Impact of Motorboat Noise on Vocalizations of Nesting Plainfin Midshipman Fish

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Abstract

As noise pollution in coastal environments continues to grow, it is imperative to understand how it may be negatively impacting marine life. The study in this chapter tested whether noise from a real motorboat would alter the vocalizations of nesting plainfin midshipman fish (*Porichthys notatus*), a soniferous toadfish

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that breeds in the intertidal zone and uses its vocalizations for courtship and defense. The results show evidence that wild plainfin midshipman guarder males may decrease their agonistic vocalizations in periods where they are exposed to large amounts of boat noise. There was an overall decrease in agonistic vocalizations on the nights when boat noise trials were run compared to control nights. While there was not a statistical difference in the number of agonistic vocalizations exhibited in sequential 10-minute periods with and without boat noise in the same night, there was a trend of fewer vocalizations during boat noise periods. This study helps elucidate how boat noise affects midshipman vocalizations in their natural habitat at the level of the individual, which has never been tested in plainfin midshipman fish and has scarcely been studied in other species.

Keywords

Sound · Behavior · Noise pollution · Toadfish · Soniferous fishes · Acoustic communication

Introduction

Many marine animals rely on sound to communicate, perceive environmental cues, and detect prey and predators (Myrberg 1997). Anthropogenic noise in the ocean has risen drastically over recent decades, causing widespread changes to underwater soundscapes (Duarte et al. 2021). Contributing to these changes are activities such as construction, seismic exploration, and commercial shipping. In coastal environments, one of the primary contributors to noise pollution is recreational boating (Hermannsen et al. 2019). Accordingly, understanding the impacts of noise pollution on underwater soundscapes has become a major focus of current conservation research (Slabbekoorn et al. 2010; Duarte et al. 2021).

Many fishes use sound to communicate, and even nonvocalizing fish species rely on low-frequency sound for environmental perception, prey and predator detection, and navigation (Popper 2003; Slabbekoorn et al. 2010; Simpson et al. 2016). Noise pollution can have many negative effects on fish, including increased mortality by predation (Simpson et al. 2016), temporary hearing loss or altered auditory thresholds (Smith et al. 2004; Vasconcelos et al. 2007), physical damage to hearing structures (McCauley et al. 2003), distribution shifts away from noisy environments (Paxton et al. 2017), physiological stress responses (Wysocki et al. 2006; Nichols et al. 2015; Mills et al. 2020), numerous behavioral changes (Sarà et al. 2007; Sebastianutto et al. 2011; Nedelec et al. 2017; Mills et al. 2020), and masking of vocalizations (Vasconcelos et al. 2007). In addition to masking, noise can cause individuals to alter the amplitude, frequency, or duration of their vocalizations or to reduce how often they vocalize in the presence of noise (Holt and Johnston 2014; Brown et al. 2021).

In this study, a model soniferous toadfish species, the plainfin midshipman (*Porichthys notatus*), was used to investigate how boat noise affects fish vocalizations. Plainfin midshipman fish rely on acoustic communication for mate attraction and defense (Zeddies et al. 2010). By rapidly contracting specialized sonic muscles attached to the gas-filled swim bladder, they produce three vocalizations: hums (tonal and lasting several minutes to over an hour), grunts (~0.5 s and either produced alone or in a series called a grunt train), and growls (frequency modulated and lasting up to several seconds; Brantley and Bass 1994; McIver et al. 2014). As the plainfin midshipman is nocturnal (Brantley and Bass 1994; McIver et al. 2014), they vocalize most often at night – hums in particular are often solely produced at night (McIver et al. 2014), with the chorus of hums peaking around midnight to 1 a.m. (Halliday et al. 2018; WDH and MBW, pers. obs.).

Every year in the late spring, plainfin midshipman fish migrate from deep waters to the shallow intertidal zone to breed. Nesting males endure a long (>60 days) and energetically costly parental care period in the intertidal zone (Bose et al. 2016), a habitat exposed to frequent noise from nearshore boat traffic (Halliday et al. 2018), during which they attract females using a mate advertisement hum, and care for their multiple clutches of eggs while continuing to attract new females (Brantley and Bass 1994). For spawning to occur, females must be able to hear and locate a male within his nest (Zeddies et al. 2010). Additionally, plainfin midshipman males use agonistic grunts and growls to defend themselves, their nests, and their young from rival males and predators (Brantley and Bass 1994; Woods et al. 2022). Consequently, masking of these vocalizations could have severe reproductive consequences and interfere with their ability to protect themselves and their territory.

The low-frequency noise generated by boats (e.g., recreational motorboats, commercial shipping vessels) can be particularly deleterious to species whose hearing is most sensitive to low-frequency sounds, and to those species that produce low-frequency vocalizations necessary for con- or heterospecific communication (e.g., defense) or for mate attraction. Like many fishes, the plainfin midshipman is most sensitive to low-frequency sound (Ladich 2014). The hum produced by nest-guarding, or "guarder" males, has a fundamental frequency of ~100 Hz, with dominant harmonics between 200 Hz and 400 Hz (Sisneros 2012; Halliday et al. 2018), while grunts and growls have a fundamental frequency of ~60–120 Hz (McIver et al. 2014). Therefore, plainfin midshipman vocalizations fully overlap the frequency range of boat noise (Halliday et al. 2018), resulting in the potential for masking of their crucially important mating hums, in addition to their agonistic low-frequency grunts and growls used for defense.

Animals sometimes alter the spectral (e.g., frequency, amplitude) or temporal characteristics of their vocalizations to overcome masking – a phenomenon known as the Lombard effect (Brumm and Zollinger 2011). Animals may also reduce their overall rate of vocalizations in the presence of noise in some cases (Miksis-Olds and Tyack 2009). This could be detrimental when the vocalizations are necessary to convey important signals, such as attracting a mate or deterring intruders. Recent work has shown that plainfin midshipman males can exhibit the Lombard effect when exposed to an artificial noise stimulus producing a tone of ~118 Hz along with several weaker harmonics (Brown et al. 2021). In that study, the males increased the amplitude of their hums, lowered the frequency of their vocalizations, and produced fewer of all three vocalizations (hums, grunts, and growls) in the presence of artificial noise. However, that study used a relatively low-amplitude artificial noise stimulus that was both overpowered by and greatly resembled plainfin midshipman hums (Brown et al. 2021). How boat noise affects plainfin midshipman vocalizations in the wild has never been investigated.

This study expands the investigation of the Lombard effect by using a true anthropogenic noise stimulus (a motorboat driven near the nests) to explore whether plainfin midshipman alter their vocalizations as a strategy to overcome masking by anthropogenic noise pollution. It was predicted that boat noise would reduce the number of vocalizations produced, resulting in fewer vocalizations during boat noise periods compared to ambient control periods within the same night. In the future, the data will be further analyzed to quantify additional parameters of the vocalizations, including any changes to frequency and amplitude in response to boat noise.

Methods

Study Location and Nest Construction

Experiments were performed in June 2022 at a private beach in the Hood Canal region of Washington, USA. Four artificial nests were constructed from 929 cm^2 concrete tiles placed on small rocks to partially prop them up off the substrate on one side to encourage fish to enter and take them up as a nest. An area of the beach with the fewest natural nests was selected, and the artificial nests were placed at least 5 m away from each other and from all suspected natural nests (i.e., medium to large rocks that looked like they would make a good midshipman nest and/or rocks that had indications of being a nest, such as having a dug-out entrance or a shell midden outside a potential entrance).

The first three nests were placed in a horizontal row, parallel to the shoreline. As there was not room for a fourth nest in line with the first three due to the presence of many suspected natural nests, the fourth was placed 6 m behind (away from the shoreline) the third nest (Fig. 1).

The artificial nests were checked for occupancy every few days at low tide or by snorkelers when the nests were underwater. Once a male was discovered in one of the nests guarding a brood of eggs, the nest was covered with plastic mesh (1 cm^2 openings) weighed down by rocks along the edges to ensure that the same focal male remained for the duration of the experiment, as well as to exclude rival males, predators, or additional mates (Brown et al. 2021; Woods et al. 2022).

Noise Stimulus

A 4-m aluminum hull boat with a four-stroke 9.9 horsepower engine was used as a noise stimulus. During the boat noise periods on each of the three trial nights, the boat was driven at full throttle continuously for 10-minute intervals, in loops with the closest point approximately 20 m from the nests (Fig. 1a). This distance was chosen

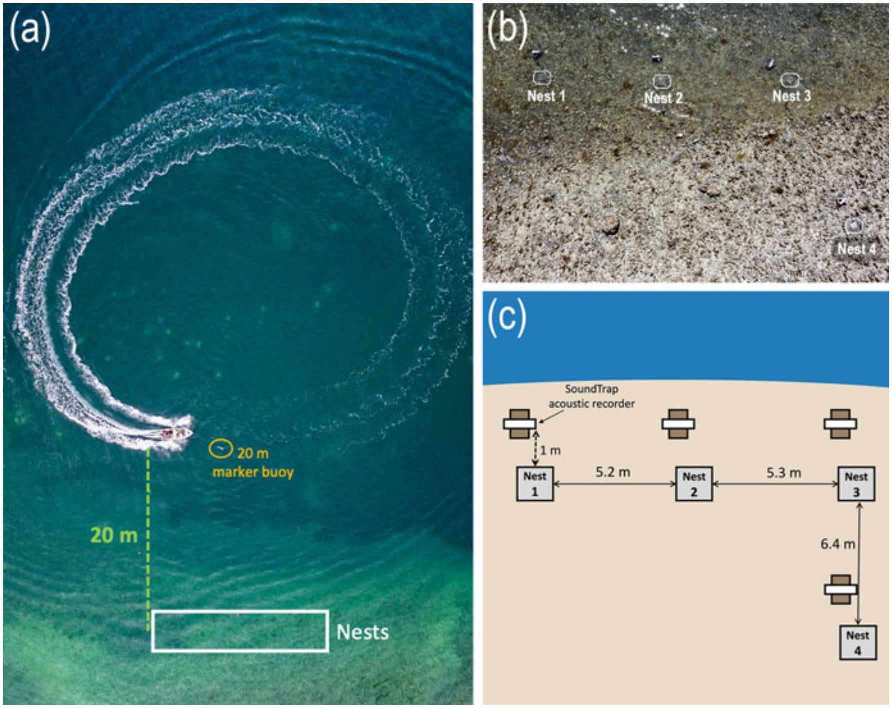

Fig. 1 Nest layout and experimental setup: (**a**) An aerial photograph of the motorboat stimulus being driven in continuous loops during a boat noise period on a trial day. The four experimental nests are underwater in the area outlined in white. The closest point of the boat loop was 20 m away from the nests (shown in green) and was marked with a 20 m marker buoy (shown in yellow) to guide the boat loops; (**b**) aerial photograph of the artificial nests and acoustic recorders at low tide; and (**c**) schematic diagram of the layout of artificial nests and SoundTrap acoustic recorders on the beach. The distances between each of the four experimental nests and the acoustic recorders are noted. Recorders were placed 1 m in front of each nest. The waterline shown is at low tide; the nests were underwater during all experimental trials, as seen in (**a**)

because the nests were in shallow water, and therefore the boat noise they would naturally experience would rarely come from boats driven directly over the nests. The boat was always driven by the same individual (MBW) for consistency. SoundTrap acoustic recorders (Ocean Instruments New Zealand) placed 1 m away from each nest (Fig. 1c) were used to record the vocalizations of the focal fish as well as the received sound levels in both the boat noise and ambient control periods (Fig. 2).

Experimental Trials

Because plainfin midshipman fish are nocturnal, this experiment was conducted at dusk. Trials were conducted between 20:10 and 21:30 for 5 consecutive days

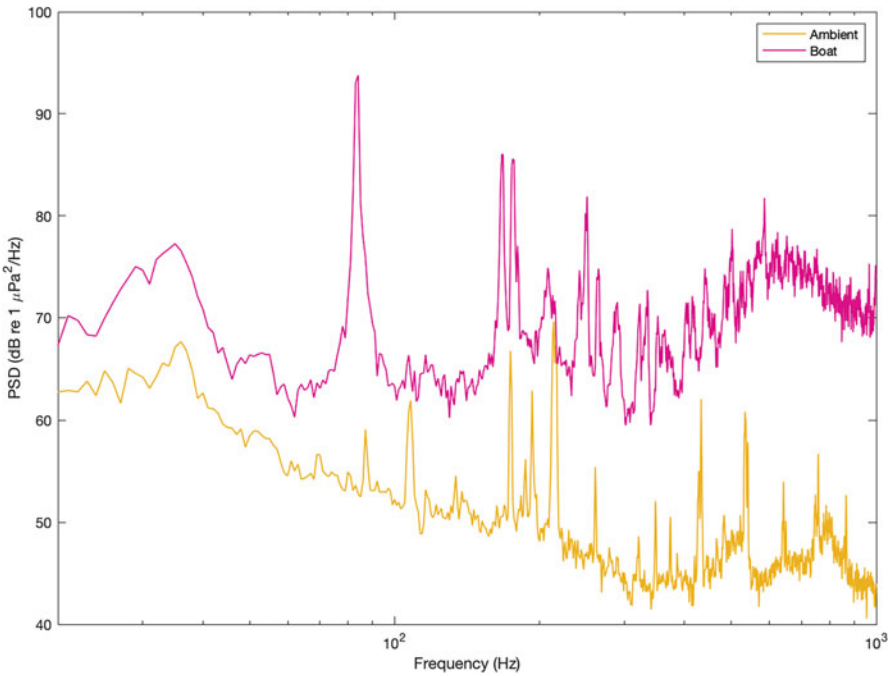

Fig. 2 Power spectral density (PSD) of the sound levels in the ambient trial periods (gold), with no motorboat or introduced noise, and the boat noise trial periods (pink), during which a motorboat with a 9.9 hp engine was driven in continuous loops at full throttle

between June 23 and 27, 2022. The 5-day sequence consisted of two control nights (with no boat noise) and three trial nights (with boat noise) in the following order: Pre-Trial Control Night, Trial Night 1, Trial Night 2, Trial Night 3, and Post-Trial Control Night (Fig. 3). On the first day, acoustic recorders were deployed, and that night (the "Pre-Trial Night") the fish were left undisturbed, and their vocalizations were recorded. The second night (Trial Night 1), boat noise trials began. Immediately before trials, the boat was quietly rowed until it was in deep water far away (>150 m) from the nests, where the engine was then started and allowed to warm up before exposing the fish to the boat noise. Starting approximately 45 min before sunset, the first boat treatment began.

Each boat noise treatment was 10 min long and consisted of the boat being driven in loops continuously (Fig. 1a). After 10 min, the boat engine was turned off and the first 10-minute ambient control period began. This was repeated until there had been three boat noise periods. There was then a 10-minute follow-up period once the boat engine was shut off for the final time (Fig. 3). Before each boat noise period, the boat was started far away (>150 m) from the nests (after a full 10 minute of engine-off ambient), and the 10-minute noise period only commenced when the boat started the full-throttle loops. The interval between the boat engine being started and the beginning of each boat noise period were not analyzed for vocalizations.

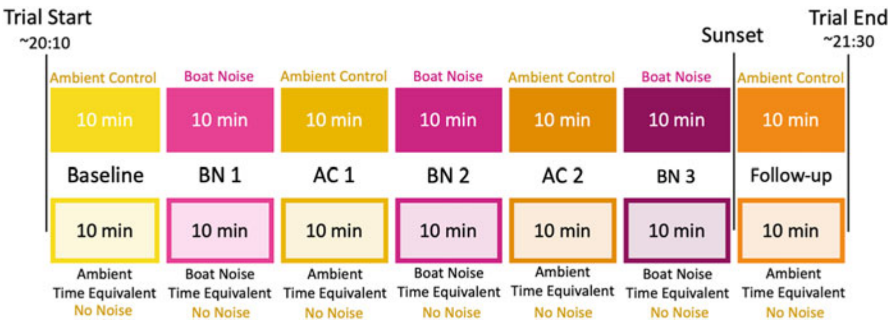

Fig. 3 Nightly timeline showing the order of trial periods during which vocalizations were analyzed. Trial nights (top) had alternating ambient and boat noise periods, and control nights (bottom) had no boat present and no noise introduced. The colors correspond to the colors of each trial period in the results figures, with variations of yellow/gold/orange as ambient control periods and variations of pink/purple as boat noise periods. (Note: The darkening colors correspond only to time of night and not stimulus intensity)

This sequence was repeated on each of the next two nights (Trial Night 2 and Trial Night 3). On the fifth and final day (Post-Trial Night), the boat was not present and no noise was introduced, but the recordings were analyzed for vocalizations. The two control nights (Pre- and Post-Trial Nights) were used to control for any patterns or variation in vocalizations relating to time of night.

Acoustic Analysis

All acoustic recordings were analyzed using Raven Pro acoustic software. Spectrograms were built in Raven Pro with 7000 samples, a Hanning window with 50% overlap, and time and frequency axes set to 10 s and 1000 Hz, respectively. The 10 minutes before the boat was initially turned on was scored as a baseline period, and each of the 10-minute boat noise and ambient control periods were scored. All vocalizations from the focal male of each nest were annotated in Raven Pro, where the peak frequency and duration of each vocalization were measured, and number of vocalizations per 10-minute period were counted. Vocalizations were assigned to the focal male based on the higher relative amplitude of the vocalizations suspected to be from the focal male compared to fainter vocalizations within the same file.

Statistical Analysis

All statistical analyses were conducted in RStudio (v.2022.07.2; R Core Team 2021). Agonistic vocalizations were defined as the sum of grunts and growls for each fish within each trial period, over each of the 5 days.

A negative binomial generalized linear mixed effects model (GLMM) (*glmmTMB* package; Brooks et al. 2017) was fit to these counts of agonistic vocalizations over the 3 trial days (i.e., days that included the boat noise treatment) to examine whether there was a difference in the number of agonistic vocalizations during boat noise periods versus ambient control periods. Nest ID was included as a random intercept to account for the within-subjects study design, and acoustic treatment (ambient control or boat noise) was the fixed effect. Likelihood ratio tests were used to assess the statistical significance of the acoustic treatment effect.

A second negative binomial GLMM was then used to assess whether there was a difference in overall vocalization count during control nights (Pre-Trial and Post-Trial Nights; no boat noise) or experimental trial nights (Trial Nights 1–3; boat noise present). Again, the nest ID was included as a random effect and the fixed effect for this model was night type (trial or control). Likelihood ratio tests were used to assess the statistical significance of the night type effect.

Statistical analyses were not performed for mating hum vocalizations because there were too few hums present in the experimental recordings.

Ethical Note

All procedures in this study complied with guidelines set by the ASAB/ABS (2012) and the Canadian Council on Animal Care (Olfert et al. 1993) and were approved by the University of Victoria Animal Care Committee (AUP: Juanes-2021-012). All procedures implemented were noninvasive. Following experimentation, the mesh was removed from the nests, all equipment was removed, and fish were allowed to continue guarding their brood in their artificial nests at the study site for the remainder of the breeding season.

Results

There was no significant difference in the number of vocalizations during the ambient control periods (including the baseline period) and the boat noise periods on the three trial nights ($\chi^2 = 1.08$, $df = 1$, $p = 0.30$; Fig. 4). However, the figures show that there may have been slightly more vocalizations in the ambient periods compared to the boat noise periods, particularly on the first and second trial nights, during which no fish vocalized in any of the boat noise periods (Fig. 5); however, this pattern was not statistically significant. As expected, there was also no difference in the number of agonistic vocalizations during the ambient and boat noise time-equivalent periods on the control nights ($\chi^2 = 0.27$, $df = 1$, $p = 0.61$; Fig. 5). However, there were overall more vocalizations during the control nights compared to the trial nights ($\chi^2 = 6.95$, $df = 1$, $p = 0.0084$; Fig. 6).

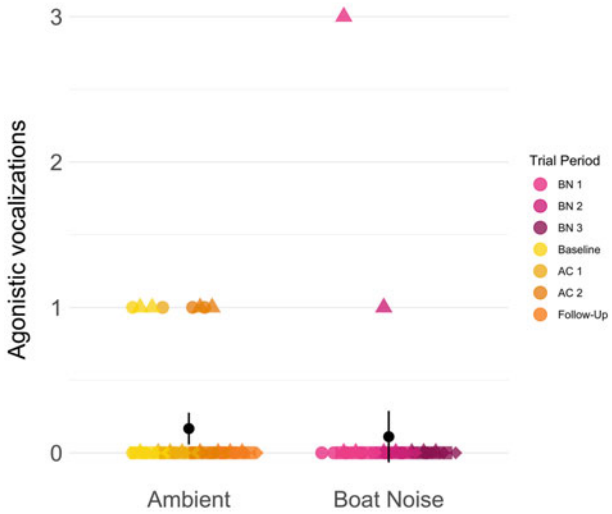

Fig. 4 The number of agonistic vocalizations (grunts and growls), exhibited by each of four nesting plainfin midshipman guarder males during each 10-minute trial period, comprised of alternating ambient control periods and boat noise periods, pooled across the three trial nights. The shapes correspond to the four individual fish tested. The means and 95% confidence intervals are shown in black

Discussion

There was evidence that nesting plainfin midshipman guarder males may decrease their agonistic vocalizations (grunts and growls) in periods when they are exposed to large amounts of boat noise. While there was not a statistical difference in the number of agonistic vocalizations exhibited in sequential 10-minute periods with and without boat noise, there was a pattern of slightly fewer vocalizations during boat noise periods. Furthermore, there was a significant overall decrease in agonistic vocalizations on nights when boat noise trials were conducted, compared to control nights.

Our findings are consistent with Brown et al. (2021) which found that plainfin midshipman guarder males elicited fewer vocalizations (grunts, growls, and hums) in the presence of introduced artificial noise. However, the present study is the first to test whether plainfin midshipman fish alter their vocalizations in response to boat noise. Brown et al. (2021) also found that the plainfin midshipman males increased the amplitude of their hums and lowered the frequency of their vocalizations (i.e., exhibited the Lombard effect) in response to the artificial noise stimulus, which had a fundamental frequency of ~118 Hz with several weaker harmonics, and which strongly resembled a midshipman mating hum. The results presented in this chapter are preliminary and represent only a small part of a larger study, which will also examine whether the males at the study site exhibited the Lombard effect in response

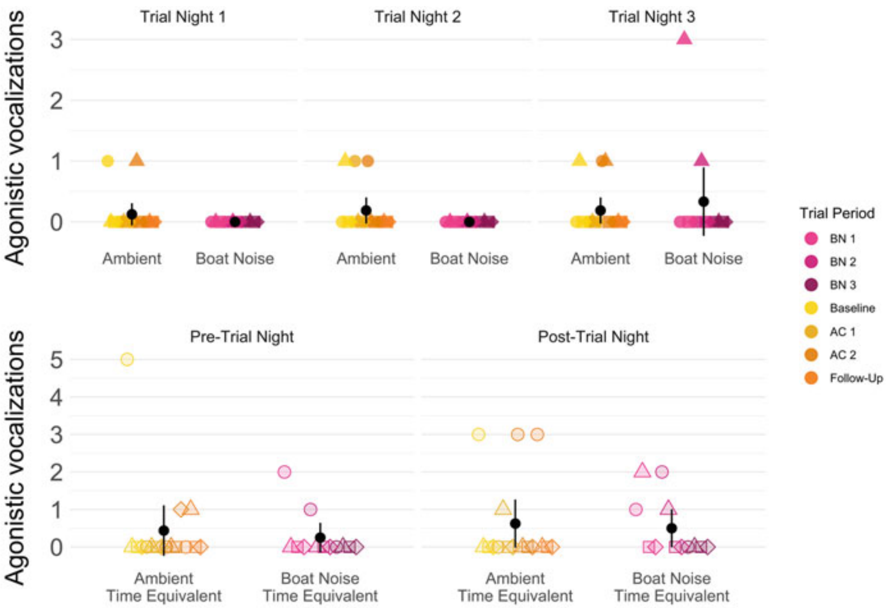

Fig. 5 The number of agonistic vocalizations (grunts and growls), exhibited by each of four nesting plainfin midshipman guarder males during each 10-minute trial period, comprised of four ambient control periods and three boat noise periods, on each night in the five-night trial sequence. Top: the three trial nights; in these trials, the boat periods consisted of a motorboat being driven continuously at full throttle. Bottom: control nights before and after the three trial nights; there was no motorboat or introduced noise present during any part of the control trials, as the control nights were analyzed to compare the vocalizations in each corresponding period to the trial nights. The shapes correspond to the four individual fish tested. The means and 95% confidence intervals are shown in black

to motorboat noise by altering the amplitude or frequency of their vocalizations. The results of this study will help us understand whether the previous results reported in Brown et al. (2021) were due to the males trying to overcome masking by low-frequency anthropogenic noise or if they were trying to outcompete what resembled the hum of an additional rival guarder male.

Several studies have found decreases in fish calling rates in the presence of noise (Ladich 2019), consistent with the results of both the present study and those of Brown et al. (2021). For example, de Jong et al. (2018) tested two species of goby in the lab and found a reduction in acoustic courtship during noise playbacks in both species. This reduction in courtship vocalizations may have contributed to the lower spawning success of painted gobies in the noise treatment group. In the field, Mackiewicz et al. (2021) observed a 32% decrease in male oyster toadfish vocalizations post-exposure to an idling boat engine compared to pre-exposure calling rates. In contrast, increases in calling rate in the presence of noise are commonly observed in birds and mammals to increase signal redundancy – an additional tactic that can be used to overcome masking (Shannon et al. 2016). This increase in calling

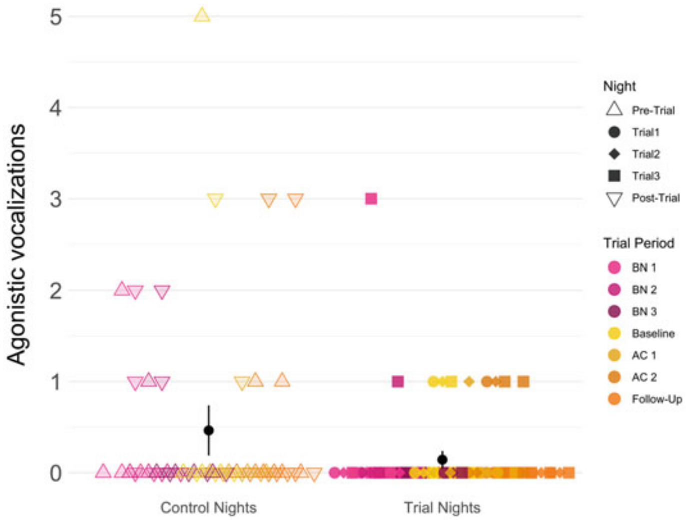

Fig. 6 The number of agonistic vocalizations (grunts and growls), exhibited by each of four nesting plainfin midshipman guarder males during each 10-minute trial period, comprised of four ambient control periods and three boat noise periods, pooled across the two control nights and the three trial nights to compare the overall number of vocalizations present on nights when boat noise was (trial nights) and was not (control nights) present. In the control night "boat noise" periods (BN 1–3; pink data points), no boat or introduced noise was present, as the control nights were used to compare equivalent time periods of the evening to the trial nights when boat noise was present. During the boat noise periods (BN 1–3; pink data points) on trial nights, a motorboat was driven in continuous loops at full throttle. During ambient control periods (Baseline, AC 1–2, and Follow-Up; gold points), the boat engine was shut off and the boat was far from the nests. The means and 95% confidence intervals are shown in black

rate has also been found in fish in a few studies (e.g., Picciulin et al. 2012), but it appears that it may be a less commonly used tactic among fishes given the number of studies reporting the opposite pattern of decreased calling rates during noisy periods.

The primary limiting factor of the current study was the small sample size. This may be why there was only a slight trend of fewer vocalizations during boat noise versus ambient trial periods but not a significant difference. However, the individual-level data of the four fish discussed in the current chapter are only one component of a larger overarching study; additional fish were tested at the group level. The group-level data contain far more vocalizations and will enable us to better assess the effect of the experimental boat noise on all three types of vocalizations – agonistic grunts and growls and the mating hum. The preliminary group-level data are pointing toward a decrease in the number of agonistic vocalizations during boat noise periods, as well as a potential decrease in humming. Further analysis of the data collected in both the group- and individual-level experiments will contribute to our growing understanding of the ways in which anthropogenic noise alters fish vocalizations.

Conclusion

It was evidenced that plainfin midshipman males may reduce their calling rate in the presence of motorboat noise, but those results were not conclusive, and additional data would be required to draw firm conclusions. The overall decrease in vocalizations on trial nights compared to control nights indicates that boat noise did decrease the rate of agonistic vocalizations. However, when comparing sequential boat noise and ambient control periods on trial nights, the data visualization suggests that there might be fewer vocalizations during boat noise periods, but that did not turn out to be a significant pattern. The results were likely impacted by the small sample size; however, a complementary experiment was conducted on groups of nesting plainfin midshipman males and the addition of those data (once analyzed) will allow stronger conclusions to be drawn. Future analysis, both on the individual-level data presented here and the group-level data still being analyzed, will include assessing whether frequency or amplitude of midshipman agonistic vocalizations or mating hums are altered by boat noise.

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