

# Acoustics of fish shelters: Background noise and signal-to-noise ratio

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Fish shelters (flat stones, shells, artificial covers, etc., with a hollow beneath) increase the sound pressure levels of low frequency sounds ( $<150$  Hz) outside the nest cavity, see Lugli [(2012). *J. Acoust. Soc. Am.* **132**, 3512–3524]. Since some calling males only produce sound when a female is inside the shelter, this study examines the effect of sound amplification by the shelter on signal-to-noise ratio (SNR) in the nest. Background noise amplification by the shelter was examined under both laboratory (stones and shells) and field (stones) conditions, and the SNR of tones inside the nest cavity was measured by performing acoustic tests on stones in the stream. Stone and shell shelters amplify the background noise pressure levels inside the cavity with comparable gains and at similar frequencies of an active sound source. Inside the cavity of stream stones, the mean SNR of tones increased significantly below 125 Hz and peaked at 65 Hz (+10 dB). Implications for fish acoustic communication inside nest enclosures are discussed.

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## I. INTRODUCTION

Many soniferous teleosts use cavities below submerged objects (e.g., flat stones, shells, cans, or other artificial covers) as calling and spawning sites. Typically, these fishes (toadfishes, gobies, blennies, etc.) employ low frequency vocalizations to deter rivals or attract prospective mates (Myrberg and Lugli, 2006). Two well-known examples are the “hum” call (main energy at around 100 Hz; Ibara *et al.*, 1983), produced by the male Plainfin midshipman (*Porichthys notatus*) from the hollow under large stones in shallow coastal environments, and the boatwhistle call (main energy from 100 to 280 Hz; Fine, 1978; Thorson and Fine, 2002a), produced by the male toadfish (*Opsanus tau*, *O. beta*) calling below natural (stones, shells) and artificial (e.g., cans) shelters in shallow bays and coasts. Although these vocalizations are usually directed toward external recipients (e.g., a ripe female), in some cases acoustic communication may take place exclusively inside the nest cavity. For instance, the male sand goby emits sounds only when the female enters the nest cavity (a hollow below a small bivalve shell, a small stone) (Lugli and Torricelli, 1999; Lindström and Lugli, 2000).

Lugli (2012) demonstrated that shelters as diverse as flat stones, small bivalve shells or artificial covers, may “amplify” low-frequency acoustic signals emitted by a small source placed inside the shelter cavity. Acoustical stimulation of the shelter with white noise (100–2000 Hz, laboratory) or pure tones (80 Hz–1 kHz, stones in the stream) determined significant pressure amplification (i.e., an amplitude gain) at frequencies below 200 Hz, the gain (from a few decibels up to 18 dB) peaking below 150 Hz (Lugli, 2012). The frequency response of the shelter was assessed mainly

by recording the probe stimulus with a hydrophone placed in front of the cavity opening to mimic a recipient fish approaching the nest. However, a few acoustical tests conducted by placing both the source and the receiver inside the shelter hollow, so as to mimic the emitter and receiver inside the nest, showed that, besides the probe, the background noise was also amplified at low frequencies.

This observation raises two important issues related to the effectiveness of low-frequency acoustic communication by fishes calling inside enclosures, namely, (1) the extent of background noise pressure amplification inside the cavity in comparison to that of an active sound source; (2) the signal-to-noise ratio (SNR) of acoustic communication by a resident fish detecting a sound generated outside or inside the cavity. Two related issues are (3) how far the background noise amplification inside the cavity would propagate outside, and (4) the behavioral responses developed by the resident fish to improve SNR of acoustic communication in the nest.

The main aim of this study was to address these questions by examining the response of the shelter solely to the presence of environmental background noise, measured under both laboratory and field conditions by placing the receiver outside or inside the shelter cavity. The SNR of tones inside the cavity was assessed using flat stones in the stream. I hypothesized that SNR is enhanced inside the cavity, thereby making the use of low-frequency sounds for communication advantageous for bottom-dwelling fishes that spawn inside enclosures. Implications for the acoustic behavior of the territorial male in the nest cavity are discussed.

## II. MATERIALS AND METHODS

### A. Laboratory measurements

The study was conducted using a subsample of natural shelters tested in the companion paper (Lugli, 2013). In the

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present investigation 10 flat stones (mean weight and range: 1950 g, 700–4100 g) and 10 bivalve shells (mean weight, number, and species: 17.2 g,  $n = 3$ , *Scapharca inaequivalvis*; 27.2 g,  $n = 5$ , *Crassostrea gigas*; 12.6 g,  $n = 2$ , *Tapes philippinarum*) were tested.

The experimental setup and the procedure for sound recording and analysis in the laboratory have already been described in a companion work (Lugli, 2012). Briefly, measurements were conducted within a 67-liter laboratory Plexiglas tank ( $55 \times 55 \times 25$  cm, wall thickness: 0.8 cm) provided with a 5-cm thick layer of medium/coarse sand on the bottom. The tank was filled with partially de-mineralized water to a depth of 20 cm. At such water depth, no frequency below 2 kHz will propagate, i.e., the energy decays exponentially with theoretically and empirically determined losses of 20 dB/10 cm (Akamatsu *et al.*, 2002).

Individual shelters were placed in the middle of the tank above the pit obtained by digging away a small amount of sand with a finger so as to leave a small aperture connecting the shelter cavity (formed by the pit and the underside of the shelter above it) to the outside. This arrangement mimicked the hollow dug by the fish and used as hiding place or nest site.

Background noise measurements were made by placing the hydrophone (B&K type 8103) inside the cavity (“MIC IN” measurement) or, in front of the opening (“MIC OUT” measurement). In the first case, the hydrophone was placed in the hollow horizontally just above the substrate, while the cable was buried in the sand as it exited from the nest opening. For the “MIC OUT” measurements, the hydrophone was suspended above the substrate by fixing it to a large photographic tripod placed on the floor above the tank. Measurements were made with the hydrophone held in place vertically (with the tip of the sensor just above the substrate) at 2 cm in front of the shelter opening (further details in Lugli, 2012).

## B. Field measurements

### 1. Response to background noise

Background noise measurements were conducted on 10 flat stones (mean weight and range: 3.5 kg, 0.8–10.5 kg) at noisy sites of stream Stirone (Northern Italy) with modest water current and presence of sources of underwater noise (e.g., small waterfalls, Lugli and Fine, 2003). Water depth was below 40 cm and the bottom was mainly coarse sand, fine gravel, and pebbles (see also Lugli *et al.*, 1992). Stones were chosen among those commonly used by gobies as shelters and nest sites (i.e., large, flat stones with a hollow underneath). The background noise was recorded using a small-size hydrophone (GLG 9190, Edmund Scientific Co., Barrington, NJ) connected to a DAT recorder (CASIO DA-7). For measurements inside the stone hollow (“MIC IN”), the hydrophone was partially buried in the substrate, approximately in the middle of the pit below the stone. The hydrophone was not allowed to touch the underside of the stone. For measurements outside the hollow (“MIC OUT”), the hydrophone was positioned on the substrate facing the stone, approximately 3 cm from the hollow opening. Each stone

was submitted to both types of measurements, and in each case, the background noise was measured twice: with the stone in place and after the stone was removed (see below).

### 2. Tone stimulation experiments

These experiments were conducted on a different group of seven flat stones (mean weight and range: 7.2 kg, 3.9–12.8 kg) at noisy sites of the stream. In addition to measuring the background noise, these stones were stimulated with pure tones following a procedure described in the previous paper (Lugli, 2012). Briefly, a sequence of pure tones in 1/3 octave steps in the range 50–500 Hz was generated with a portable analog signal generator (MINIRATOR MR1; NEUTRIK AG, Shaan, Liechtenstein) connected to an output transformer in turn connected to a small underwater buzzer (details in Lugli, 2012) acting as sound source. Background noise and tones were recorded with the hydrophone positioned in the pit below the stone as described for the measurement of the background noise alone (above). Each stone was stimulated by placing the buzzer on the bottom (1) inside the hollow, at 3–4 cm from the hydrophone (“SOURCE IN”) and (2) outside the hollow, at 10–15 cm from the opening (“SOURCE OUT”) (Fig. 1). The level of sound stimulation was set to produce peak levels of tones within the range of the stream goby sound levels measured at the same distance in the field (Lugli *et al.*, 1995). Thus, during the SOURCE OUT measurements, the stone was stimulated with tone levels about 20 dB lower than during the SOURCE IN measurements (note: for this range of input



FIG. 1. (Color online) Picture of the position of the hydrophone (GLG 9190) and the buzzer during the “SOURCE OUT” measurement of a flat stone (weight: 580 g). Inset: The hydrophone shown without the stone above. All photos are taken in laboratory for convenience.

values, the amplitude gain of the shelter is independent of source level; Lugli, data unpublished). For each type of measurement, the acoustic test consisted of measuring the tone sequence and the background noise in the presence of the stone above the pit and after the stone was removed.

### C. Experimental procedure and analysis of data

All shelters were tested by recording the background noise, or the background noise + tone sequence (field only), with ( $S^+$  record) and without ( $S^-$  record) the shelter on the substrate, the two recording periods lasting 10 (background noise)/30 (tone sequence + background noise) s each and being separated by a silent period of few seconds to allow removal of the shelter.

All field and laboratory measurements were acquired with the PC (sound blaster CREATIVE X-Fi. Sampling rate: 44.100 Hz) using the real-time spectrogram function of AVISOFT and stored as wave files. Fast Fourier transforms (FFT) of each noise segment/tone were computed using AVISOFT (FFT length: 1024 Hz, frame size: 100%, Hamming window). The presence of enhancement of noise/tone frequencies by the shelter was assessed by computing the amplitude difference (AD, dB) of the acoustic signal of interest between  $S^+$  and  $S^-$  records. Background noise was analyzed within 8 Hz wide bands in the range 50–500 Hz. A positive value of AD for a given noise band/tone would mean amplitude gain by the shelter, whereas a negative value would mean amplitude loss (further details below). Thus, the plot of AD values with frequency can be viewed as the frequency response of the shelter (1) to presence of the background noise alone, acting as “environmental” driving stimulus, or (2) to the tone mixed with the background noise. It should be noted that the tone level measured by the hydrophone was, usually, at least 10 dB higher than the background noise level within the corresponding frequency band. Lower SNRs were observed only sporadically for tones below 80 Hz during the SOURCE OUT measurements without the shelter ( $S^-$  records). Therefore, the contribution of the background noise to the tone level was generally negligible. This allowed a reliable estimation of SNR, i.e., the tone level (dB) minus the noise level per unit bandwidth (dB) (Yost, 2000). The value of SNR was determined for each tone using the corresponding 1/3rd octave band of the spectrum of background noise, recorded during the same measurement, for noise level calculation. Computation of SNR for the  $S^+$  record and  $S^-$  record allowed me to determine the gain in SNR of the shelter for each tone ( $\text{gain in } \text{SNR}_x = \text{SNR}_x^{S^+} - \text{SNR}_x^{S^-}$ ,  $x = \text{tone}$ ).

### D. Statistics

The laboratory stone and shell mean gain function for the background noise measured inside (MIC IN measurements) or outside (MIC OUT measurements) the cavity was computed by averaging the values of AD (dB) within each frequency band and calculating the 95% confidence levels (Sokal and Rohlf, 1981; see also Lugli, 2012). The relationship between gain peak amplitude and frequency with stone weight was examined using the Pearson product-moment

correlation test (Sokal and Rohlf, 1981). The same analysis was not attempted for shells because they were of different shapes.

The mean frequency response of the 10 field stones to the stream background noise was computed separately for the MIC IN and MIC OUT measurements following the same procedure described for laboratory shelters. The mean gain (+95% confidence interval) in SNR of the seven field stones was determined for each tone and plotted separately for SOURCE IN and SOURCE OUT measurements.

## III. RESULTS

### A. Laboratory measurements

The background noise present in the experimental tank (Fig. 2, left spectrograms) was mainly low-frequency noise with baseline spectrum levels from 45 to 60 dB (re  $1 \mu\text{Pa}/\text{Hz}^2$ ) and multiple peaks of energy mostly below 500 Hz. Most shelters showed remarkable amplitude gains of background noise frequencies in the range 60–220 Hz, when the hydrophone was in the pit (Fig. 2, upper-right spectrogram) but not in front (Fig. 2, lower-right spectrogram) of the shelter opening. Individual gain functions for the background noise measured inside the hollow differed among shelters both in term of amplitude levels and peak frequency (Fig. 3). In general, the gain peaked either at around 100 or 160 Hz in

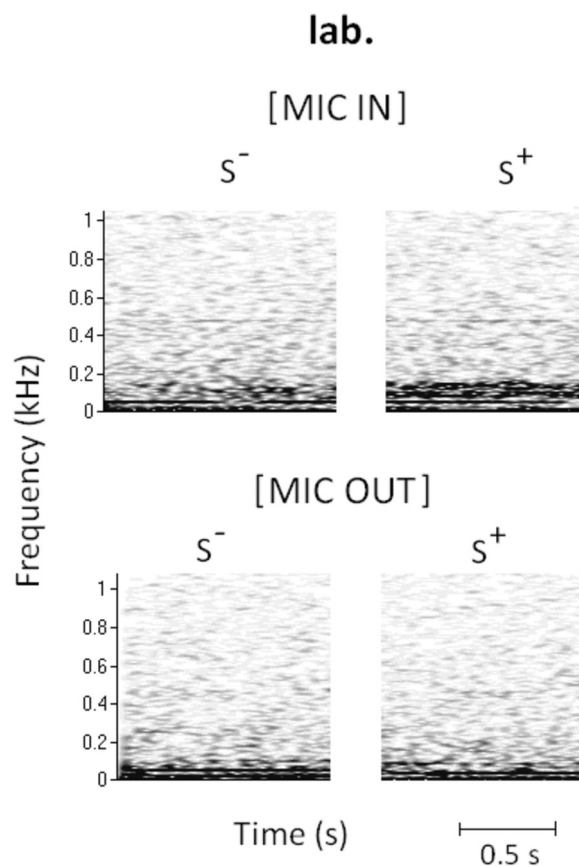


FIG. 2. Spectrogram of the background noise (frequency band: 0–2 kHz, FFT length: 520, Hamming window) recorded during  $S^-$  and  $S^+$  periods for two different laboratory stones with the hydrophone positioned inside the stone hollow (MIC IN, top plot), or in front of the hollow opening (MIC OUT, bottom plot) (see text for explanations).



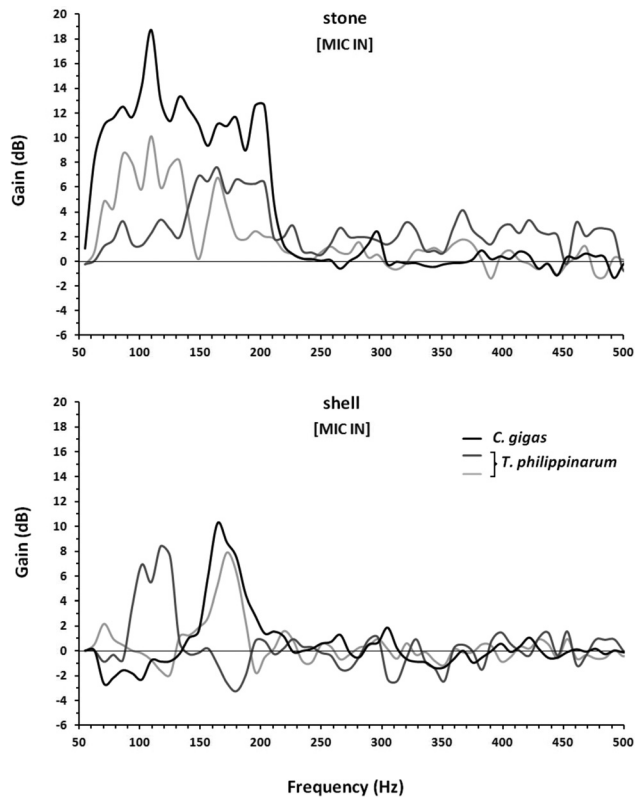


FIG. 3. Individual gain functions of three stones (upper plot) and three shells (lower plot) taken as an example, for the background noise measured with the hydrophone inside the hollow (MIC inside).

most shelters (examples in Fig. 3). However, gain was higher (up to 20 dB) and extended over a broader frequency range in stones. Stones showed significant amplitude gains for background noise frequencies in the range 70–220 Hz (Fig. 4, gray area on the upper graph) with a mean gain peak at 110 Hz (12 dB), whereas shells showed significant gains for the background noise frequencies around 100 Hz (3 dB) and 160 Hz (6 dB). Maximum gain of stones increased significantly with stone weight ( $r^2=0.821$ ,  $P < 0.01$ ,  $n = 10$ ; Fig. 5), whereas peak frequency was unrelated to stone weight ( $r^2=0.251$ , NS,  $n = 10$ ). The background noise amplification by stone and shell cavity was not detected when the hydrophone was in front of the shelter opening (see Fig. 7 for the same result obtained for field stones).

## B. Field measurements

The background noise of the stream (Fig. 6) was likely low-frequency turbulence and flow noise below 100 Hz (Lugli and Fine, 2003) and bubble noise above 200 Hz. Noise frequencies below 200 Hz were amplified inside the cavity (i.e., with the stone above the hydrophone). Gain peaked at around 100 Hz (range: 78–109 Hz,  $n = 7$ ), the peak amplitude averaging 7.5 dB (range: 4–15 dB,  $n = 7$ ) (Fig. 7, bottom graph). There was no background noise amplification outside the cavity, as measured by the hydrophone in front of the cavity opening (Fig. 7, top). Amplitude of tones below 150 Hz increased inside the cavity (an example is shown in Fig. 7, top). Gain peaked at tone frequencies around 100 Hz (range: 50–125 Hz,  $n = 7$ ), its peak amplitude averaging

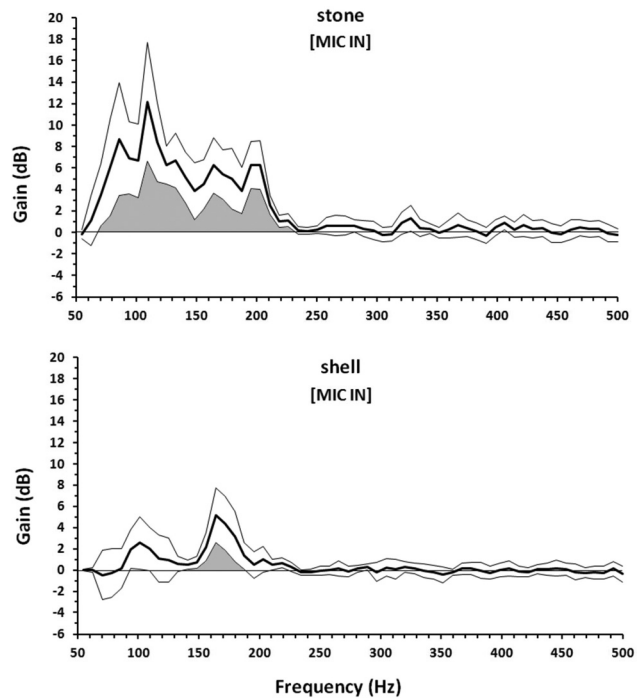


FIG. 4. Mean amplitude gain of stones ( $n = 10$ ) and shells ( $n = 10$ ), for the background noise measured with the hydrophone inside the hollow (MIC inside). The thin lines on each plot indicate the 95% confidence interval of the mean gain (thick line). The shadowed area below the lower limit of the confidence interval marks the frequency region with statistically significant gains.

17.5 dB (range: 10–31 dB,  $n = 7$ ). The SNR of tones below 125 Hz was increased below the stone (Fig. 8, top). SNR gain had a maximum at tones below 100 Hz in all but one stones, the maximum gain averaging 13.4 dB (range: 8–22 dB,  $n = 7$ ). The analysis of the mean gain of SNR of tones (Fig. 9) showed the stone increased the ratio significantly at all tones below 125 Hz (Fig. 9, shaded area on top graph), the maximum mean SNR gain (+10 dB) occurring at 65 Hz. There was no amplitude or SNR increase inside the cavity when tones were broadcasted outside (Figs. 8 and 9, bottom graphs).

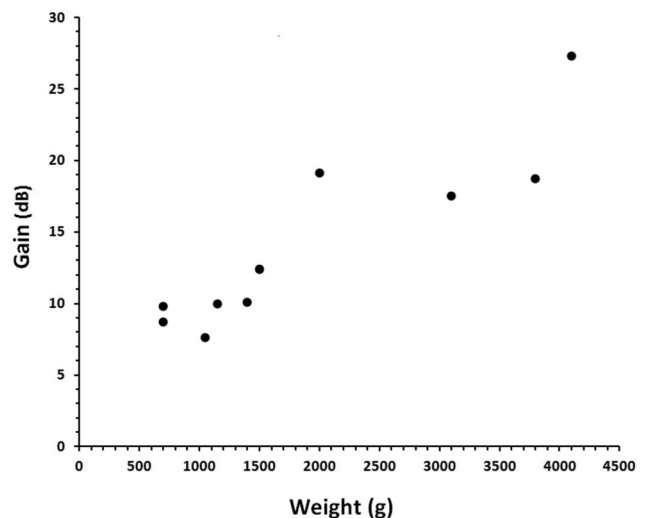


FIG. 5. Relationship of peak gain with weight of stone ( $n = 10$ ).

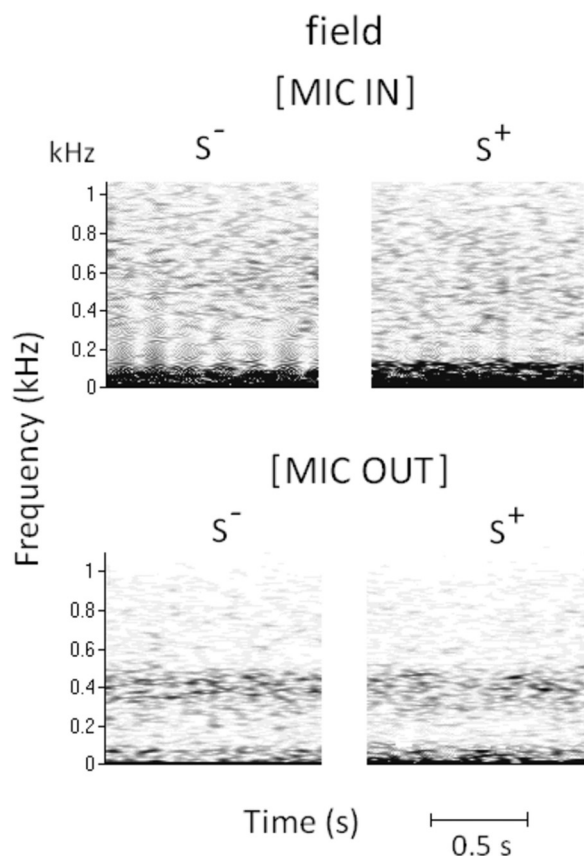


FIG. 6. Spectrogram of the background noise (frequency band: 0–2 kHz, FFT length: 520, Hamming window) recorded during  $S^-$  and  $S^+$  conditions of two different field stones with the hydrophone positioned inside the stone hollow (top plot), or in front of the hollow opening (bottom plot) (see text for explanations).

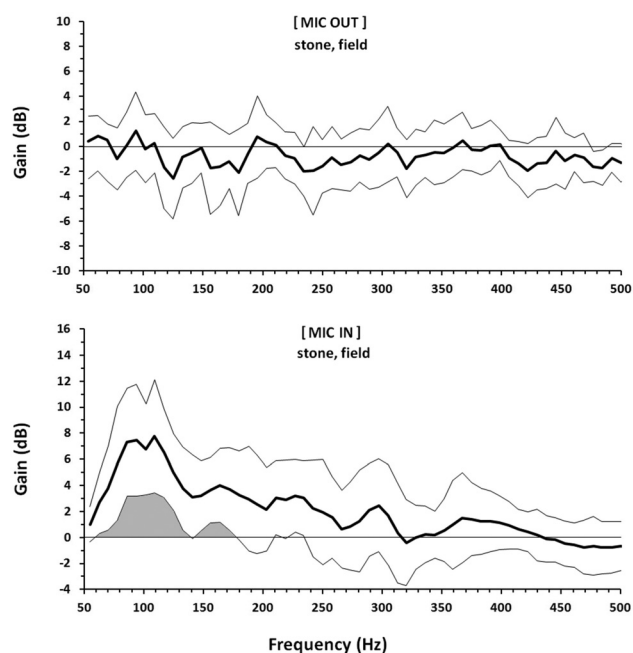


FIG. 7. Mean frequency response (thick line) and 95% confidence limits of the mean (thin lines) of field stones to the background noise measured with the hydrophone in front of the opening (top) and inside the hollow (bottom).

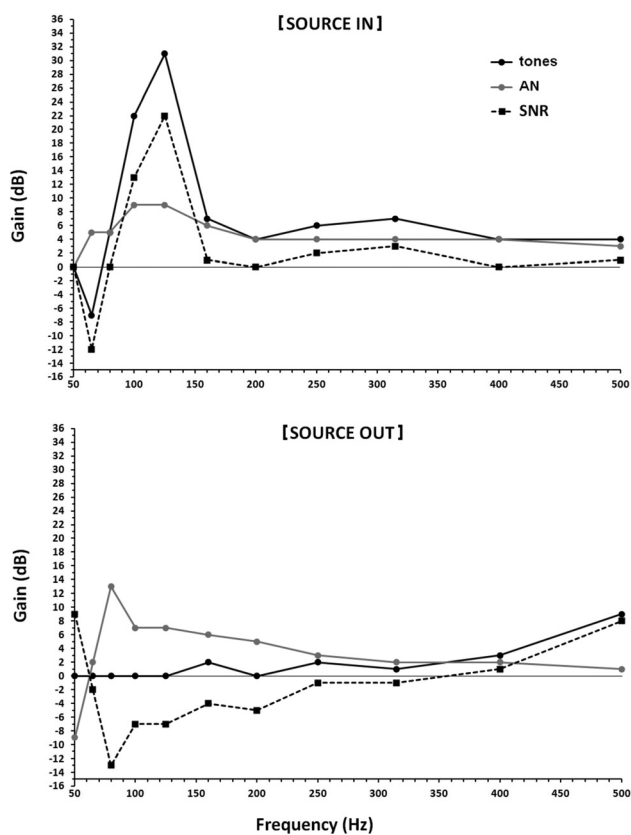


FIG. 8. The frequency response of the hollow of a field stone (taken as an example) to tones (continuous black line) and background noise (broken line), plotted together with the corresponding gain in SNR (continuous gray line), when the stone was driven by tones broadcasted inside (top) or outside (bottom) the hollow (see Sec. II for explanations).

#### IV. DISCUSSION OF RESULTS

In a companion study (Lugli, 2012) I showed that flat stones, bivalve shells and artificial covers used by fishes as shelters and nest sites may amplify the acoustic pressure of pure tones and broad band probe signals emitted by a small sound source (a hemispheric piezoelectric transducer) placed inside the shelter cavity at frequencies below 200 Hz. Results showed that amplitude gain was higher for stones (maximum gain: 6–18 dB) than small bivalve shells (maximum gain: 3–8 dB). This study supports and strengthens further these conclusions by showing that bivalve shells and flat stones may amplify the low-frequency environmental background noise measured inside the shelter cavity with comparable gains and at similar frequencies. For example, in both studies the mean maximum gain of stones at around 100 Hz was 12 dB under laboratory conditions and 8 dB in the stream. In addition, in both studies there was a similar positive relationship between maximum gain and stone weight. Differences were also noted, however. Mean gain of shells (6 dB in both studies) peaked at around 100 Hz when the shelter was driven by the sound source inside the cavity (Lugli, 2012), and at 170 Hz by exploiting the environmental background noise as probe (this study). In addition, unlike the results reported in the companion paper (Lugli, 2012) for the shelter driven by the buzzer inside the cavity, in the present study no amplitude gain was detected by the receiver placed in front of the shelter opening. Apparently, the background noise collected by the

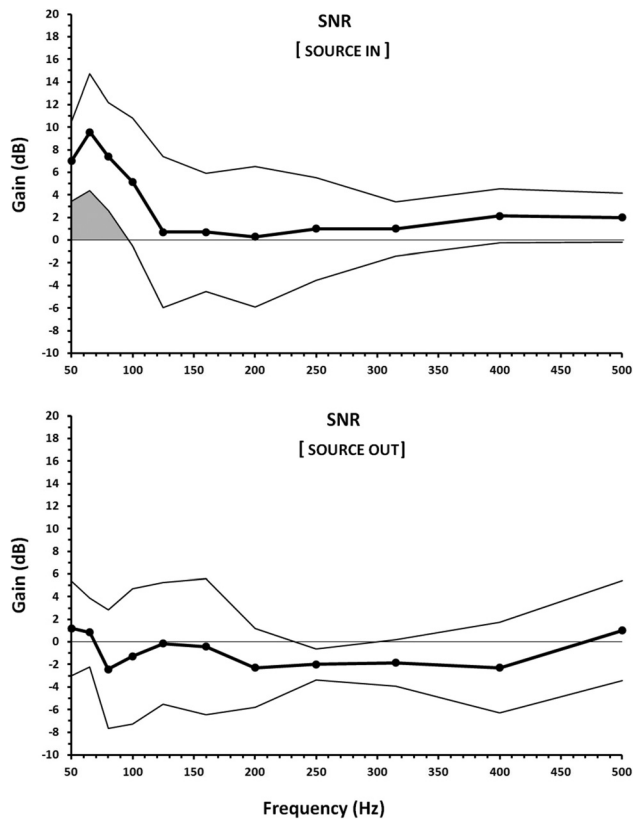


FIG. 9. Mean SNR gain inside the hollow of stream stones ( $n = 7$ ), when the stone was driven by tones broadcasted inside (upper plot) or outside (bottom plot) the hollow. The upper and lower limits (thin lines) of the 95% confidence interval of the mean value (thick line) are shown. The shaded area marks tone frequencies with statistically significant SNR gain.

shelter (coupled to the substrate) is only amplified inside the cavity, i.e., the shelter, *per se*, cannot act as a acoustic radiator in absence of an active sound source inside it. It is not clear from this study whether the background noise energy amplified by the shelter (stones and shells in laboratory, stones in the stream) propagated through the water medium or the bottom. Indirect evidence suggests the latter explanation is more likely since results of tonal stimulation tests of flat stones conducted in the stream showed amplitude gain in the cavity is barely present or totally absent when the source was placed outside (see also [Lugli, 2012](#)).

The findings of the present study may improve our understanding of acoustical communication by bottom-dwelling teleosts (e.g., toadfishes, gobies, sculpins) using underwater covers as breeding sites. Many species calling inside cavities emit sounds with dominant frequencies below 200 Hz ([Myrberg and Lugli, 2006](#)), an adaptation which may be the result of environmental selective pressures determined, in part, by the amplification properties of the nest hollow ([Lugli, 2012, 2013](#); this study). However, for an effective acoustic communication the sound must also be detected by intended receivers with a favorable SNR. The results of acoustical tests conducted in laboratory and in the stream showed that a fish inside the cavity may experience increased low frequency background noise levels up to 20 dB higher than outside. The presence of elevated noise levels in the cavity might mask hearing thresholds, and

negatively affect the SNR of (1) outside sounds detected by the resident male, or (2) sounds emitted by the resident male toward another male, or female, inside the nest. These issues were addressed by performing tone stimulation experiments on flat stones in the stream with the speaker placed inside or outside the cavity. When the speaker was placed outside, the SNR of tones below 150 Hz (i.e., the range of background noise frequencies enhanced by the stone) tended to decrease inside the cavity. This effect, however, was not observed in all stones and, overall, it was not significant. On the other hand, if the speaker was inside the cavity, the SNR of low-frequency tones was remarkably increased, particularly below 100 Hz. Indeed, the maximum mean SNR gain (+10 dB) of field stones occurred at 65 Hz. Thus, the stone increased the acoustic pressure of a sound emitted inside the cavity to higher extent than the background noise pressure at lower frequencies. From the perspective of acoustic communication this finding suggests that, when both the emitter and receiver are in the nest, gain in SNR inside the hollow is greatest if the sound energy is concentrated below 100 Hz. Two particle-motion sensitive species, the stream goby, *Padogobius bonelli*, and the Arno goby, *Gobius nigricans*, call and spawn under stones of the kind tested in the present study. In the stream goby, the pulse spectrum of the pre-spawning sound (a vocalization emitted by the male when the female enters the nest cavity, [Lugli et al., 1995](#)) usually peaks below 100 Hz. In the Arno goby, the frequency of the tone sound (a vocalization emitted by the male toward a female approaching or entering the nest cavity, [Lugli et al., 1996](#)) ranges from 60 to 90 Hz. Apparently, both species seems to exploit the amplification properties of the cavity to enhance the SNR of their sounds when the receiver (e.g., a ripe female) is inside the nest. [Note: [Lugli and Fine \(2007\)](#) showed that pressure and velocity spectra of the goby sounds are similar. Furthermore, the amplitude gain by the shelter cavity is similar for sound pressure and particle velocity at low frequency; Lugli, unpublished data). Thus, the above conclusions hold regardless of the physical quantity being measured (i.e., acoustic pressure vs particle displacement or its derivatives).] Of course, background noise amplification inside the cavity has no effect on SNR of a sound broadcasted from the nest and detected by an external receiver.

Although the stone is not likely to decrease dramatically the SNR of an external sound reaching a receiver inside cavity, background noise amplification by the shelter might impair the detection of low frequency acoustic cues by the male inside the nest, especially in places close to sources of elevated levels of low-frequency noise, e.g., waterfalls or breaking waves. Perception of noise frequencies enhanced by the shelter (50–200 Hz) may involve both the lateral line and the inner ear. The lateral line of the fish is primarily sensitive to pressure gradients associated to the local flow field generated by a close source of sound (e.g., a speaker inside the cavity) at frequencies from 10 Hz to just above 100 Hz ([Kalmijin, 1988](#); [Coombs and Montgomery, 1999](#)). On the other hand, the ear of auditory nonspecialists (e.g., a goby) is sensitive to the particle motion associated to the low-frequency acoustic near field of the source ([Popper and Fay, 1999](#)). Among teleosts lacking auditory specializations,



those using shelters as calling and nest sites have the best hearing frequencies in the range from just below 100 Hz up to only 200–300 Hz (e.g., [Lugli et al., 2003](#)), i.e., the range of frequencies most enhanced by the shelter. Thus, because of pressure amplification by the hollow, a sheltered male must be exposed to higher levels of low-frequency background noise than outside. This fact might affect the behavior of the male in his nest in important ways. For instance, the male goby spends a significant amount of time patrolling the outer environment of the nest by standing still below the shelter with the head at, or just outside, the opening. Interestingly, gobies have a developed head canal system but, typically, lack of trunk lateral line ([Miller, 1986](#)). This posture might increase the SNR of communication and favor the correct detection of relevant sound stimuli from the outside environment because the enhanced background noise levels present inside the nest cavity would not interfere with detection of low frequencies by the ear and/or the head lateral line system of the fish at the nest opening. On the other hand, sound production among gobies takes place mostly, or exclusively, inside the nest cavity ([Lugli et al., 1995](#)). In this way, the calling male would maximally exploit the low-frequency amplification by the shelter since the sound-producing mechanism in these fishes is located in the head region ([Parmentier et al., 2013](#)). Like gobies, the male toadfishes call from the nest (typically a large stone), lying often with the head just outside the hollow and the remaining part of the body below the shelter ([Barimo and Fine, 1998](#); Michael Fine, personal communication). Besides calling, the male toadfish must keep track of neighbors' calling behavior in order to acoustically tag their sounds ([Thorson and Fine, 2002b](#)). Thus, listening to neighbors' sounds appears as much as important as the sound production for the nesting male toadfish. Results of this study indicate that the male posture with the head just outside the hollow would increase the efficiency of sound communication for two main reasons: the male could (a) produce louder sounds by exploiting sound amplification properties of the nest (the sonic apparatus of toadfishes is located in the trunk of the fish body), and (b) improve listening by avoiding auditory masking from elevated background noise levels inside the nest (but the lateral line of the fish would be potentially masked by background noise frequencies at around or below 100 Hz).

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