A baseline underwater soundscape of an intensely human-exploited estuarine and the effects of vessel traffic sound

Juan Pons [1], Román Uibrig [1], Juan Molina [1, 2] and Claudia Pons [3,4]

[1] Argentine institute of oceanography (Instituto argentino de oceanografía); juan_pons@yahoo.com,

[2] Department of Biology, Biochemistry and Pharmacy, National South University (Departamento de Biología, Bioquímica y Farmacia–UNS) , Bahía Blanca 410083 , Argentina; jmmolina@criba.edu.ar.

[3] Comisión de Investigaciones Científicas de la Provincia de Buenos Aires, Argentina
[4] Universidad Abierta Interamericana. Buenos Aires, Argentina.

Abstract. In this article we studied the anthropically impacted natural environmental sound in the port of Bahía Blanca, located in the southern province of Buenos Aires, Argentina. To acquire the acoustic signals, an omni-directional passive hydrophone was used. The acoustic signals were analysed using scripts implemented in the R programming language. Temporal series without maritime traffic were used as a baseline to describe the soundscape in the harbour area by estimating its power spectral density (PSD). Subsequently, the acoustic environment was analysed with the presence of two man-made acoustic sources "boat" and "ship" in the vicinity. Finally, the calculated normal soundscape level in the harbour has a magnitude of 116.25 dB re 1 µPa.

Keywords: Underwater acoustics, sound propagation, anthropogenic impacts.

1 Introduction

The industrial activity in harbours produces sounds that alter the natural acoustic field of their surroundings [1]. The growth of human activity generates diverse impacts on terrestrial and marine environments [2]. In the underwater environment, anthropogenic sound originates from maritime traffic, the activity of smaller vessels involved in channel or dock maintenance, and coastal industries that utilize machinery, among other sources [3]. These acoustic sources affect marine life in various ways. Maritime traffic contributes to low-frequency (<1 kHz) and mid-frequency (1 kHz-5 kHz) ranges, impacting marine life as it overlaps with the auditory levels of marine mammals and fish [4-6]. It has been estimated that since the pre-industrial era, maritime traffic noise has increased by approximately 20 dB in the low-frequency bands [7-8].

For fish, the acoustic field in which they reside is crucial in terms of survival and reproduction. They use it to detect predators [9], select their habitat [10-11], and communicate with other individuals, among other functions. Nearly all fish species produce sounds and acquire acoustic information from their environment, which, along with other sources of information such as visual, chemical, or electromagnetic cues, is vital for their feeding, survival, and reproduction [12-13]. Recent studies on reef ecosystem regeneration have found that the acoustic cues of a healthy reef are different from those of a degraded one, and the former produces an attraction effect on nearby fish [14].

Therefore, it is important to understand the natural acoustic field of areas where the management of a fishery resource takes place. Considering that industrial activity will increase in the coming years, it is necessary to characterize the current normal environment in harbours and estuaries, in order to establish a baseline for future comparisons and to study variations in the fishery resource caused by the increase in anthropogenic noise pollution [15-16]. In this article we studied the anthropically impacted natural environmental sound in the port of Bahía Blanca, located in the southern province of Buenos Aires, Argentina. Specifically, this study aims to analyse the alterations that occur in the underwater acoustic field due to the industrial ship traffic activity of the harbour.

The article is organized as follows. Section 2 describes the materials and methods used to characterize the underwater ambient sound in the harbor of Bahía Blanca from the different acoustic sources contributing to its composition. Then section 3 develops the mathematical models of the acoustic characteristics for the normal soundscape of the harbor on one hand, and the perturbed environment resulting from the interference of two vessel traffic acoustic sources, on the other hand. Section 4 shows the comparison between both scenarios and discuss the results. Finally, section 5 presents the conclusions.

2 Materials and Methods

To acquire the acoustic signals, an ITC-1180 omni-directional passive hydrophone with a signal preamplifier was used, with the following specifications: 20 Hz - 20 kHz operating frequency, 400 meters of maximum depth, >-180 dB re 1V/µPa reception sensitivity, and 25 dB preamplifier gain.

The hydrophone directional responses and attenuation within the operating frequency range are graphically represented in Figure 1. The acoustic signals were digitized at the output of the preamplifier, connected to the surface via a 25-meter cable, using a SoundBlaster G3 digitalizer. A sampling rate of 44.1 kHz (44.1 kSs) was used, sufficient to represent all the information present in the 20 Hz - 20 kHz spectrum. The digital data were processed using NCH Software's Sound Wave Editor and Audacity 3.2.5 programs, and saved in .wav format files for subsequent analysis.

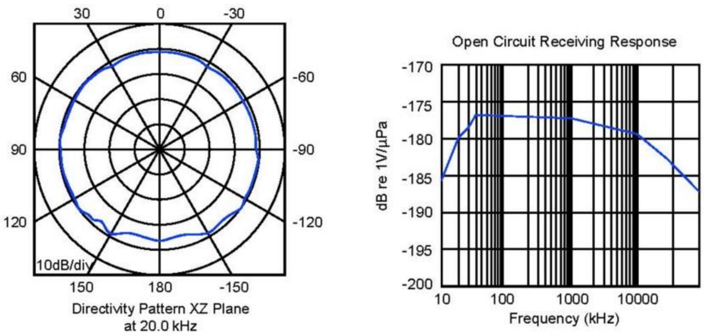

Fig. 1. Hydrophone directional responses and frequency response..

2.1 Software Tools

The acoustic signals were analysed using a script implemented in the R programming language. The following libraries were used for this purpose: *gsignal*, *av* and *ggplot2*. From audio files with the temporal samples, the power spectral density (PSD) was estimated. PSD is a function that shows the power distribution of the analysed signal across its frequency components. It is estimated using the Welch method [17], which involves dividing the temporal signal into overlapping segments and calculating the periodogram for each of these sequences. The resulting periodograms are averaged. Prior to the calculation, a Hamming window is applied to the segments containing the temporal signal to smooth unwanted effects in the individual Fourier transform.

Assuming the signal originates from a wide-sense stationary (WSS) process, all the information describing the dynamics of the process is represented in its PSD. The Welch method is applied with a Hamming window and a discrete fast Fourier transform (DFFT) length of 1024. The overlap of segments for each temporal signal is set to 0.5. It is necessary to apply a logarithmic scale to the resulting PSD to analyse the frequency bands with lower power density, as the spectral power is concentrated in low frequencies (<10 kHz). Prior to power estimation, the data is normalized and the following formula to obtain the temporal values on a scale (X_{scaled}) is applied:

$$X_{scaled} = (X_{origin} - X_{med}) / S$$

where: X_{origin} is the original value of the sample, X_{med} is the sample mean and S the sample standard deviation.

2.2 Location

The Bahía Blanca estuary, situated in the southwest of Buenos Aires province, Argentina, exhibits distinct geomorphological and tidal features. Two rocky terraces, positioned at depths between 12 meters and 18 meters, have been identified through studies conducted by Aliotta, Minor Salvatierra et al.[18]. The estuary is governed by a mesotidal regime. Extensive research on its geomorphology and sedimentary dynamics has been undertaken, as evidenced by studies led by several authors [19-21].

The estuary's circulation is characterized by a semi-diurnal and quasi-stationary tidal wave pattern. Tidal range varies from 2.3 meters to 1.4 meters at the mouth and 3.8 meters to 2.7 meters at the head, during spring and neap tides respectively [21]. Tidal range and current amplitude increase towards the upper reaches, indicating hypersynchronous behavior [22]. The geological foundation in the coastal zone comprises Plio-Pleistocene continental deposits, primarily silty sands and sandy silts cemented with calcium carbonate [23].

Extensive industrial and harbour buildings have been constructed around the northern margin of the estuary, where oil refineries, grain stockpiling and organic fertilizer companies have established their factories. Being also an active import/export port there is frequent heavy ship transit in the area. The measurements were taken at the West pier of the Nautical Club within the port of Bahía Blanca, as shown in Figure 2.

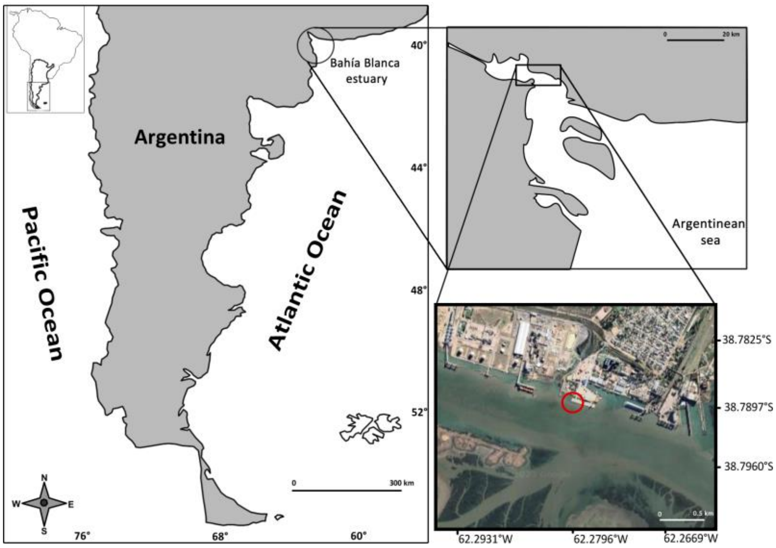

Fig. 2. Sampling site within Bahía Blanca estuary. Argentina

2.3 Sampling Techniques

The anthropogenic activities in Bahía Blanca estuary encompass most of the environments of the estuary, so having an "unimpacted soundscape" of the estuary is mostly impossible. Instead, we characterize the soundscape of the harbour without vessel traffic, and then compare it with two levels of maritime traffic. The hydrophone was deployed from the described pier location, submerged to a depth of one meter. At the time of data recording, there was a water column of 2 meters at the head of the pier. The recordings of the acoustic signals lasted between 2-3 minutes. Three temporal records of approximately three minutes each were taken and saved in separate audio wave files (extension “.wav”).

One acoustic record was taken without the presence of visible maritime traffic. For the next record, a 5-meter length motorboat with a 30 HP outboard motor was positioned approximately 300 meters away from the sampling location. We will refer to this acoustic source as "boat". The third record was taken with a larger boat located 200 meters away. This boat was a 24-meter length service vessel with two 650 HP motors. At the time of recording, it was engaged in bathymetry tasks. We will refer to this acoustic source as "ship". The temporal series without maritime traffic was used as a baseline to describe the soundscape in the harbour area by estimating its PSD. Subsequently, the acoustic environment was analysed with the presence of the “boat” and “ship” in the vicinity. The estimated PSDs were compared, and the power contributions in different frequency bands made by the vessels to the normal soundscape were described.

2.4 Power spectral density analysis

The power spectral densities were estimated using the Welch’s method. Let X(j), j = 0, …, N-1 be a sample from a stationary, second order stochastic sequence (audio records). We take segments, possibly overlapping, of length L with the starting points of these segments D units apart. Let $X_1(j) = X(j)$, j=0, …, L- 1 be the first such segment. Similarly $X_K(j) = X(j+ (K – 1) D)$, j = 0, …,L-1.

We then take the finite Fourier transforms $A_1(n)$, .., $A_K(n)$ of these sequences. Here:

$$A_k(n) = 1/L \sum_{j=0}^{L-1} X_k\,(j) W(j) e^{-2kijn/L} \quad (1)$$

and $i=(-1)^{1/2}$. Finally, we obtain the K modified periodograms

$$I_k(f_n) = L/U\,|A_k(n)|^2$$

where $f_n = n/L$; n=0, .., L/2 and

$$U = 1/L \sum_{j=0}^{L-1} W^2\,(j) \quad (2)$$

The spectral estimate is the average or these periodograms, i.e.

$$\hat{P}(f_n) = 1/K \sum_{k=1}^{K} I_k\,(f_n) \quad (3)$$

Finally a logarithmic scale is applied to the estimated PSD

$$sp = log_{10}\left(\hat{P}(f_n)\right) \quad (4)$$

2.5 Sound pressure level analysis

To analyse the sound pressure level (SPL) of the different sound sources, we considered the average sensitivity of the hydrophone at -180 dB re 1V/µPa. With this value provided by the manufacturer, we obtain a transfer factor (FT) of 1 mV/Pa.

The calculation employed is as follows:

-180 dB re 1V/µPa = 20 log10(FT • V/Pa / V/10^{-6} Pa) =
20 log10(FT • V/Pa / V/µPa)

Hence, FT = 0.001 V/Pa = 1 mV/Pa. The built-in amplifier gain, according to the manufacturer's specifications, is 25 dB. This gives us a gain factor (G) of 17.78.

25 db= 20 log10(G) : G = 17.78

Finally, the transfer value (FT • G) for the hydrophone is 17.78 mV/Pa. The range for the Analogue-to-Digital conversion of the SoundBlaster G3 is [-1V,1V]. All analogue values of the acoustic signal fall within this interval.

2.6 Strength Analysis

We calculated the magnitude of target strength for each acoustic source, by applying-sonar equations [24] considering the transmission loss (TL) for spherical spreading TL= 20 log(r) (r distance to the source in meters) and attenuation approximated by Ainslie M, McColm J [25].

$$\alpha = 0.106\,(f_1 f^2 / (f^2+f_1^2))\, e^{(pH-8)/0.56} + 0.52\,(1+T/43)(S/35)\,(f_2 f^2 / (f^2+f_2^2))\, e^{-z/6} + 0.00049\, f^2\, e^{-(T/27+z/17)} \quad (5)$$

where $f_1 = 0.78(S / 35)^{1/2} e^{T/26}$ and $f_2 = 42\, e^{T/17}$, α is attenuation (dB km^{-1}), f is frequency (kHz), pH is acidity, T is temperature (°C), S is salinity (‰), and z is depth (km). The measured sea conditions were T= 9.4°C, pH=8.3 and S=34ppt. Attenuation was calculated for frequency f=5kHz. Audacity 3.2.5 software obtained from https://www.audacityteam.org/ was used to analyze the recorded signals.

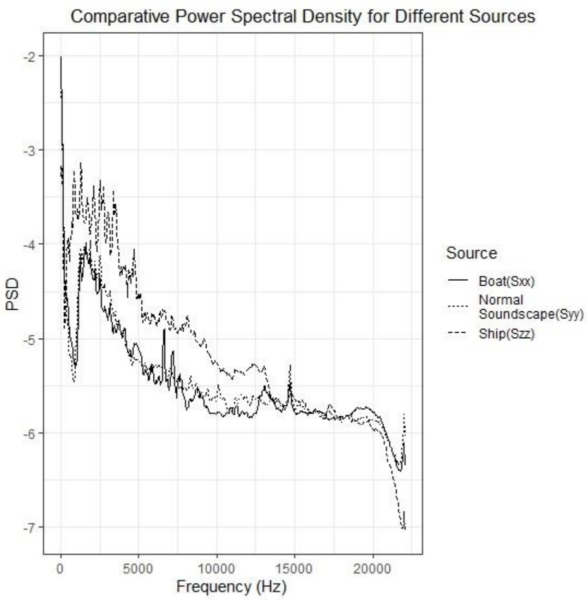

Fig.3 Comparison of the power spectral density of the normal soundscape (Syy)and the additional sources of sound, "boat" (Sxx) and "ship" (Szz)

3 Results

3.1 Power spectral densities

The PSD for the normal soundscape (Syy), the same environment with the contribution of "boat" (Sxx), and "ship" (Szz) in the area can be comparatively observed in Figure 3. In addition, Figure 4 shows the difference between the estimated PSDs expressed in squared values.

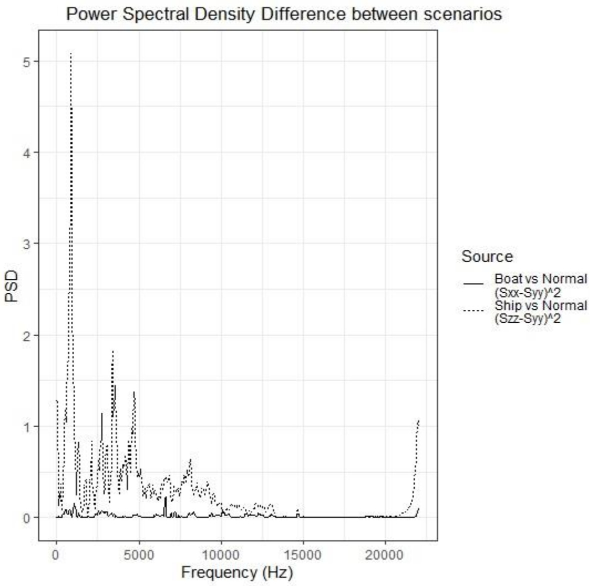

Fig.4 Power spectral density differences between two scenarios presented by the two types of vessels

3.2 Sound pressure level

The result for the selected signal interval is -30.36 dBV, which is equal to 0.03 VRMS. Applying the transfer factor for the hydrophone, we obtain the sound pressure (SPL), which amounts to 1.687 Pa SPL = VRMS / (FT • G) : P = 0.03 V / 0.01778 V/Pa = 1.687 Pa. The analysis is repeated for the records corresponding to the soundscape of the environment, the boat and the ship. The results are presented in Table 1.

Table 1. Acoustic pressure (in Pa) of the different sound sources in Bahía Blanca estuary.

Acoustic pressure (Pa)	Distance (m)	Sound source
0.65	-	Normal soundscape
0.85	300	Soundscape + Boat
1.687	200	Soundscape + Ship

3.3 Signal strength

The target strength for the “boat” signal was TS_{boat} = 155.97 dB re 1 µPa @ 1m and for the “ship” TS_{ship}=166.60 dB re 1 µPa @ 1m. The normal soundscape level has a magnitude of 116.25 dB re 1 µPa.

4 Discussion

The underwater ambient sound recorded in the harbour of Bahía Blanca exhibits particular characteristics that result from the different acoustic sources contributing to its composition. Analysing Figure 3, it can be observed that the majority of acoustic power for the environment is located below 2.5 kHz. There is a subsequent decay up to the frequency of 7.5 kHz, beyond which it remains relatively stable for the rest of the frequency band. Above 20 kHz, there is a significant power decrease due to hydrophone limitations. Local power peaks can be observed around 1 kHz, which likely correspond to the contribution of anthropogenic sound in the environment. A spectral power maximum is observed around the frequency of 14.5 kHz. The traffic sound produced by the "boat" acoustic source present in the area, contributes to the normal soundscape at frequencies of 6.2 kHz, 6.8 kHz, 7.5 kHz, and 13 kHz, where significant power peaks appear. The rest of the curve replicates the PSD obtained for the normal soundscape. In the case of the "ship" acoustic source, it shows a significant power contribution in the frequency range below 5 kHz. A more detailed comparison can be observed in Figure 4. This graph compares the PSD corresponding to the "boat" acoustic source (Sxx) and the "ship" acoustic source (Szz), calculating their squared difference with respect to the ambient PSD (Syy). The graphs highlight the significant contribution made by the "ship" acoustic source to the environment. This contribution occurs at frequencies below 10 kHz, mainly within the 20 Hz - 5 kHz range. It can be compared to the less significant contribution made by the "boat" acoustic source and its spectral distribution. SPL showed a contribution of 0.2 Pa for the "boat" and 1.02 Pa for the "ship" in the normal soundscape. These values are compatible with those found in the literature [7], that reports a typical antrophogenic noise of target strength TS=160 dB re 1 µPa @ 1m for a small boat outboard engine. Low frequency sounds from ships such as the ones characterized in this study can travel hundreds of kilometres and increase ambient noise levels over vast areas [26, 27, 28]. For Bahía Blanca estuary, this means that even though the heavy vessel traffic occurs mainly in the norther region (Fig. 2), the acoustic disruptions of traffic sound are likely to spread to the whole ecosystem.

Sound disruption from man-made sources is known to affect the normal biological behaviour of animals that employ sound [29]. Among the vast diversity of fish species, which numbers over 33,000, at least 800 belonging to more than 100 families have been identified as sound producers [30]. The emitted sounds serve diverse purposes, including feeding, mating, and conflict [31]. Female fish may utilize sound detection to locate vocal males and discern suitable mates [32]. Notably, numerous commercially significant fish, such as croakers and drums from the Sciaenidae family, are known sound producers [33] and are common inhabitants of Bahía Blanca estuary [34]. Consequently, any factors, including anthropogenic sources of sound, that hinder the recognition of these natural sounds can adversely impact these fish species [35]. For Bahía Blanca estuary, the sound of vessel traffic recorded and analysed in this paper are well within the auditory capacity of most fishes [36, 37] which means that most sound-sensitive fish species would be able to hear the sounds produced by small vessels as they enter and exit the harbor, resulting in a disruption of their natural acoustic behaviour.

Marine mammals are also known to employ sound extensively, to find food, communicate between individuals and navigate through their environment [38, 39]. Potential effects from exposure to anthropogenic noise such as those recorded in the present study are varied and can include hearing impairment, stress, changes in behaviour, and acoustic 'masking' (obscuring important natural sounds) [40]. Specifically, Bahía Blanca estuary is mainly inhabited by two species of marine mammals, the small Franciscana dolphin (*Pontoporia blainvillei*) and the southamerican sea lion (*Otaria flavescens*) [41]. *P. blainvillei* employs a series of whistles, clicks and pulses to communicate [42]. The whistles produced by adults, in particular, are produced and heard at 1.6 and 94.6 kHz [43], overlapping with the frequencies of the vessel traffic recorded in Bahía Blanca harbor. Newborns produce clicks in the range of 8-14 kHz [44], again overlapping with vessel traffic noise. Echolocation also plays an important role in *P. blainvillei* feeding ecology, and while it occurs at high frequencies (above 100kHz) [45], little is known about the potential effects of man-made sounds on the normal functioning of the echolocation in this species. *O. flavescens* have a permanent male colony established in the southern portion of the bay, and males can be seen resting in buoys and other harbour constructions [41]. There is no specific hearing study in this species, but closely related species show underwater hearing sensitivity between 1.2-26 kHz at 20db [46]. While there are no studies on the potential deleterious effects of noise available for the marine mammals inhabiting Bahía Blanca estuary, our results show that the anthropogenic soundscape in Bahía Blanca harbour could be potentially disruptive for these species' behaviour.

5 Conclusions

This study described the main characteristics of the underwater soundscape in the harbour area of Bahía Blanca by analysing its power spectral density, sound pressure level and target strength. We analysed the acoustic characteristics for the normal environment of the harbour, and then calculated the contributions of two vessel traffic acoustic sources to the normal soundscape. The baseline produced in this work will be essential to analyse the underwater acoustic field in Bahía Blanca harbour and to identify sources of acoustic contamination due to the increasing industrial ship traffic activity of the harbour.

Our results warn against the potential acoustic disruptions produced by vessel traffic within the estuary, as many species within the estuary utilize sound to perform their normal biological activities, which may get distorted, masked, or otherwise disrupted.

Future studies should focus on characterizing the sounds produced by the local marine species present in the estuary of Bahía Blanca to better understand the extent of the acoustic disruptions produced by the human activities within the estuary.

References

1. Ballesteros, M., Fernandez, M., Quintana, S., Ballesteros, J., & González, I. (2010). Noise emission evolution on construction sites. Measurement for controlling and assessing its impact on the people and on the environment. *Building and Environment*, 45, 711-717. https://doi.org/10.1016/J.BUILDENV.2009.08.011.
2. Grimm, N.B., Foster, D., Groffman, P., Grove, J.M., Hopkinson, C.S., Nadelhoffer, K.J., et al., 2008. The changing landscape: Ecosystem responses to urbanization and pollution across climatic and societal gradients. Front. Ecol. Environ. 6 (5), 264–272
3. Shannon, G., McKenna, M.F., Angeloni, L.M., Crooks, K.R., Fristrup, K.M., Brown, E.,et al., 2016. A synthesis of two decades of research documenting the effects of noiseon wildlife. Biol. Rev. 91 (4), 982–1005
4. Willi ams, R., Wright, A.J., Ashe, E., Blight, L.K., Bruintjes, R., Canessa, R., 2015. Impacts of anthropogenic noise on marine life: Publication patterns, new discoveries, andfuture directions in research and management. Ocean Coast Manag. 115, 17–24
5. De Jong, K., Amorim, M.C.P., Fonseca, P.J., Heubel, K.U., 2018. Noise affects multimodal communication during courtship in a marine fish. Front. Ecol. Evol. 6 (July), 1–8.
6. Duarte, C.M., Chapuis, L., Collin, S.P., Costa, D.P., Devassy, R.P., Eguiluz, V.M., et al.,2021. The soundscape of the Anthropocene ocean. Science 371 (6529), eaba4658
7. Hildebrand, J.A., 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser. 395, 5–20.
8. Frisk, G.V., 2012. Noiseonomics: the relationship between ambient noise levels in the sea and global economic trends. Sci. Rep. 2 (1), 2–5.
9. Remage-Healey, L., Nowacek, D.P., Bass, A.H., 2006. Dolphin foraging sounds suppress calling and elevate stress hormone levels in a prey species, the Gulf toadfish. J. Exp. Biol. 209 (22), 4444–4451
10. Tolimieri, N., Jeffs, A., Montgomery, J.C., 2000. Ambient sound as a cue for navigation by the pelagic larvae of reel fishes. Mar. Ecol. Prog. Ser. 207, 219–224
11. Montgomery, J.C., Jeffs, A., Simpson, S.D., Meekan, M., Tindle, C., 2006. Sound as an orientation cue for the pelagic larvae of reef fishes and decapod Crustaceans. Adv.Mar. Biol. 51, 143–196.
12. Popper, A.N., 2003. Effects of anthropogenic sounds on fish. Fisheries 28 (10), 24–31
13. Hawkins, A.D., Popper, A.N., 2018. Effects of man-made sound on fishes. In: Slabbekoorn, H. (Ed.), Effects of Anthropogenic Noise on Animals, vol. 66,pp. 415–429
14. Gordon, T., Radford, A., Davidson, I., Barnes, K., McCloskey, K., Nedelec, S., Meekan, M., McCormick, M., & Simpson, S. (2019). Acoustic enrichment can enhance fish community development on degraded coral reef habitat. Nature Communications, 10. https://doi.org/10.1038/s41467-019-13186-2.
15. Kunc, H., & Schmidt, R. (2019). The effects of anthropogenic noise on animals: a meta-analysis. Biology Letters, 15. https://doi.org/10.1098/rsbl.2019.0649.
16. Simpson, S., Radford, A., Nedelec, S., Ferrari, M., Chivers, D., McCormick, M., & Meekan, M. (2016). Anthropogenic noise increases fish mortality by predation. Nature Communications, 7. https://doi.org/10.1038/ncomms10544.
17. Welch, P.D. (1967). The use of Fast Fourier Transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms. IEEE Transactions on Audio and Electroacoustics, AU-15 (2): 70–73.
18. Salvatierra, M.M., Aliotta, S. and Ginsberg, S.S., 2015. Morphology and dynamics of large subtidal dunes in Bahía Blanca estuary, Argentina. Geomorphology, 246, pp.168-177.
19. Aliotta, S. and Perillo, G.M., 1987. A sand wave field in the entrance to Bahía Blanca estuary, Argentina. Marine geology, 76, pp.1-14.

20. Aliotta, S., Ginsberg, S.S., Spagnuolo, J.O., Farinati, E., Giagante, D. and Vecchi, L.G., 2013. Late Quaternary in a South Atlantic estuarine system: Stratigraphic and paleontologic indicators of coastal evolution. Journal of South American Earth Sciences, 45, pp.194-208.
21. Cuadrado, D.G., Gómez, E.A. and Ginsberg, S.S., 2003. Large transverse bedforms in a mesotidal estuary. Latin American Journal of Sedimentology and Basin Analysis, 10(2), pp.163-172
22. Perillo, G.M.E., Piccolo, M.C., Parodi, E. and Freije, R.H., 2001. The Bahía Blanca Estuary, Argentina. In Coastal marine ecosystems of Latin America (pp. 205-217). Berlin, Heidelberg: Springer Berlin Heidelberg.
23. Fidalgo, F., 1983. Algunas características geomorfológicas dentro del partido de La Plata, Provincia de Buenos Aires. Revista de la Asociación Geológica Argentina, Buenos Aires, 38(2), pp.263-273.
24. Urick RJ (1975) Principles of underwater sound. McGrawHill, New York
25. Ainslie M, McColm J (1998) A simplified formula for viscous and chemical absorption in sea water. J Acoust Soc Am 103:1671–1672
26. [Southall, B.L., Scholik-Schlomer, A.R., Hatch, L., Bergmann, T., Jasny, M., Metcalf, K., Weilgart, L. and Wright, A.J., 2017. Underwater noise from large commercial ships—international collaboration for noise reduction. Encyclopedia of Maritime and Offshore Engineering, pp.1-9.
27. De Jong, C.A.F., 2009, January. Characterization of ships as sources of underwater noise. In NAG/DAGA International Conference on Acoustics, Rotterdamn, The Netherlands.
28. Kozaczka, E. and Grelowska, G., 2018. Propagation of ship-generated noise in shallow sea. Polish Maritime Research, (2), pp.37-46.
29. Erbe, C., Marley, S.A., Schoeman, R.P., Smith, J.N., Trigg, L.E. and Embling, C.B., 2019. The effects of ship noise on marine mammals—A review. Frontiers in Marine Science, 6, p.606.
30. Bass, A.H. and Ladich, F., 2008. Vocal–acoustic communication: From neurons to behavior. In Fish Bioacoustics: With 81 Illustrations (pp. 253-278). New York, NY: Springer New York.
31. Putland, R.L., Montgomery, J.C. and Radford, C.A., 2019. Ecology of fish hearing. Journal of Fish Biology, 95(1), pp.39-52.
32. Casaretto, L., Picciulin, M. and Hawkins, A.D., 2015. Seasonal patterns and individual differences in the calls of male haddock Melanogrammus aeglefinus. Journal of Fish Biology, 87(3), pp.579-603.
33. Popper, A.N., Hawkins, A.D. and Sisneros, J.A., 2022. Fish hearing "specialization"–a re-evaluation. Hearing research, 425, p.108393.
34. Molina, J.M.; Blasina G.E.; Lopez Cazorla, A. Ecology and biology of fish assemblages. In The Bahía Blanca Estuary, 2020 eds: Fiori S., Pratolongo, P. Springer, Switzerland. ISBN-978-3-030-66485-5.
35. Popper, A.N. and Hastings, M.C., 2009. The effects of anthropogenic sources of sound on fishes. Journal of fish biology, 75(3), pp.455-489.
36. Popper, A.N. and Hawkins, A.D., 2019. An overview of fish bioacoustics and the impacts of anthropogenic sounds on fishes. Journal of fish biology, 94(5), pp.692-713.
37. Ladich, F. and Fay, R.R., 2013. Auditory evoked potential audiometry in fish. Reviews in Fish Biology and Fisheries, 23, pp.317-364.
38. Ellison, W.T., Southall, B.L., Clark, C.W. and Frankel, A.S., 2012. A new context-based approach to assess marine mammal behavioral responses to anthropogenic sounds. Conservation Biology, 26(1), pp.21-28.
39. Reichmuth, C. and Southall, B.L., 2012. Underwater hearing in California sea lions (Zalophus californianus): Expansion and interpretation of existing data. Marine mammal science, 28(2), p.358.
40. Wright, A.J., Soto, N.A., Baldwin, A.L., Bateson, M., Beale, C.M., Clark, C., Deak, T., Edwards, E.F., Fernández, A., Godinho, A. and Hatch, L.T., 2007. Do marine mammals experience stress related to anthropogenic noise?. International Journal of Comparative Psychology, 20(2).

41. [41] Giardino, G., Luengos Vidal, E.M., Massola, V., Mandiola, M.A., Gana, J.C., Rodríguez, D. and Bastida, R., 2021. Marine Mammals: Is the Bahía Blanca Estuary and Its Area of Influence Important for Their Conservation?. The Bahía Blanca Estuary: Ecology and Biodiversity, pp.359-395.
42. [42] Cunha, H.A., Medeiros, B.V., Barbosa, L.A., Cremer, M.J., Marigo, J., Lailson-Brito, J., Azevedo, A.F. and Sole-Cava, A.M., 2014. Population structure of the endangered franciscana dolphin (Pontoporia blainvillei): reassessing management units. PloS one, 9(1), p.e85633.
43. Cremer, M.J., Holz, A.C., Bordino, P., Wells, R.S. and Simões-Lopes, P.C., 2017. Social sounds produced by franciscana dolphins, Pontoporia blainvillei (Cetartiodactyla, Pontoporiidae). The Journal of the Acoustical Society of America, 141(3), pp.2047-2054.
44. Tellechea, J.S. and Norbis, W., 2014. Sound characteristics of two neonatal franciscana dolphins (Pontoporia blainvillei). Marine Mammal Science, 30(4), pp.1573-1580.
45. Melcón, M.L., Failla, M. and Iñíguez, M.A., 2012. Echolocation behavior of franciscana dolphins (Pontoporia blainvillei) in the wild. The Journal of the Acoustical Society of America, 131(6), pp.EL448-EL453.
46. Reichmuth, C., Holt, M.M., Mulsow, J. et al. Comparative assessment of amphibious hearing in pinnipeds. J Comp Physiol A 199, 491–507 (2013). https://doi.org/10.1007/s00359-013-0813-y