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Reliable characterization of sound features in fishes begins in open-water environments[a)]

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ABSTRACT:

Many fishes use sounds to communicate in a wide range of behavioral contexts. In monitoring studies, these sounds can be used to detect and identify species. However, being able to confidently link a sound to the correct emitting species requires precise acoustical characterization of the signals in controlled conditions. For practical reasons, this characterization is often performed in small sized aquaria, which, however, may cause sound distortion, and prevents an accurate description of sound characteristics that will ultimately impede sound-based species identification in open-water environments. This study compared the sounds features of five specimens of the silverspot squirrelfish *Sargocentron caudimaculatum* recorded at sea and in aquaria of different sizes and materials. Our results point out that it is preferable to record fish sounds in an open-water environment rather than in small aquaria because acoustical features are affected (sound duration and dominant frequency) when sounds are recorded in closed environments as a result of reverberation and resonance. If not possible, it is recommended that (1) sound recordings be made in plastic or plexiglass aquaria with respect to glass aquaria and (2) aquaria with the largest dimensions and volumes be chosen. © *2023 Acoustical Society of America.* https://doi.org/10.1121/10.0020149

I. INTRODUCTION

Many fishes use sounds for communication purposes in a wide range of behavioral contexts related to aggression (e.g., competitive feeding, intra- and interspecific chase, and territory defence), distress or alarm situations, conspecific identification, and reproduction (e.g., courtship interactions, mate choice, mate quality assessment, and coordination of gamete release ; Lobel *et al.*, 2010; Amorim *et al.*, 2015). The increasing number of studies concerning fish vocal abilities indicates that acoustic communication is an important aspect of teleost biology in freshwater and at sea and should be integrated as such in the study of this group. As a result, fish bioacoustics has gradually gained recognition. It has switched from studies on few target species to long-term, large-scale monitoring studies, which are capable of providing high resolution information on population, community, and ecosystem dynamics (Bolgan and Parmentier, 2020; Parmentier *et al.*, 2021). Such kinds of studies require the use of modern techniques, such as passive acoustic monitoring (PAM), that rely on the recording of soundscapes using passive acoustic recorders (Rountree *et al.*, 2006; Farina and James, 2016; Bertucci *et al.*, 2020; Di Iorio *et al.*, 2021). This methodology has been proven to provide information in terrestrial (Gasc *et al.*, 2013; Sueur *et al.*, 2014) and aquatic environments with a particular interest in fish (Ruppé *et al.*, 2015; Bertucci *et al.*, 2015; Desiderà *et al.*, 2019). In marine ecosystems, this technique has become quite popular with respect to freshwater, notably due to the considerable lack of descriptive studies on fish sounds in freshwater habitats (Rountree *et al.*, 2019; Desjonquères *et al.*, 2020). Using PAM, sounds emitted by fish for communicative purposes can be used not only as a proxy of species diversity but also to give information about biological processes such as diel and seasonal cycles of biological events, relative abundance, delimitation of spawning areas, etc. (Rountree *et al.*, 2006; Bolgan and Parmentier, 2020).

However, there is still a significant lack of knowledge and gaps in fish bioacoustics that limits reliable species identification and the ability to provide a solid picture of the fish communities. In most monitoring studies, fish sounds are often classified into categories (referred to as sound types) based on qualitative and quantitative acoustic properties (Desiderà *et al.*, 2019; Raick *et al.*, 2023). A sound type refers to sounds that share similar acoustic features. It is usually presumed to be emitted by one species and/or regroups sounds from multiple, sometimes closely related

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species. Moreover, a species can also produce different sound types as has been observed in the well-studied genus *Dascyllus* (Mann and Lobel, 1998; Parmentier *et al.*, 2010). Using sonic signatures for species identification, therefore, continues to be a challenge to bioacousticians. This identification is usually performed in two ways. The first way implies the use of underwater camera coupled with hydrophones, allowing the identification of vocal species as they produce sounds. This, though, works better with species that stay in the vicinity of their territory and whose sounds are associated with body movements or displays. The second way requires to catch and keep species in captivity within tanks (Amorim *et al.*, 2013; Horvatić *et al.*, 2019; Chang *et al.*, 2022). The goal is then to elicit fish to produce sounds and use the acoustical features of these sounds to establish relationships with sounds recorded in the field (Parmentier *et al.*, 2011; Parmentier *et al.*, 2022). This method allows to isolate the sounds produced by a species without ambiguity from other sources (Rountree *et al.*, 2006). However, the characteristics of sounds are hard to assess due to many physical constraints when recording in small tanks (Parvulescu, 1964,1967; Rogers *et al.*, 2016) because it can modify the acoustic properties (e.g., dominant frequency, sound-pressure level, sound duration, or pulse period; Fish and Mowbray, 1970; Akamatsu *et al.*, 2002; Okumura *et al.*, 2002; Parmentier *et al.*, 2014) and make it more difficult to establish relationships. In small sized tanks, indeed, the effects of reverberation and resonance are greater. Reverberation is defined as the persistence of sound in an enclosed space as a result of multiple reflections against walls after sound generation has stopped (Yost, 1994). In acoustics, resonance refers to the capacity of a material structure to vibrate at a certain frequency (Hawk, 2018), which is called resonant frequency. Depending on its dimensions, each aquarium has its proper resonant frequency. The spectrum shape of fish sound recorded inside small tanks can be measured faithfully under two conditions (Okumura *et al.*, 2002): (1) the fish sound frequency range is lower than the minimum resonant frequency of the tank, and (2) the hydrophone is placed within the range of attenuation length from the fish. Attenuation length is defined as the length which causes a $-20\,\text{dB}$ sound reduction (Okumura *et al.*, 2002). Therefore, in the perspective of reliable species identification, improving our understanding of the effects of the recording environment on sound characteristics is essential. Although the existence of pitfalls when recording sounds in tanks has been known for decades, those have been poorly described or overlooked in many bioacoustics studies (Jézéquel *et al.*, 2022). Akamatsu *et al.* (2002) investigated how water depth and distance from the transducer modified artificial sounds (five-cycle tone bursts of 1-kHz sound) in a 170-l rectangular glass tank, and Parmentier *et al.* (2014) examined the effects of different experimental conditions (floating cages and concrete and fiberglass tanks of various sizes) on sound characteristics in *Sciaenops ocellatus*.

The present study aims to address, simultaneously, the main limitations of these latter two studies as (1) it will use true fish sounds (instead of artificial sounds as in Akamatsu

et al. 2002), (2) the same specimens will be tested in different recording environments on the same day, and (3) sounds will be recorded when fish are handheld (i.e., in the same behavioral context), which assures standardization and an accurate comparison of sounds. This technique has been validated in several teleost families at sea and in freshwater (e.g., Kaatz and Lobel, 2001; Parmentier *et al.*, 2011; Mélotte *et al.*, 2016; Parmentier *et al.*, 2021; Raick *et al.*, 2022). For the purpose of our study, sounds of five specimens of the holocentrid *Sargocentron caudimaculatum* were recorded at sea and in tanks made of different materials (plastic, plexiglass, and glass) and various sizes to investigate how the recording environment distort sounds. Our results are not exclusive to the marine environment.

II. MATERIALS AND METHODS

A. Animals

Five specimens of the silverspot squirrelfish (*S. caudimaculatum*, Rüppell 1838) [111–171 mm total length (TL)] were collected using nets by snorkeling at night in April 2022 on the coral reefs of Moorea (French Polynesia). After capture, fish were brought back in coolers filled with seawater and housed at the "Centre de recherches insulaires et observatoire de l'environnement" (CRIOBE). Fish were maintained in group in a 1500 L tank with running seawater coming directly from the environment. Rocks were provided to allow fish to shelter. All of the specimens were released at the end of the experiment.

B. Sound recordings and analyses

Sounds of each specimen were first recorded at sea and then randomly in four different environments on the same day (Table I). Water temperature during recordings was 30 °C. Sounds were recorded with an Orca hydrophone (sensitivity, $-186\,\text{dB}$ re $1\,\text{V}/\mu\text{Pa}$) connected via an Orca amplifier (ORCA Instrumentation, Brest, France) to a Tascam recorder (TASCAM DR-05X, Milton Keynes, UK). Sample rate was 48 kHz. The hydrophone was placed at the center of the different tanks in all three dimensions. The fish were handheld at a distance of 5 cm from the hydrophone (mouth toward the hydrophone and parallel to the longest tank wall) with the dorsal and pectoral fins blocked. At sea, the fish were also placed at 5 cm from the hydrophone and 15 cm deep in the water. Between the recordings, specimens were placed back in the group aquarium to rest for 15 min. Small fin clips in their caudal fins permitted their identification. Recordings *per se* were fast (~3 min per environment per fish). About 30 sounds were recorded for each fish in each environment. From these sounds, the 15 best-quality sounds (i.e., with the highest signal-to-noise ratios) were selected for the analyses. Minimum resonant frequency of the recording tanks and attenuation lengths for *S. caudimaculatum* sound frequencies have been calculated based on the equations of Akamatsu *et al.* (2002) (Table I).

Sounds were manually investigated using the software Avisoft-SAS Lab Pro 5.2.13 (Avisoft Bioacoustics,

TABLE I. Characteristics of the five recording environments. Numbers in brackets correspond to water height in the tanks. Recordings made at sea were performed in lagoons with ~1 m water depth. The name of the recording environment, composed of two parts, refers to (1) the material composing the tank and (2) the water volume during recordings (in liters, l). Minimum resonant frequency of the different tanks and attenuation length have been calculated based on the equations of Akamatsu *et al.* (2002). Values of attenuation length are similar for sound dominant frequencies of *S. caudimaculatum* (<300 Hz). L, length; W, width; H, height; D, diameter.

Name	Environment	Dimensions (L × W × H) or (D × H) (cm)	Total volume (l)	Water volume (l)	Resonant frequency (kHz)	Attenuation length (cm)
Plastic15	Plastic basin	35 × 29 × 22 (15)	22	15	6	10
Glass119	Glass tank	55 × 85 × 35 (25.5)	164	119	3,3	18
Plexi190	Plexiglass tank	138 × 55 × 30 (25)	228	190	3,3	17
Plastic720	Plastic pool	172 × 60 (31)	1393	720	2,5	41
Sea	Lagoon					

Glienicke, Germany). They were first low pass filtered (2000 Hz). Then, six acoustic variables were measured from sounds (Fig. 1): (1) sound duration (ms), (2) number of pulses, (3) periods of pulses (measured as the peak-to-peak intervals between two consecutives pulses, ms), (4) duration of the last pulse (ms) based on oscillograms, (5) dominant frequency (defined as the frequency with the highest energy, Hz) of the complete sound, and (6) of the second pulse in the sound based on power spectra. Second pulse was chosen because sounds were mostly composed of 3–4 pulses and we preferred to take frequency measurements on a pulse inside the sound (i.e., to avoid the first and last pulses of a series).

C. Statistical analyses

The influence of the recording environment on sound features was assessed for each individual separately. We made this choice to investigate if the different specimens showed the same pattern of results. Significance level = 0.05. Shapiro-Wilk tests were used first to examine the distribution of the data in each group (i.e., each recording environment). When the assumption of normality was met in all of the groups (the five different environments), Levene's tests were performed to assess the assumption of homoscedasticity. Despite the use of log and square root transformed data, these assumptions were not met. This procedure, repeated for each individual, allowed us to decide that nonparametric tests should be used in the analyses. First, we investigated the presence of a correlation between sound and last pulse durations on the whole dataset using the nonparametric Spearman correlation. A Kruskal-Wallis test followed by Dunn's multiple comparison test (with Bonferroni correction) for pairwise comparisons between recording environments were then performed for all individuals. Variability of the acoustical variables was also assessed for each recording environment through the values of standard deviations. Differences between recording environments in acoustical variables were acknowledged only when at least four specimens of the five (80%) gave the same significant results.

III. RESULTS

Sounds were recorded in all of the experimental conditions. In each case, specimens of *S. caudimaculatum*

produced calls that consisted of trains of a variable number of pulses (2.6 ± 0.5–4.9 ± 0.3) with gradually increasing pulse periods toward the end of the call.

Sound frequency range of *S. caudimaculatum* (<300 Hz; Table II) is much lower than the minimum resonant frequency of all experimental aquaria (Table I). Similarly, the recording distance from the mouth of the fish to the hydrophone in this study was ~5 cm, which is well within the attenuation length of all aquaria (Table I).

Sounds recorded under different conditions were highly and positively correlated to the duration of their last pulse (Spearman's rho = 0.93; *p*-value < 0.0001). Consequently, only sound duration was kept for further analyses.

A. Differences in acoustical features between recording environments

Sounds recorded in the glass tank (Glass119) were significantly longer (168–221 ms) than those recorded at sea (57–77 ms) and in the large plastic tank [Plastic720; 61–83 ms; df (degrees of freedom) = 4, *p* < 0.001; Figs. 2 and 3(a); Table II; supplementary Table S1].[1] Although differences were not always significant, sound duration varied similarly in almost all individuals: (1) sounds were the shortest at sea, (2) their duration then increased as the size of the plastic and plexiglass tanks decreased, and (3) sounds were the longest in the glass tank (Table II). The number of pulses was significantly different between the plexiglass tank (Plexi190) and Plastic720 (df = 4, *p* < 0.01 for four out of five individuals; Table II; supplementary Table S1).[1] We did not find differences in the pulse periods between the recording environments [Fig. 3(b); Table II; supplementary Table S1].[1]

Dominant frequency of sounds was significantly lower in Glass119 than in Plexi190 and plastic tanks [df = 4, *p* < 0.01 for four out of five individuals; Fig. 4(a); Table II; supplementary Table S1].[1] Similarly, the dominant frequency of the sounds recorded in the glass tank tended to be smaller than those in the sea in four specimens out of five (131–154 Hz in Glass119 vs 177–215 Hz in the sea). More generally, the dominant frequency decreased when sounds were recorded in glass tanks, whereas it increased when sounds were recorded in plastic tanks with respect to the sea. Finally, the dominant frequency of the second pulse of
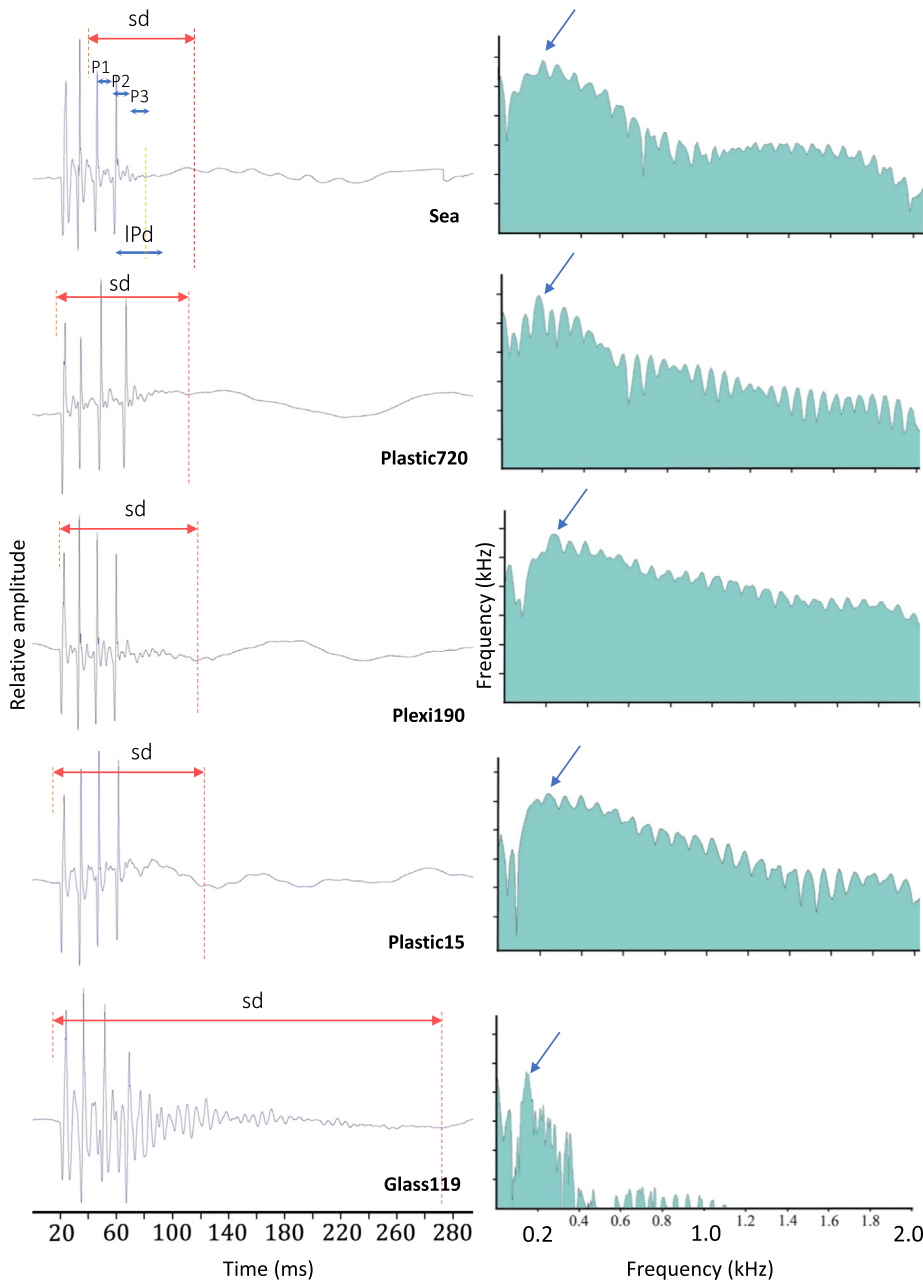
FIG. 1. (Color online) Oscillograms (left) and power spectra (right) of four-pulse sounds produced by the same individual of *S. caudimaculatum* in the five different recording environments are shown. sd, sound duration; P1, P2, P3, pulse periods; lPd, last pulse duration. The blue arrows on the power spectra indicate the dominant frequency of each sound (Hz). Note that dominant frequency is lower in Glass119 and the modification in the shape of the power spectrum with respect to the other recording environments.

sounds was only found significantly different between Glass119 and Plastic720 [Fig. 4(b); Table II; supplementary Table S1].[1]

B. Variability of the acoustic traits

In a general way, variability of traits followed the patterns observed for the acoustical parameters themselves. The variability of sound duration was greatly modified by the recording environment: it increases from the sea to decreasing sized plastic tanks, to glass tanks [Fig. 3(c)]. There was no effect of the recording environment on the variability of pulse periods or the number of pulses in the sound [Fig. 3(d)]. Variability of the dominant frequency of sounds decreases with the values of dominant frequency: the smaller the dominant frequency, the lower the variability of

this trait, as observed in the glass tank and the sea with respect to the plastic tanks [Fig. 4(c)]. No clear pattern was observed for the dominant frequency of the second pulse [Fig. 4(d)].

IV. DISCUSSION

High-quality sounds are required to make accurate acoustical characterization and establish relationships between species and sounds recorded in the field through PAM (Parmentier *et al.*, 2011; Parmentier *et al.*, 2022). It has been demonstrated that the recording environment can modify sounds, especially in small tanks (Akamatsu *et al.*, 2002; Novak *et al.*, 2018), in narrowband fish (Kaatz and Lobel, 2001; Parmentier *et al.*, 2014) and broadband marine crustaceans sounds (Jézéquel *et al.*, 2019; Jézéquel *et al.*,

TABLE II. Summary of the acoustic characteristics (mean $\pm$ sd). ID, specimen number; ENV, recording environment; TL, total length.

ID	ENV	Sound duration (sd) (ms)	Number of pulses	Last pulse duration (ms)	Pulse periods (ms)	Dominant frequency of the sound (Hz)	Dominant frequency of the second pulse (Hz)	TL (cm)
1	Plastic15	98 $\pm$ 32	4.2 $\pm$ 0.4	55 $\pm$ 28	13 $\pm$ 1	226 $\pm$ 44	176 $\pm$ 29	16.7
1	Glass119	219 $\pm$ 30	3.8 $\pm$ 0.4	179 $\pm$ 32	14 $\pm$ 1	147 $\pm$ 9	155 $\pm$ 21	16.7
1	Plexi190	86 $\pm$ 12	4.6 $\pm$ 0.5	38 $\pm$ 10	13 $\pm$ 1	252 $\pm$ 43	197 $\pm$ 23	16.7
1	Plastic720	70 $\pm$ 9	3.8 $\pm$ 0.4	30 $\pm$ 4	13 $\pm$ 1	269 $\pm$ 67	296 $\pm$ 74	16.7
1	Sea	70 $\pm$ 12	4.5 $\pm$ 0.5	23 $\pm$ 3	12 $\pm$ 2	215 $\pm$ 29	187 $\pm$ 20	16.7
2	Plastic15	121 $\pm$ 21	4.9 $\pm$ 0.3	68 $\pm$ 20	13 $\pm$ 3	213 $\pm$ 26	173 $\pm$ 37	17.1
2	Glass119	221 $\pm$ 34	4.1 $\pm$ 0.4	175 $\pm$ 30	13 $\pm$ 2	154 $\pm$ 14	179 $\pm$ 23	17.1
2	Plexi190	89 $\pm$ 13	4.8 $\pm$ 0.4	39 $\pm$ 10	13 $\pm$ 2	234 $\pm$ 13	190 $\pm$ 23	17.1
2	Plastic720	61 $\pm$ 8	3 $\pm$ 0	29 $\pm$ 7	16 $\pm$ 2	208 $\pm$ 19	214 $\pm$ 12	17.1
2	Sea	63 $\pm$ 10	4 $\pm$ 0	27 $\pm$ 6	11 $\pm$ 2	187 $\pm$ 19	174 $\pm$ 10	17.1
3	Plastic15	82 $\pm$ 7	3 $\pm$ 0	46 $\pm$ 6	18 $\pm$ 3	248 $\pm$ 26	264 $\pm$ 20	11.1
3	Glass119	168 $\pm$ 29	3 $\pm$ 0	135 $\pm$ 28	16 $\pm$ 2	233 $\pm$ 63	247 $\pm$ 64	11.1
3	Plexi190	88 $\pm$ 11	3.5 $\pm$ 0.5	47 $\pm$ 5	16 $\pm$ 3	225 $\pm$ 20	243 $\pm$ 53	11.1
3	Plastic720	62 $\pm$ 5	3 $\pm$ 0	30 $\pm$ 3	15 $\pm$ 3	243 $\pm$ 10	263 $\pm$ 64	11.1
3	Sea	57 $\pm$ 6	3.1 $\pm$ 0.3	23 $\pm$ 3	14 $\pm$ 2	185 $\pm$ 11	186 $\pm$ 21	11.1
4	Plastic15	101 $\pm$ 16	3.9 $\pm$ 0.3	56 $\pm$ 14	14 $\pm$ 2	213 $\pm$ 14	195 $\pm$ 23	13.6
4	Glass119	214 $\pm$ 24	3.1 $\pm$ 0.3	178 $\pm$ 21	16 $\pm$ 1	150 $\pm$ 1	155 $\pm$ 22	13.6
4	Plexi190	82 $\pm$ 13	3.5 $\pm$ 0.5	45 $\pm$ 6	14 $\pm$ 2	228 $\pm$ 46	193 $\pm$ 23	13.6
4	Plastic720	63 $\pm$ 10	3 $\pm$ 0	34 $\pm$ 9	13 $\pm$ 1	228 $\pm$ 73	185 $\pm$ 36	13.6
4	Sea	77 $\pm$ 9	3.9 $\pm$ 0.4	32 $\pm$ 5	14 $\pm$ 3	181 $\pm$ 19	170 $\pm$ 9	13.6
5	Plastic15	100 $\pm$ 21	3 $\pm$ 0	60 $\pm$ 19	19 $\pm$ 2	204 $\pm$ 39	188 $\pm$ 24	14.5
5	Glass119	183 $\pm$ 36	3 $\pm$ 0	143 $\pm$ 36	20 $\pm$ 4	131 $\pm$ 34	142 $\pm$ 19	14.5
5	Plexi190	104 $\pm$ 15	2.6 $\pm$ 0.5	71 $\pm$ 12	19 $\pm$ 3	206 $\pm$ 30	196 $\pm$ 18	14.5
5	Plastic720	83 $\pm$ 6	3 $\pm$ 0	42 $\pm$ 6	19 $\pm$ 2	222 $\pm$ 27	205 $\pm$ 23	14.5
5	Sea	67 $\pm$ 6	3 $\pm$ 0	34 $\pm$ 4	18 $\pm$ 3	177 $\pm$ 13	174 $\pm$ 6	14.5

2022). Akamatsu *et al.* (2002) showed that dominant frequency, sound-pressure level, and power spectrum of artificial signals recorded in a 170-l glass tank were significantly distorted compared to those of the original signals. Distortions can be minimized following certain criteria. Ideally, sound recordings should be conducted in an open body of water with a depth and width exceeding the wavelength of the targeted sound (Akamatsu *et al.*, 2002). At research stations, probability of having access to aquaria fulfilling these criteria is very low. For instance, for the sound dominant frequency of *S. caudimaculatum* ($<$300 Hz), the ideal depth and width would be at least 5 m (even more with lower frequencies). For practical reasons, researchers, thus,

mainly use smaller aquaria to perform acoustic experiments, sometimes without even considering recording fishes directly in the field. Of course, there are also some constraints in the latter case (variations of water temperature, ambient noise, wind and waves, etc.) but it is likely possible to overcome most of them. This study is the first to compare the effects of reverberation, resonance, and tank properties (composing materials and size) on real fish sounds recorded in the same behavioral context in controlled laboratory conditions and in the field.

Although Kaatz and Lobel (2001) did not find differences in pulse waveform or pulse duration between sounds of the catfish *Orinocodoras eigenmanni* recorded in the field and small aquarium, when close to a hydrophone (7.5 cm), our results support that the type of material composing the recording tanks and their sizes can modify the acoustical features of sounds with respect to those recorded in an open body of water (i.e., at sea). All sound features except pulse periods were influenced by the material primarily and the size of the tanks secondarily. The sound features support that *S. caudimaculatum* produces sounds using fast-contracting sonic muscles that are connected to the swimbladder (Parmentier *et al.*, 2011). As this kind of sound-producing mechanism implies that the different pulses result from the contraction of bilateral muscles under the activation pattern of neuronal circuit (Ladich and Bass, 2005; Banse *et al.*, 2021), it easily explains that the pulse period is not affected by the environment. The same kinds
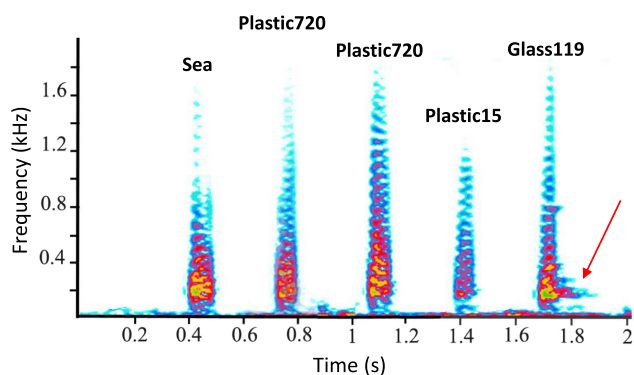

FIG. 2. (Color online) Spectrogram of five recorded sounds of *S. caudimaculatum* (one in each recording environment). For Glass119, the arrow indicates the increase in sound duration.
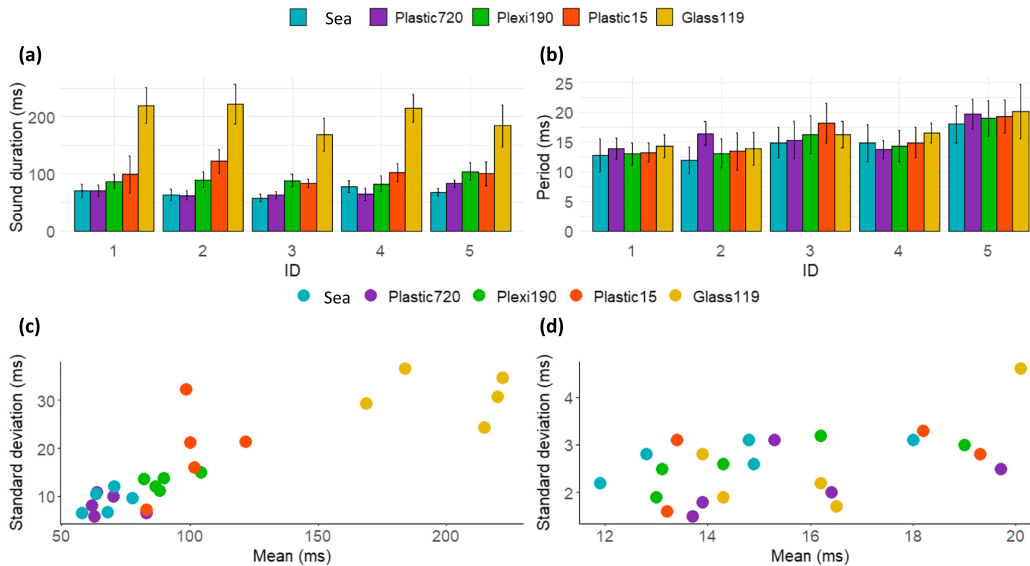
FIG. 3. (Color online) Barplots [(a),(b)] and scatterplots [(c),(d)] representing the acoustical variables (sound duration and pulse period) measured on sounds for each individual and recording environment and their variability, respectively. (a) Sound duration (ms), (b) pulse period (ms), (c) variability of sound duration (ms), and (d) variability of pulse period (ms) are shown.

of results should apply to the number of pulses that composed a sound. In the framework of this study, the difference observed in the pulse number between the plexiglass tank and plastic pool can, therefore, not be explained by the recording environment but could most likely be attributed to the fish motivation.

At the opposite, sound duration and dominant frequency measured on the complete call were the most affected. Sounds recorded in the glass tank were indeed much longer than those recorded in the sea and in the plastic and plexiglass tanks, no matter their size. Although Glass119 and Plexi190 were the most similar in terms of dimensions and volume, it was not the case for the acoustical parameters of

sounds recorded in these two environments. The plexiglass tank seems to alter sounds in the same way that plastic tanks do. Size seems to prevail on material among plastic and plexiglass tanks: the bigger the recording tank, the smaller the distortion of sound duration. These results are in agreement with previous studies performed with the croaking gourami (*Trichopsis vittata*) and red drum (*S. ocellatus*), respectively (Akamatsu *et al.*, 2002; Parmentier *et al.*, 2014). These authors showed that sounds are distorted in small and large tanks made of concrete, glass, and fiberglass. More precisely, Akamatsu *et al.* (2002) demonstrated the substantial effect of small sized tanks on the power spectrum level and dominant frequency of sounds. Parmentier *et al.* (2014) found that
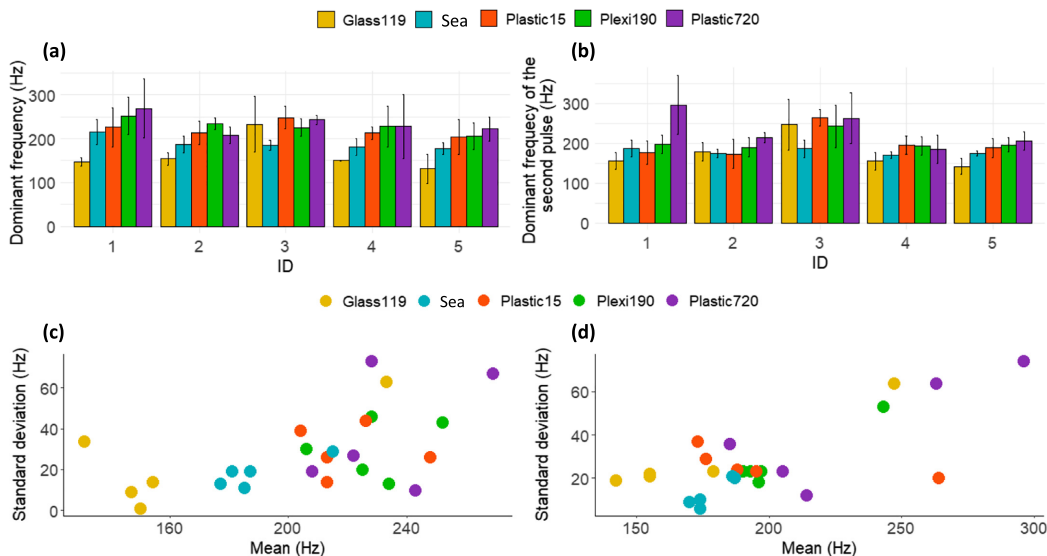

FIG. 4. (Color online) Barplots [(a),(b)] and scatterplots [(c),(d)] representing the acoustical variables (dominant frequency and dominant frequency of the second pulse) measured on sounds for each individual and recording environment and their variability, respectively. (a) Dominant frequency (Hz), (b) pulse periods (ms), (c) variability of dominant frequency (Hz), and (d) variability of the dominant frequency of sound (Hz) are shown.

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sound duration, pulse duration, pulse period, and dominant frequency of sounds recorded in fiberglass tanks (6 m^3 and 13 m^3) were significantly higher than in sounds recorded in floating cages. Sound duration was also longer in concrete tank (13 m^3) than in the open sea. The study in the red drum *S. ocellatus* reported differences in the pulse period, which is not the case here. The differences found in the pulse period can hardly be attributed to the recording environment because it corresponds to the muscle contraction rate (Sprague, 2000). In this study, sounds were recorded using the same individuals placed in different environments on the same day. The study on *S. ocellatus* concerned different populations that were not recorded simultaneously. This previous study lasted two months (Parmentier *et al.*, 2014). Recent studies on three sciaenid species (*Argyrosomus regius*, *Umbrina cirrosa*, and *S. ocellatus*) showed that spawning period can affect the pulse period (Bolgan *et al.*, 2020).

Similar to fish, broadband sounds of marine crustaceans, mostly characterized in tanks, are also deformed in these closed environments (Jézéquel *et al.*, 2019; Jézéquel *et al.*, 2022). The latter authors compared sounds produced by lobsters in tank and in the field and found significant differences in all sound features (temporal, power, and spectral).

In this study, sound distortion is more likely due to reverberation than resonance. Indeed, the calculated minimum resonant frequency of all experimental tanks is much higher than the sound frequency of *S. caudimaculatum*. Moreover, calculated attenuation lengths vary from to 10 to 41 cm for all aquaria. Here, fish sounds were recorded at ~5 cm from the hydrophone. This distance is well within the attenuation length of all aquaria. Therefore, each frequency component should attenuate similarly at frequencies much below the resonant frequency (Akamatsu *et al.*, 2002). We were not interested in sound-pressure level because this acoustical feature is mostly affected by fish size. We would, however, not have been able to use this information as the power spectrum level attenuates exponentially within a short distance when (1) the minimum resonant frequency > sound frequency and (2) sounds are recorded within the attenuation length (Akamatsu *et al.*, 2002). Nonetheless, the power spectrum of Glass119 is quite different from the power spectrum of the other recording environments because of reverberation. Depending on the material composing the tanks, with proper absorption and reflection coefficients, reflective waves can be produced and cause interference, which deform sounds. Because glass is a more reflective material than plastics, this would explain that sounds are significantly distorted when recorded in this environment.

V. CONCLUSION

According to our results, recording fish sounds in tanks, and mainly in glass tanks, is not recommended to provide accurate characterization of the fish acoustic signature. As formerly advised by Myrberg *et al.* (1986), studies on fish acoustic communication should be, at best, carried out at sea (or, more generally, in open-water environments). For obvious practical reasons, different behavioral studies are conducted in tanks. However, the results of this study support that the temporal and frequency patterns of sounds can be altered by the recording environment, features that can be important in fish communication experiments using species-specific sounds (Spanier, 1979; Myrberg *et al.*, 1978) or rely on these characteristics for fish identification (e.g., like in PAM studies). Yet, working at sea also presents disadvantages. For instance, the background noise can mask fish sounds because they are too weak. In most species, sounds attenuate to background noise level within few meters of the emission point because the absorption coefficients of low-frequency sounds (typical of most fish) are high in shallow water environments (Fine and Lenhardt, 1983; Bass and Clark, 2003). In some of them (Gobiidae, Cottidae), sounds attenuate within a few centimeters only, making it difficult to record sounds in natural environment (Colleye *et al.*, 2013; Lugli and Fine, 2003; Lugli, 2015). Submissive sounds in clownfish and damselfish, for example, are not detected in field recordings, although they were highlighted in tanks (Colleye and Parmentier, 2012; Parmentier *et al.*, 2006). Overall, our study points out that it is preferable to record fish sounds in open-water bodies than in tanks because many acoustical features are modified when sounds are recorded in closed environments due to reverberation and resonance. If not possible, it is better to (1) favor recordings of sounds in plastic or plexiglass tanks with respect to glass tanks and (2) choose tanks with the greatest dimensions and volumes.

[1]See supplementary material at https://doi.org/10.1121/10.0020149 for Table S1. Results of the Dunn's tests (with Bonferroni correction).

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