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Exposure to anthropogenic noise affects feeding but not territory defence in damselfishes

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Anthropogenic noise is a recognized global pollutant with well-documented effects on the behaviour, physiology and survival of many marine species. However, there is a gap in our understanding of how noise impacts reef fishes under natural conditions without direct manipulation. To address this, we conducted field experiments to examine how two types of sound sources affect the behaviour of an endemic southwestern Atlantic reef fish, *Stegastes fuscus*. Both motorboat noise playback (0.2–1 kHz) and pure tone (0.4 kHz) influenced behavioural traits of the species. Specifically, individuals reduced their foraging rates when exposed to either sound and spent more time refuging during pure tone exposure. Despite these changes, fish did not exhibit increased agonistic interactions during any of the sound exposures. Our findings indicate that both motorboat playback and pure tone negatively affect damselfishes by increasing antipredator behaviour, seen through increasing refuge time and decreasing foraging rates, which could potentially impact their fitness and population dynamics.

Marine biodiversity faces many threats, such as overfishing, climate change and noise pollution, which, whether intentional or not, poses a significant threat to it. An increase in noise pollution has been globally documented, affecting both coastal and oceanic environments (Duarte et al., 2021). Anthropogenic sounds, here referred to as noise, are derived from many sources and can be categorized into two main groups: (1) low-frequency sounds (with peak frequencies <1 kHz) generated by shipping activities (e.g. commercial and recreational boats), sea bed drilling, pile driving and air guns; (2) mid- to high-frequency sounds produced by military sonar, seismic surveys and other sources (Hawkins & Popper, 2018; Popper & Hawkins, 2019; Slabbekoorn et al., 2010). As underwater soundscapes undergo rapid changes (Duarte et al., 2021), there is an urgent need to assess the impacts of these anthropogenic sounds on marine life and to fill the gaps in our understanding to deliver effective mitigation measures for these yet comparatively neglected impacts.

Acoustic cues play a crucial role in many daily life activities of marine organisms, including foraging, territorial behaviour and mating. It also guides orientation, settlement, habitat use and many other critical life functions (Cole, 2010; Gordon et al., 2018; Jolivet et al., 2016; Radford et al., 2011) and can indicate habitat quality (Freeman & Freeman, 2016). Motorized vessels, such as large ships and recreational boats, are a significant and growing source of low-frequency noise (Bittencourt et al., 2014, 2020; Sertlek et al., 2019; Whitfield & Becker, 2014), and many fish species are capable of detecting sounds within this frequency range (Popper, 2003). There is increasing evidence that boat-generated noise can influence fish behaviour (e.g. by increasing foraging and antipredator responses and by decreasing agonistic interactions and parental care) (Bracciali et al., 2012; Picciulin et al., 2010; Sebastianutto et al., 2011), as well as their physiology (e.g. increases in metabolic, ventilation and heart rates) (Mills et al., 2020; Simpson et al., 2016), potentially threatening the survival of various reef fish species (McCormick et al., 2018). Recent research has examined underwater

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noise pollution from small vessels along the Brazilian coast (Bittencourt et al., 2014; Campbell et al., 2019) and its effects on cetaceans (Martins et al., 2018; Pires et al., 2021; Rossi-Santos, 2019). However, there is a lack of experimental approaches to how noise impacts reef fishes, particularly their behaviour under natural conditions and with no direct manipulations. Investigating the effects of anthropogenic noise on key species (Bracciali et al., 2012; Leduc et al., 2021), such as the territorial herbivorous Brazilian damselfish, *Stegastes fuscus*, is essential for understanding its impact on the reef ecosystems and establishing acceptable noise levels and species indicators for long-term monitoring.

Damselfishes are a keystone group within reef benthic communities, playing a crucial role in maintaining diversity (Hata & Ceccarelli., 2016). Many of these fishes are territorial and act as farmers, managing algal diversity and coral zonation (Ceccarelli et al., 2001). They are also known for their sound production, which is closely associated with different ecological interactions, including agonistic behaviours related to territory and nest defence (Frédérich & Parmentier, 2016) and species recognition during reproduction (Cole, 2010). Previous research has highlighted damselfish as significant bioindicators for assessing the impacts of noise pollution (Holmes et al., 2017; Nedelec et al., 2016; Vazzana et al., 2017). This is particularly true for territorial species, which, due to their restricted home ranges, are more susceptible to such disturbances (Benevides et al., 2019; Daros et al., 2016).

The Brazilian damselfish is the most prevalent territorial herbivore in shallow reefs along the Brazilian coast (Chaves et al., 2021; Ferreira et al., 2004). This species plays a crucial ecological role in shaping benthic communities through its grazing and territorial behaviour (Barneche et al., 2009; Ferreira et al., 1998). By aggressively defending their territory and excluding other herbivores, *S. fuscus* enhances the diversity of algae and associated cryptofauna within their territories. Their presence also boosts primary productivity in these areas, highlighting their significant trophodynamic role in shallow reef habitats (Ferreira et al., 1998). *Stegastes* spp. produce sounds within the frequency range of 250−1500 Hz (Myrberg, 1972; Myrberg & Spires, 1972) and exhibit a peak auditory sensitivity at 500 Hz (Egner & Mann, 2005; Myrberg & Spires, 1980). Thus, due to the overlap between their peak hearing sensitivity and the broadband noise frequencies generated by motorboats, these fish are particularly vulnerable to such disturbances, serving as an optimal ecological model for studying the effects of anthropogenic noise on marine life.

In this paper, we examined the impact of anthropogenic noise on the behaviour of the Brazilian damselfish in a multi-use marine reserve, by conducting field experiments. Our objectives were (1) to evaluate how two types of sound sources (motorboat playback: 0.2−1 kHz; pure tone: 0.4 kHz) affect different behaviours (foraging, refuging and agonistic interactions) under natural conditions and (2) to assess any residual effects of short-term sound exposure. We hypothesized that exposure to both sound treatments (motorboat playback and pure tone) would result in noticeable behavioural changes, such as reduced foraging rates, increased aggression and increased refuging.

METHODS

Ethical Note

This project was carried out under the permit of the Brazilian Institute of Environment and Natural Resources (Licence SISBIO number 88256-1). Fish were not captured or handled during this study, and the video and audio recordings were minimally intrusive for these animals. Sound exposures were performed below harmful intensities for the species, based on the hearing thresholds for the genus *Stegastes* (between 85 and 140 dB re 1 μPa).

Study Area

We conducted field experiments in shallow rocky reefs at Arraial do Cabo, Rio de Janeiro state, Brazil (23°44′S, 42°W), over a 12-day period from January to June 2022 (Table 1). This area has been designated as a multi-use marine reserve since 1997, allowing only local fishermen to explore, and where different fishing gears (e.g. gillnets, hook and line, spearfishing) are employed (Fogliarini et al., 2021). The region also experiences significant nautical tourism (Giglio, Bender, et al., 2017; Giglio, Ternes, et al., 2017), which impacts local underwater soundscape, particularly during high season (Campbell et al., 2019; Jesus et al., 2020). The Arraial do Cabo region consists of an isthmus and two islands dominated by rocky shores. Upwelling events in the area are triggered by a combination of prevailing winds and coastal morphology, which leads to distinct habitat conditions: the western side of the isthmus, which is directly affected by cold upwelling waters (<18 °C), and the eastern side with comparatively higher mean water temperatures (averaging 22 °C) (Cordeiro et al., 2020). The study sites, Pedra Vermelha and Maramutá (Fig. 1), are located on Cabo Frio Island, which has restrictions on human use, including the prohibition of recreational diving and a limited number of anchored boats. These sites are sheltered from both wave exposure and local upwelling, presenting clear waters and a mean average water temperature of 22 °C (Cordeiro et al., 2020). They sustain a high diversity reef community with clashes of tropical and subtropical components (Cordeiro et al., 2014, 2016; Ferreira et al., 2001). The benthos coverage is predominantly composed of an epilithic algal matrix, zoanthids, massive corals and fire corals (Cordeiro et al., 2014). Populations of the Brazilian damselfish are mainly composed of adult individuals (13−17 cm total length, TL), whose territories cover a significant part of the substrate in shallow habitats ranging from 2 to 5 m (Ferreira et al., 1998). We selected these sites for their similar environmental conditions, minimal nautical traffic and high abundance of the target species, ensuring a controlled setting for the experiments.

Acoustic Data

For the first sound stimulus (T1), we created playback tracks using a coherent sum of different recordings of boat noise played in

Table 1
Environmental conditions of trials

Site	Water temperature (°C)	Weather	Waves	Day	Month	Year
Pedra Vermelha	22	Clear	No	28	Jan	2022
Maramutá	22	Clear	No	28	Jan	2022
Pedra Vermelha	22	Clear	No	1	Feb	2022
Maramutá	22	Clear	No	1	Feb	2022
Pedra Vermelha	21	Sunny	No	16	Feb	2022
Maramutá	21	Sunny	No	16	Feb	2022
Pedra Vermelha	24	Sunny	No	21	Feb	2022
Maramutá	24	Sunny	No	21	Feb	2022
Maramutá	20	Sunny	No	15	Mar	2022
Pedra Vermelha	20	Sunny	No	15	Mar	2022
Maramutá	22	Cloudy	No	22	Mar	2022
Pedra Vermelha	22	Cloudy	No	22	Mar	2022
Maramutá	22	Sunny	No	26	Apr	2022
Pedra Vermelha	22	Sunny	No	5	May	2022
Maramutá	22	Sunny	No	5	May	2022
Maramutá	24	Sunny	No	9	May	2022
Maramutá	23	Cloudy	No	16	May	2022
Pedra Vermelha	23	Sunny	No	17	May	2022
Pedra Vermelha	23	Sunny	No	8	Jun	2022

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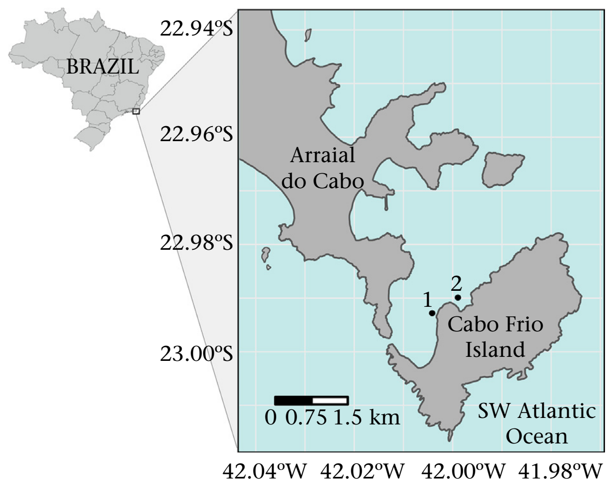

Figure 1. Map of the study area highlighting the two sites of the experiments (1 = Maramutá; 2 = Pedra Vermelha), located in Cabo Frio Island, in Arraial do Cabo, Brazil.

a loop for 10 min. We made these recordings during the daytime of intense nautical traffic in the Arraial do Cabo Marine Reserve (23°44′S, 42°W) (Jesus et al., 2020). To ensure accuracy and validate the trials, we recorded the projected noise using a hydrophone (DigitalHyd SR-1 from Marsensing Lda, sensitivity of -169.4 dB re 1 μPa at 1000 Hz, sampling frequency 52 Hz, resolution of 16 bits). For the second sound stimulus (T2), we used a pure tone of 0.4 kHz, also played in a loop for 10 min. The median distance between the hydrophone and the loudspeaker was 20 m. Sound from one experimental site could not be heard at the other site, which was verified by recordings that were limited by distance and the presence of rocky reefs. To calibrate and characterize the underwater soundscape during the trials, we analysed the acoustic data via spectrograms with Raven Pro 1.6 bioacoustics software (Cornell Lab of Ornithology, Ithaca, NY, U.S.A.). We used a 30 s window of the audio recordings to illustrate the changes in the soundscape between different periods (Fig. 2).

Experimental Overview

We randomly selected 35 territories of *S. fuscus* across the study sites (19 for playback, 16 for pure tone), ensuring that each territory was separated by at least 2 m. We conducted all experiments between 0900 and 1200 hours to align with the peak activity periods of the target species and scheduled them during weekdays to avoid periods of high nautical traffic, thereby minimizing potential interference during the experiments. We centrally positioned an underwater loudspeaker (Lubell LL-1424HP; 0.2−9 kHz), 197 dB re 1 μPa at 1 m at 600 Hz), at least 2 m from any individual territory, allowing it to cover multiple territories simultaneously (Fig. 3). The speaker was initially turned off for 15 min: 5 min for the acclimation period (Nanninga et al., 2017) and 10 min to establish baseline behaviour (control period). Each trial consisted of 10 min of one of the following experimental conditions: treatment 1 (T1): playback of small vessel noise recorded during days of intense traffic (0.2−1 kHz); treatment 2 (T2): a pure tone (0.4 kHz). Both transmissions involved 30 s of signal and 30 s of silence, with a source level (SL_{RMS}) of approximately 140 dB, with a calculated received level of 120 dB. During sound exposure, fish were subjected to 30 s of sound every minute for a total duration of 10 min. We chose small boat noise as it represents the most common source of anthropogenic noise in the area, and we chose the pure tone to evaluate generalized responses to this frequency. We assessed fish responses to the experimental approaches using remote underwater videos (RUVs). We placed GoPro Hero 4 cameras on the rocky substrate at 1 m from the fish territories, covering an area of 2 m^2, with careful placement by a scuba diver. Each territory had one video camera to prevent further interference. Once in position, cameras recorded continuously for at least 45 min, while the diver kept a 10 m distance to avoid influencing the experiments (Longo & Floeter, 2012). Each RUV sample consisted of a 30 min video shot. No direct manipulation of the fish occurred during the trials.

Behavioural Analysis

In the laboratory, we analysed only the central 30 min of each video recording to minimize any potential influence from the diver on fish behaviour (Longo et al., 2014). We visually estimated the total length of each fish, ranging from 13 cm to 17 cm, and we quantified various behavioural aspects. We focused on three main behavioural categories, as follows. (1) Agonistic interactions: the number of chasing/aggressive strikes towards other fish/min. We defined a chase as any instance where a fish rapidly swam towards another fish, causing the latter to escape, regardless of physical contact. (2) Foraging: the number of bites/min on the substrate or at a drifting particle in the water column. We defined a bite as any instance where a fish stroked the benthos with its jaws opened and subsequently closed it jaws, regardless of whether it ingested the material (Longo et al., 2014); (3) Refuging: time spent hiding in a shelter structure/min, with at least 50% of the body within the shelter.

We divided the observations into three 10 min periods: 10 min prior to the sound treatment (control, 'pre'), the 10 min trials of the soundtrack ('during') and the 10 min following the sound treatment ('post'). The observer watched the videos without audio to remain naïve to the treatments. We present clips of each behaviour in the Supplementary Material.

Statistical Analysis

We analysed differences in behaviours (chase, refuge, foraging), time periods (pre, during, post sound exposure), treatments (boat noise, pure tone) and the interaction of treatment and period in a full model using a generalized linear mixed-effect model (GLMM) with Poisson distribution. Since each trial consisted of filming one to four individuals during the sound stimulus, we included individuals as random factors nested in trials to account for within-trial variability. We square-root-transformed the data to decrease the effect of outliers. As we detected no interaction effects between time periods and treatments, we analysed behaviours separately using the same model structure. Specifically, we used linear mixed-effect models (LMMs) to analyse the frequency of chases and time spent refuging and GLMMs with Poisson distribution for foraging rates. To minimize type I errors, we set the significance threshold at <0.01. We kept the zeros in data sets to account for the effects of dependency between different behaviours because fish could be engaged in a different behaviour than the one quantified. We inspected all residuals of the models to evaluate model adjustment (see Supplementary Material). We did pairwise comparison among time periods between treatments using estimated marginal means (Searle et al., 1980).

We generated waveform and spectrogram graphics in Python (Python Software Foundation, https://www.python.org). We performed all statistical analyses and other plots in R software (R Core Team, 2023). We ran GLMM and LMM models using 'lmer' and 'glmer' functions from the 'lme4' package (Bates et al., 2015, version 1.1−33), and we performed pairwise comparisons with the

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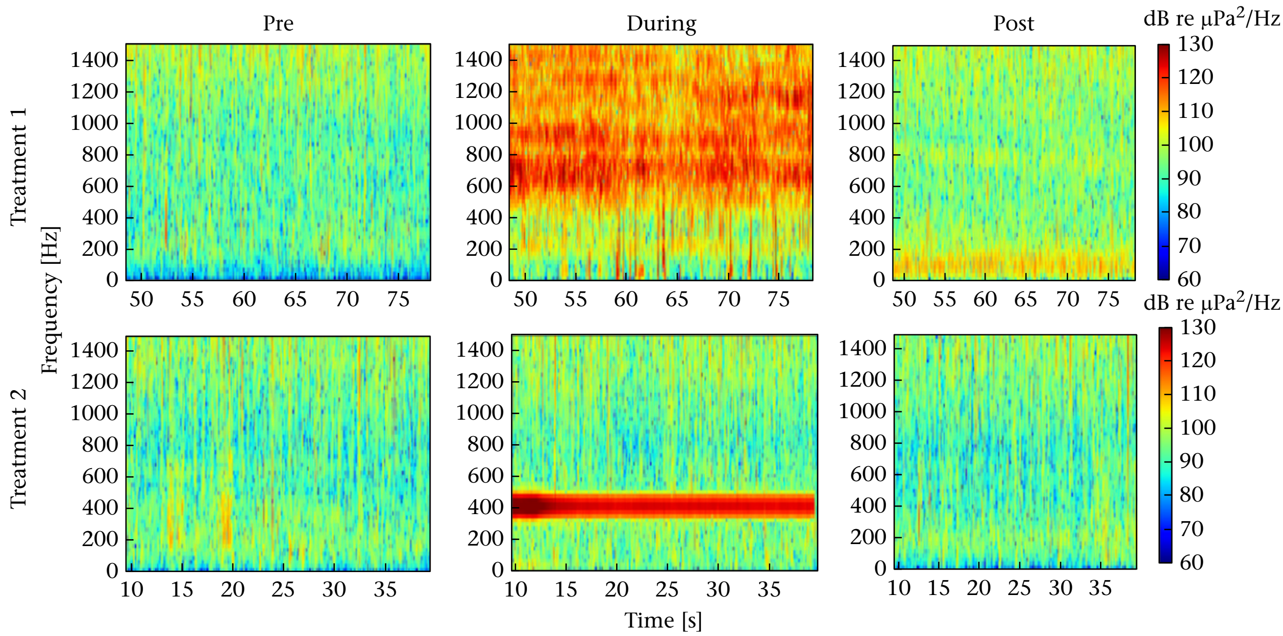

Figure 2. Spectrograms of the underwater soundscape during field experiments, for a 30 s window of audio recordings of each treatment (treatment 1 = playback; treatment 2 = pure tone). Fast Fourier transform (FFT) length = 1024, Hamming evaluation window, 50% window overlap, 0–1500 Hz.

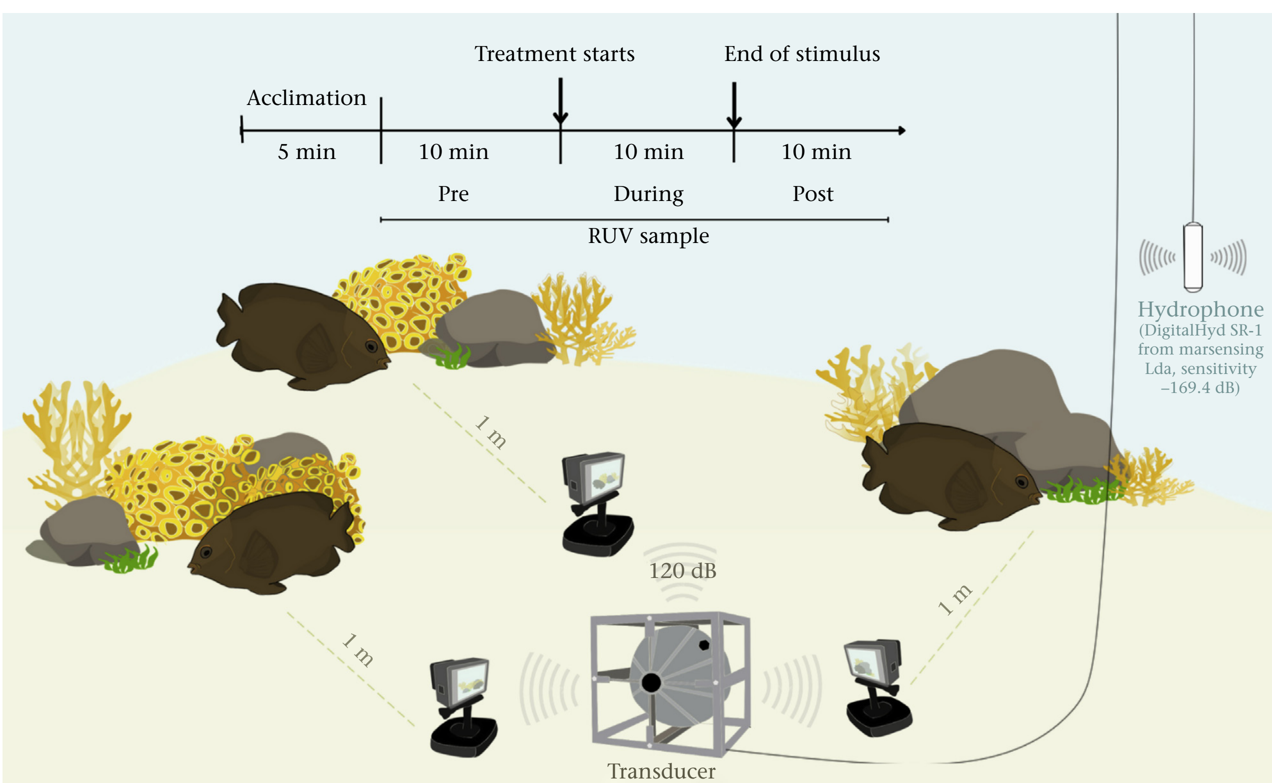

Figure 3. Experimental overview (not scaled) showing a timeline of trials. RUV: remote underwater video.

‘emmeans’ function from the ‘emmeans’ package (Lenth, 2023, version 1.8.6).

RESULTS

The full model indicated significant differences only between behaviours (time: F=2.17, P = 0.91; behaviour: F = 65.64, P < 0.001; time*behaviour: F = 0.43, P = 0.71). Refuging and foraging behaviour of fish varied significantly between periods in both treatments (Fig. 4). Fish spent more time refuging during the 10 min period of sound exposure compared to the 10 min before sound exposure for the pure tone (P = 0.0001) but not for playback (P > 0.01) (refuging mean ± SD: control = 14.3 ± 16.4; stimulus = 37.9 ± 39.6; after = 15.3 ± 20.6). Foraging rates were also

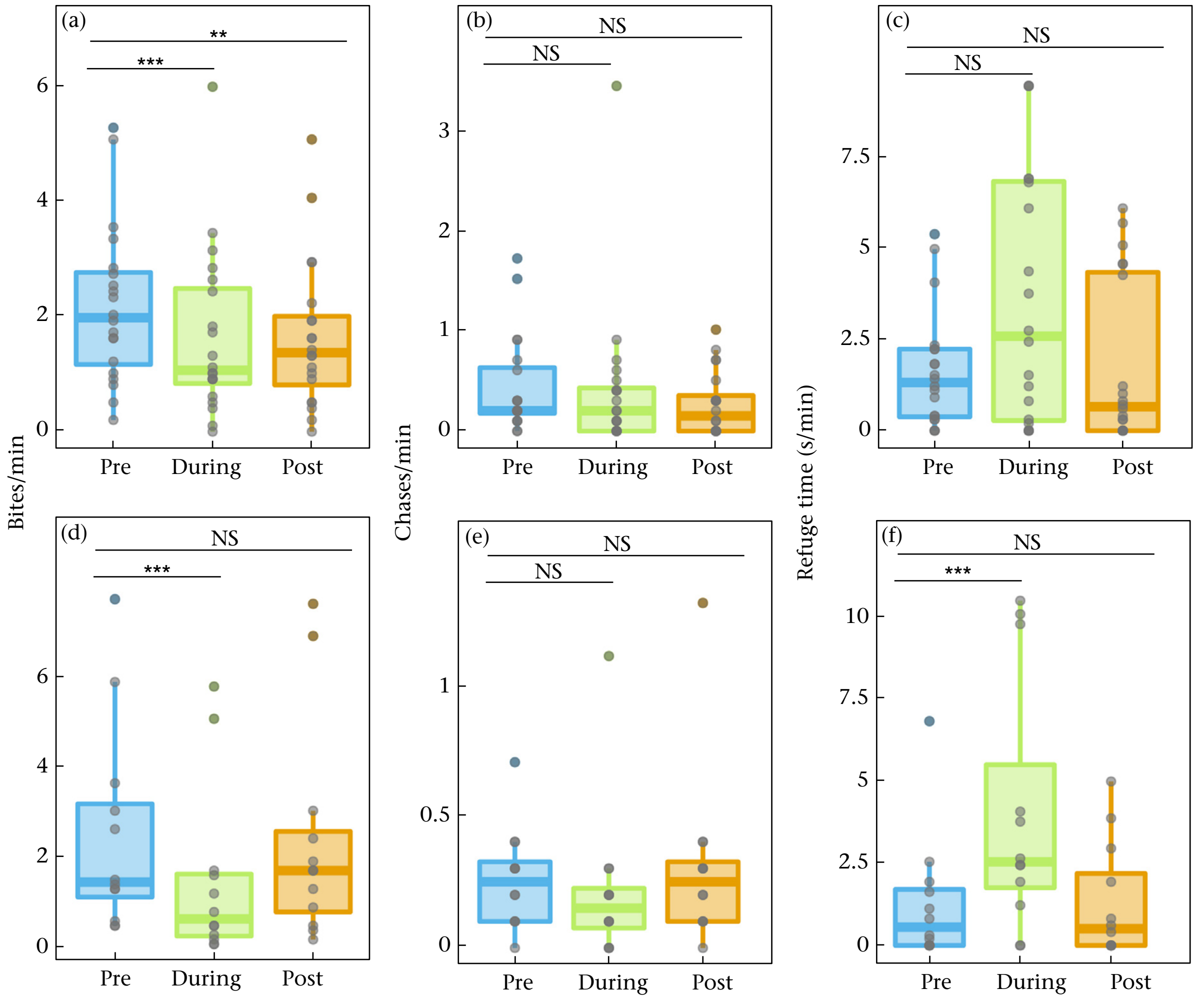

Figure 4. Comparative behaviour responses for both experimental approaches before (pre = blue), during (= green) and after (post = orange) sound exposure. Boxes represent interquartile ranges and lines within boxes represent median values across 19 individuals for the playback and 16 for the pure tone. Each dot represents an individual. (a) Bite rates in playback; (b) chasing in playback; (c) refuging in playback; (d) bite rates in pure tone; (e) chasing in pure tone; (f) refuging in pure tone. *P< 0.01 (estimated marginal means tests). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

significantly lower during sound exposure compared to pre-exposure for both treatments (playback: $P = 0.0001$; pure tone: $P < 0.0001$). In the 10 min following sound exposure, fish refuging behaviour returned to similar values to the moment of pre-exposure, for both treatments (Table 2). We present the behavioural responses of each individual during the treatments in Fig. 5. The chasing activity of the Brazilian damselfish was reduced in 45.8% of individuals during playback and in 65% of individuals during pure tone, but we did not observe any significant differences between periods ($P > 0.01$; Fig. 4b–e).

Table 2
Comparisons of behaviours before (pre), during and after (post) sound exposure

Source of variation	Z ratio	P
Feeding rates		
T1 pre – **T1** during	4.57	**0.0001**
T1 pre – T1 post	3.68	**0.003**
T1 during – T1 post	-0.91	0.94
T2 pre – **T2** during	7.79	**<0.0001**
T2 pre – T2 post	0.67	0.99
T2 during – **T2** post	-7.18	**<0.0001**
Time refuging	*T* ratio	*P*
T1 pre – T1 during	-2.75	0.08
T1 pre – T1 post	0.56	0.99
T1 during – T1 post	3.31	**0.018**
T2 pre – T2 during	-4.89	**0.0001**
T2 pre – T2 post	0.31	0.99
T2 during – T2 post	5.19	**<0.001**

Summary of estimated marginal means results of behaviours testing the effect between periods for *S. fuscus*. The bold type denotes significant differences at $\alpha = 0.01$.

DISCUSSION

Our study revealed that anthropogenic noise induces behavioural changes in the conspicuous damselfish *S. fuscus* in southern Atlantic reefs. Both pure tone (0.4 kHz) and playback (0.2–1 kHz) significantly disrupted key behaviours. During sound exposure, fish were more likely to seek refuge (for T2) and spent less time foraging (both treatments) compared to pre- and post-exposure periods. These findings align with previous studies with damselfishes from other regions. For instance, Nedelec et al. (2016) observed that *Dascyllus trimaculatus* increased refuging behaviour during short-term motorboat playback exposure in a field experiment using relocated experimental anemones in the lagoon of Moorea, French Polynesia. In the southern Atlantic, Leduc et al. (2021) observed significant reductions in foraging rates of *S. fuscus*, due to land-based noise pollution, from carnival commemoration. While there

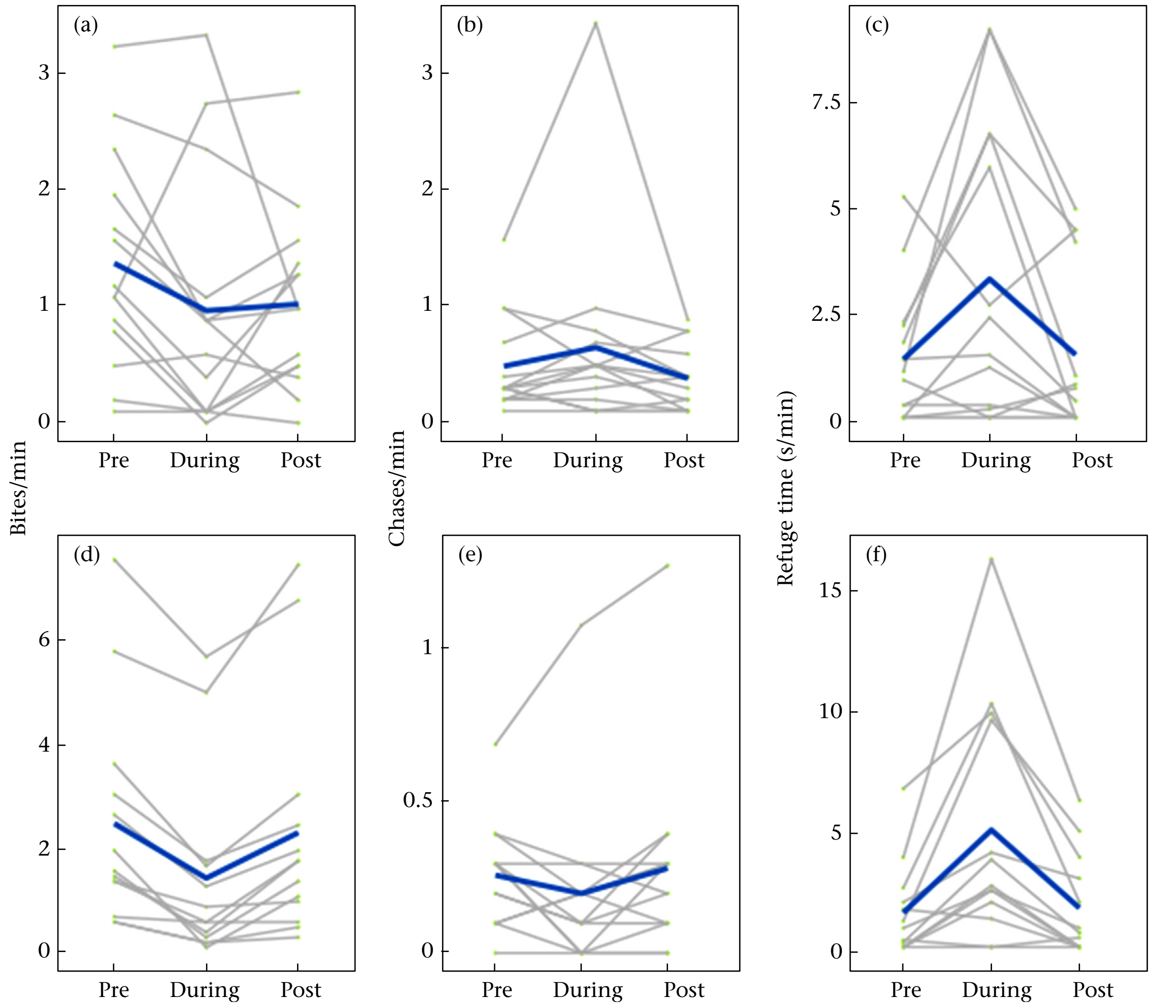

Figure 5. Comparative individual responses for both experimental approaches before (pre), during and after (post) sound exposure. Grey lines join the values from the same individual and thicker blue lines show the median values. (a) Bite rates in playback; (b) chasing in playback; (c) refuging in playback; (d) bite rates in pure tone; (e) chasing in pure tone; (f) refuging in pure tone. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

have been recent field experiments conducted under different manipulation conditions (e.g. Nedelec et al., 2016: using caged experimental anemones; Leduc et al., 2021: testing land-based noise pollution), our results provide evidence that underwater anthropogenic noise impacts this species under natural conditions by altering their behaviour. Given that behavioural changes are often the initial response to environmental stressors, further research is needed on whether and how these changes persist through time and their potential effects on population dynamics and the species' functional role within the reef system.

Foraging is a critical daily activity for fish and is often one of the first behaviours disrupted when facing threats. Previous research has demonstrated that noise exposure can significantly impact foraging in both laboratory and field. For instance, Bracciali et al. (2012) observed a considerable reduction in foraging rates in the planktivorous damselfish *Chromis chromis* when exposed to intense boat noise and nautical traffic in a southern Mediterranean Marine Protected Area. Similarly, Voellmy et al. (2014) reported altered foraging responses in two sympatric freshwater fish species, *Gasterosteus aculeatus* and *Phoxinus phoxinus*, which showed reduced food intake during noise exposure in tank-based experiments. While laboratory experiments offer controlled acoustic conditions, extrapolation of the results must be treated with caution, as field responses may differ. The long-term implications of reduced foraging are significant, as decreased foraging rates can directly impact fish fitness. Reduced foraging can lead to poorer body conditions, stunted growth and decreased reproductive success (King et al., 2015). Additionally, the energetic costs associated with less frequent feeding events might compel fish to modify their behaviour in an attempt to compensate for food intake during less favourable conditions (Bracciali et al., 2012). Future studies should consider how the trade-off between predator avoidance and foraging activity varies among individuals and how this might affect population dynamics.

Another common behavioural response when animals face threats is refuging (Cooper & Blumstein, 2015). In a study in the same region, Benevides et al. (2019) observed that the Brazilian damselfish increased its refuging time in response to the presence of a diver. Our experiments showed similar antipredator responses to sound stimuli, suggesting that anthropogenic noise is perceived as a threat. Comparable refuging behaviour has been documented in other species: the red-mouth goby, *Gobius cruentatus*, in a Natural Marine Reserve in the northern Adriatic Sea (Picciulin et al., 2010), and the domino damselfish, *D. trimaculatus*, in Moorea, French Polynesia (Nedelec et al., 2016). For territorial species like the Brazilian damselfish, increased refuging time can lead to missed feeding opportunities and weakened territory defence. Since damselfishes play a crucial functional role in reef systems by controlling algae diversity and abundance (Hata & Ceccarelli, 2016), increased refuge time could negatively impact community dynamics and structure by reducing the time available for other essential daily activities.

Organisms exposed to anthropogenic stressors, such as anthropogenic sounds, often exhibit increased agonistic interactions due to heightened stress. For instance, the anemonefish *Amphiprion chrysopterus* showed increased aggression in response to motorboat noise playback, in both short- and long-term field experiments (Mills et al., 2020). Contrary to our hypothesis, the Brazilian damselfish did not show significant changes in chasing behaviour between periods, although we observed a tendency towards reduced chasing during sound exposure. Notably, we did not detect significant patterns regarding intra- and interspecific chases in response to sound. One possible explanation for these contrasting results is risk assessment. While maintaining a territory is beneficial, it imposes high energy costs (Eurich et al., 2018). For *S. fuscus,* the energy expenditure required to escalate chasing behaviour during sound exposure may not be justified, especially when individuals are already spending more time refuging. Another possible explanation could be a potential decrease in the number of other fish entering the territory during noise exposure. If noise deters potential intruders, territorial pressure might diminish, reducing the need for aggressive chases. Although we did not directly quantify territorial pressure, future studies should explore this by assessing the presence and activity of potential intruders in response to noise exposure. Additionally, density-dependent factors might influence agonistic behaviour, suggesting that patterns could vary across species, habitats and locations. Further research is needed to explore how agonistic patterns evolve and their potential effects on reproductive opportunities and territory productivity. Understanding these dynamics will provide deeper insights into the direct impacts of anthropogenic sounds on territory maintenance.

Our results indicate that the anthropogenic sounds applied for 10 min had no carryover effects on fish behaviour, as individuals returned to pre-exposure levels once the sound ceased. This contrasts with Mills et al. (2020), who observed short-term (5 min) carryover effects of motorboat playback on both behaviour and physiology of the orange-fin anemonefish, *A. chrysopterus*. Similarly, Nedelec et al. (2017) found persistent behavioural effects in cleaning interactions, with elevated levels of jolting clients even after the sound exposure ended. In our study, however, damselfishes returned to baseline levels of both foraging and refuging behaviour after sound had ceased in both treatments. Given that our study focused on short-term evaluation (30 min trials), we do not know whether these effects would persist over a longer duration or whether fish might habituate to longer sound exposures. Future research should consider longer observation periods and incorporate different metrics, including physiological markers, to fully assess the potential long-term impacts of anthropogenic noise on fish behaviour and other critical life functions (Mills et al., 2020).

Both sound sources influenced the behaviour of *S. fuscus*, but their impact varied in intensity. Contrary to previous research suggesting that pure tones generally have a milder effect on fish behaviour (Cox et al., 2018), our results show a more pronounced response to the pure tone. This difference may be due to variations in the acoustic parameters, such as peak frequency, between our study and prior research, indicating a more generalized response to sounds in this frequency. Specifically, the pure tone frequency that we used in our experiment was based on Olivier et al. (2014), which identified that *Stegastes rectifraenum* emits sounds primarily at 400 Hz during foraging and agonistic interactions. The overlap between this frequency and the signals produced by *S. fuscus* could explain the stronger response observed. Previous studies have demonstrated that different types of sounds can differentially impact reef fish, especially within low-frequency bands (McCormick et al., 2018; Velasquez Jimenez et al., 2020). These findings highlight the need for further research into how different sound properties affect marine species. Such research is crucial for developing noise mitigation strategies for marine traffic.

In situ studies, such as ours, are vital for understanding the ecological responses of fish to stressors, like anthropogenic noise, as these responses can often differ from those observed in laboratory settings (Banse et al., 2023). While laboratory experiments offer controlled conditions, they can also influence acoustic transmission and fish behaviour in ways that may not fully represent natural conditions (Akamatsu et al., 2002; Mouy et al., 2023). In this context, field studies provide a more ecologically valid perspective by reflecting a more realistic representation of the impact of noise on the behaviour of the studied organism. Conducting field-based experiments can be challenging, including the need to account for natural fluctuations in external variables. In our study, we addressed these challenges by carefully selecting trial days with similar environmental conditions and ensuring that we conducted experiments at the same time of day. We also recorded the local soundscape before the trials and visually monitored the area to prevent interruptions from passing boats, thereby minimizing potential confounding factors. To achieve a comprehensive understanding of the effects of anthropogenic noise on marine life and understand the generalized responses to noise treatments, different frequencies should be tested to cover a broader range of the hearing sensitivity of the species. Additionally, future research should ideally integrate both laboratory and field approaches. Combining these methods can offer a more nuanced view of how noise impacts fish behaviour and ecological dynamics, enhancing our ability to develop effective noise mitigation strategies (Lessa et al., 2023).

Conclusions

In our field experiment, we observed that both types of sounds had significant effects on *S. fuscus* behaviour, leading to short-term increases in antipredator responses. This finding underscores the negative impact of anthropogenic noise on damselfishes, which could have broader implications given the high and increasing density of boats along the coast. Understanding these effects is crucial for management and species conservation, as heightened antipredator behaviour can lead to disruptions in population dynamics and key ecological processes, such as herbivory. The more we know about the sublethal impacts of noise on such key species, the more we can do for conservation and management efforts across different coastal environments, including reef systems. To effectively address these challenges, future studies should integrate a variety of approaches, such as behavioural and physiological studies, as well as in situ and ex-situ experiments, over both short- and long-term frames. This comprehensive approach will help identify susceptibilities to noise in reef dynamics and provide a clearer understanding of this neglected impact. Moreover, future experiments must also include the noise tolerance thresholds of fish species and sound propagation effects in different habitats. Establishing these tolerance thresholds of key species, such as the Brazilian damselfish, will enable the development of noise limits for different anthropogenic sources, facilitating better management strategies to mitigate the impacts of noise pollution on marine systems.

Author Contributions

Viviane Barroso: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis. **Cesar A.M.M. Cordeiro:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Data curation. **Carlos E.L. Ferreira:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Aléxia A. Lessa:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fábio C. Xavier:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Data Availability

Data are available as Supplementary Material.

Declaration of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary Material

Supplementary material associated with this article is available, in the online version, at https://doi.org/10.1016/j.anbehav.2025.123130.

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