Hz and 440 Hz frequency sounds resulted in lower egg numbers and heartbeats in *D. magna*. However, the use of pure tones that do not refer to any kind of noise pollution in nature as well as the absence of information on sound levels make these

results difficult to compare with the results of this chapter and also difficult to extrapolate to natural populations.

Concerning water fleas' natural enemies, it was reasonable to expect from the FR results that water fleas had experienced predation by *Chaoborus* larvae in the mesocosms. However, contrary to this assumption, noise did not alter the FR of *Chaoborus* larvae nor their behavior assessed through the number of body rotations. The main difference between this chapter and the study by Rojas et al. (2021), where *Chaoborus* larvae displayed more body rotations with motorboat noise, is that this study accounted for repeated exposure (i.e., chronic noise), what Rojas et al. (2021) did not. So, it might be that *Chaoborus* larvae show more body rotations when exposed to noise for the first time and then resume normal behavior with repeated exposure, a phenomenon also referred to as "habituation" that has not been addressed in the present chapter as the response of "naïve" larvae was not tested. Habituation to noise has been reported in many species including fishes (Johansson et al. 2016; Kusku 2020; Rojas et al. 2021) and aquatic invertebrates (Hubert et al. 2022), and could result from sensory or motor fatigue, or associative learning between the repetition of a given stimulus and the absence of any threat.

Similar FRs irrespectively of the noise condition does not support the hypothesis that the water fleas of the noisy mesocosms benefited from a noise-induced reduction in *Chaoborus* predation. Surprisingly, the FR of *Chaoborus* larvae was of type I (linear increase of *per capita* predation rate with increasing prey density), while they were found to display a type-II FR (decelerating rise to an asymptote) in previous studies (Cuthbert et al. 2019; Krylov 1992; Spitze 1992; with *Daphnia pulex*, *D. longispina*, and *Culex pipiens* as prey, respectively). Regarding the *Chaoborus* and *Daphnia* populations used in this chapter, the highest prey density used ($n = 48$) was not enough to reach saturation, and it is not possible to exclude an effect of noise at higher prey densities. Another reason why it was difficult to use the behavior of the *Chaoborus* larvae to explain the increase in cladocerans in the noisy mesocosms could be that predation tests in small and highly controlled experiment units are not representative of the foraging patterns occurring in more complex systems (i.e., the mesocosms used in this chapter). For instance, many zooplanktonic species including *Chaoborus* larvae and *Daphnia* show vertical migrations (Dawidowicz et al. 1990; Haupt et al. 2009). Noise might disturb trophic links within zooplankton through alterations in the species-specific spatial patterns. In other words, the tests performed in aquariums might have underestimated the negative effect of noise on *Chaoborus* predation.

To understand how noise influenced the zooplanktonic communities of the mesocosms, a focus was made on the trophic link between *Chaoborus* larvae and *Daphnia*, and no work was made on the other ecological interactions, in particular competition. Cladocerans are known to compete with rotifers and copepods for common food resources (Gilbert 1988; Lehtiniemi and Gorokhova 2008), copepods being the second planktonic group (after cladocerans) in terms of abundance in the mesocosms. The response of freshwater copepods to noise remains unknown, but a negative effect could make the competition even more asymmetric in favor of cladocerans. The three groups are also engaged in apparent competition by sharing

Chaoborus larvae as predator (Elser et al. 1987; Swüste et al. 1973). An interesting perspective would be to assess their respective contribution to *Chaoborus*' diet under chronic noise.

To conclude, this chapter suggests that chronic motorboat noise is likely to disturb the composition and dynamics of freshwater zooplankton without providing evidence for any alteration in the trophic link between *Daphnia* sp. and *Chaoborus* larvae. The effects of chronic motorboat on freshwater zooplankton probably involve the modulation of ecological interactions, but this remains to be further investigated. This chapter also illustrates how scaling up individual responses obtained in highly controlled conditions to the level of communities remains tricky. Additional research on the long-term effect of noise on freshwater zooplankton, as well as on fish-dominated planktonic communities, is needed.

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References

Bolker BM (2008) Ecological models and data in R. Princeton University

Castilho-Noll MSM, Arcifa MS (2007) Mesocosm experiment on the impact of invertebrate predation on zooplankton of a tropical lake. Aquat Ecol 41(4):587–598. https://doi.org/10.1007/s10452-007-9112-4

Cuthbert RN, Al-Jaibachi R, Dalu T, Dick JTA, Callaghan A (2019) The influence of microplastics on trophic interaction strengths and oviposition preferences of dipterans. Sci Total Environ 651: 2420–2423. https://doi.org/10.1016/j.scitotenv.2018.10.108

Dawidowicz P, Pijanowska J, Ciechomski K (1990) Vertical migration of Chaoborus larvae is induced by the presence of fish. Limnol Oceanogr 35(7):1631–1637. https://doi.org/10.4319/lo.1990.35.7.1631

Dudgeon D, Arthington AH, Gessner MO, Kawabata Z-I, Knowler DJ, Lévêque C, Naiman RJ, Prieur-Richard A-H, Soto D, Stiassny MLJ, Sullivan CA (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. Biol Rev 81(2):163–182. https://doi.org/10.1017/S1464793105006950. Cambridge Core

Elser MM, von Ende CN, Sorrano P, Carpenter SR (1987) Chaoborus populations: response to food web manipulation and potential effects on zooplankton communities. Can J Zool 65(12): 2846–2852. https://doi.org/10.1139/z87-433

Fernández Robledo JA, Yadavalli R, Allam B, Pales Espinosa E, Gerdol M, Greco S, Stevick RJ, Gómez-Chiarri M, Zhang Y, Heil CA, Tracy AN, Bishop-Bailey D, Metzger MJ (2019) From the raw bar to the bench: bivalves as models for human health. Dev Comparat Immunol 92: 260–282. https://doi.org/10.1016/j.dci.2018.11.020

Francis CD, Barber JR (2013) A framework for understanding noise impacts on wildlife: an urgent conservation priority. Front Ecol Environ 11(6):305–313. https://doi.org/10.1890/120183

Gilbert JJ (1988) Suppression of rotifer populations by Daphnia: a review of the evidence, the mechanisms, and the effects on zooplankton community structure1. Limnol Oceanogr 33(6): 1286–1303. https://doi.org/10.4319/lo.1988.33.6.1286

Haupt F, Stockenreiter M, Baumgartner M, Boersma M, Stibor H (2009) Daphnia diel vertical migration: implications beyond zooplankton. J Plankton Res 31(5):515–524. https://doi.org/10.1093/plankt/fbp003

Holling CS (1959) The components of predation as revealed by a study of small-mammal predation of the European Pine Sawfly. Can Entomologist 91(5):293–320. https://doi.org/10.4039/Ent91293-5. Cambridge Core

Hubert J, Booms E, Witbaard R, Slabbekoorn H (2022) Responsiveness and habituation to repeated sound exposures and pulse trains in blue mussels. J Exp Mar Biol Ecol 547:151668. https://doi.org/10.1016/j.jembe.2021.151668

Johansson K, Sigray P, Backström T, Magnhagen C (2016) Stress response and habituation to motorboat noise in two coastal fish species in the Bothnian Sea. In: The effects of noise on aquatic life II, pp 513–521

Jolivet A, Tremblay R, Olivier F, Gervaise C, Sonier R, Genard B, Chauvaud L (2016) Validation of trophic and anthropic underwater noise as settlement trigger in blue mussels. Sci Rep 6(1):1–8

Krylov PI (1992) Density-dependent predation of Chaoborus flavicans on Daphnia longispina in a small lake: the effect of prey size. Hydrobiologia 239(3):131–140

Kusku H (2020) Acoustic sound–induced stress response of Nile tilapia (Oreochromis niloticus) to long-term underwater sound transmissions of urban and shipping noises. Environ Sci Pollut Res 27(29):36857–36864

Lehtiniemi M, Gorokhova E (2008) Predation of the introduced cladoceran Cercopagis pengoi on the native copepod Eurytemora affinis in the northern Baltic Sea. Mar Ecol Prog Ser 362: 193–200

McCauley RD, Day RD, Swadling KM, Fitzgibbon QP, Watson RA, Semmens JM (2017) Widely used marine seismic survey air gun operations negatively impact zooplankton. Nat Ecol Evol 1(7):1–8

McRae L, Deinet S, Freeman R (2017) The diversity-weighted living planet index: controlling for taxonomic bias in a global biodiversity indicator. PLoS One 12(1):e0169156. https://doi.org/10.1371/journal.pone.0169156

Mickle MF, Higgs DM (2018) Integrating techniques: a review of the effects of anthropogenic noise on freshwater fish. Can J Fish Aquat Sci 75(9):1534–1541. https://doi.org/10.1139/cjfas-2017-0245

Phillips JN, Termondt SE, Francis CD (2021) Long-term noise pollution affects seedling recruitment and community composition, with negative effects persisting after removal. Proc R Soc B Biol Sci 288(1948):20202906. https://doi.org/10.1098/rspb.2020.2906

Popper AN (2003) Effects of anthropogenic sounds on fishes. Fisheries 28(10):24–31. https://doi.org/10.1577/1548-8446(2003)28[24:EOASOF]2.0.CO;2

Popper AN, Hawkins AD (2018) The importance of particle motion to fishes and invertebrates. J Acoust Soc Am 143(1):470–488. https://doi.org/10.1121/1.5021594

Pritchard DW, Paterson RA, Bovy HC, Barrios-O'Neill D (2017) FRAIR: an R package for fitting and comparing consumer functional responses. Methods Ecol Evol 8(11):1528–1534. https://doi.org/10.1111/2041-210X.12784

R Core Team (2018) R: A language and environment for statistical computing. R Foundation for Statistical Computing. https://www.R-proje ct.org/

Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PTJ, Kidd KA, MacCormack TJ, Olden JD, Ormerod SJ, Smol JP, Taylor WW, Tockner K, Vermaire JC, Dudgeon D, Cooke SJ (2019) Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol Rev 94(3):849–873. https://doi.org/10.1111/brv.12480

Rojas E, Thévenin S, Montes G, Boyer N, Médoc V (2021) From distraction to habituation: ecological and behavioural responses of invasive fish to anthropogenic noise. Freshw Biol 66(8):1606–1618. https://doi.org/10.1111/fwb.13778

Sabet SS, Van Dooren D, Slabbekoorn H (2016) Son et lumière: Sound and light effects on spatial distribution and swimming behavior in captive zebrafish. Environ Pollut 212:480–488. https://doi.org/10.1016/j.envpol.2016.02.046

Slabbekoorn H, Bouton N, van Opzeeland I, Coers A, ten Cate C, Popper AN (2010) A noisy spring: the impact of globally rising underwater sound levels on fish. Trends Ecol Evol 25(7): 419–427

Smith CS, Ito M, Namba M, Nakaoka M (2018) Oyster aquaculture impacts Zostera marina epibiont community composition in Akkeshi-ko estuary, Japan. PLoS One 13(5):e0197753. https://doi.org/10.1371/journal.pone.0197753

Sordello R, Ratel O, Flamerie De Lachapelle F, Leger C, Dambry A, Vanpeene S (2020) Evidence of the impact of noise pollution on biodiversity: a systematic map. Environ Evid 9(1):20. https://doi.org/10.1186/s13750-020-00202-y

Spitze K (1992) Predator-mediated plasticity of prey life history and morphology: Chaoborus americanus Predation on Daphnia pulex. Am Nat 139(2):229–247. https://doi.org/10.1086/285325

Sueur J, Aubin T, Simonis C (2008) SEEWAVE, A free modular tool for sound analysis and synthesis. Bioacoustics 18(2):213–226. https://doi.org/10.1080/09524622.2008.9753600

Swüste HFJ, Cremer R, Parma S (1973) Selective predation by larvae of *Chaoborus flavicans* (Diptera, Chaoboridae): with 4 tables in the text. SIL Proc, 1922–2010 18(3):1559–1563. https://doi.org/10.1080/03680770.1973.11899643

Turner J (2004) The importance of small planktonic copepods and their roles in pelagic marine food webs. Zool Stud 43:255–266

Vanni MJ, Findlay DL (1990) Trophic cascades and phytoplankton community structure. Ecology 71(3):921–937. https://doi.org/10.2307/1937363

Vargas CA, Martínez RA, Escribano R, Lagos NA (2010) Seasonal relative influence of food quantity, quality, and feeding behaviour on zooplankton growth regulation in coastal food webs. J Mar Biol Assoc U K 90(6):1189–1201. https://doi.org/10.1017/S0025315409990804. Cambridge Core

Ver Hoef JM, Boveng PL (2007) Quasi-poisson vs. negative binomial regression: how should we model overdispersed count data? Ecology 88(11):2766–2772. https://doi.org/10.1890/07-0043.1

Wale MA, Briers RA, Diele K (2021) Marine invertebrate anthropogenic noise research–trends in methods and future directions. Mar Pollut Bull 173:112958

Williams-Subiza EA, Epele LB (2021) Drivers of biodiversity loss in freshwater environments: a bibliometric analysis of the recent literature. Aquat Conserv Mar Freshwat Ecosyst 31(9): 2469–2480. https://doi.org/10.1002/aqc.3627

Yağcılar Ç, Yardımcı M (2021) Effects of 432 Hz and 440 Hz sound frequencies on the heart rate, egg number and survival parameters in water flea (Daphnia magna). J Ecol Eng 22(4)

Yiwei J, Berggren F (2018) Effects of anthropogenic noise pollution on herbivorous grazing