Integrating philology with acoustic signal analysis for decoding complex communication systems of marine animals

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Abstract

The study investigates the merging of philology and acoustic signal processing to decipher the systems of interspecific communication used by marine mammals. Most marine animals, such as cetaceans and pinnipeds, use complex systems of vocal and non-vocal signals to communicate, interact socially, navigate, and integrate into their aquatic environments. Previous research in the field of acoustic communication analysis has been primarily structural and/or phonetic, with no attention to the disengagement of communication's fundamental and applied cognitive functions. The study proposes to bring structure to and address the possible semantics of marine mammals' vocalizations by integrating philology into their analysis. The research is the first, and hopefully not the last, in the field of marine animal communication to attempt to provide a comprehensive solution for the fusion of bio-acoustics and linguistics, offering a working structure for the field of Marine Bio-Linguistics. The research has the potential to provide a thorough exploration of the intricacies and depths of the communications of marine mammals, and of the advanced intercommunications of marine mammals and humans, to provide valid and factual research for the conservation of the inter-relationships of the marine environment and of the communications of the marine mammals and humans.

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Introduction

The vast intricacies of the animal kingdom, the communication systems of marine mammals, particularly the cetaceans (whales, dolphins, and porpoises), and pinnipeds (seals, walruses, and sea lions), are most developed, complex, and sophisticated. Members of these groups use vocalizations and other sounds, and they are critical for performing essential life activities such as navigation, foraging, socializing, and mating. Beyond the great complexity and diversity of these sounds, understanding of communication systems in marine animals is still in its infancy. It remains rudimentary and primarily linear, focusing mainly on the spectral (pitch and frequency), temporal (life of the sound), and structural (patterns of the sounds) characteristics of the vocals. (Oyewole, Awolaju and Ayomide, 2025; Rajan, Chidambaram and Rajesh, 2025). Advances in bioacoustics have greatly improved the identification and categorization of sounds produced by marine mammals. However, the field is yet to move beyond the perception of sounds and to signal the understanding of the sounds produced. In this regard, the incorporation of philology, the textual and contextual study of sounds, is essential. (Mccowan, Hanser and Doyle, 1999). While philology is primarily limited to human language and communication, it offers viable analytical frameworks to grasp the semantic and syntactic dimensions of sounds produced by marine mammals, to the extent that communicating systems can be analytically deciphered by means of structured systems of language. (Khyade, Pawar and Khilare, 2018; Mishachandar and Vairamuthu, 2024). Within the fields of bioacoustics, linguistics, and signal processing, there is a growing interest in the marine phonosemantics discipline, which studies the use of sound to inquire into various effects and meanings. This, in turn, refers to the core of marine phonosemantics and the use of sound in various contexts. (Richerson and Boyd, 2010). This focus on dynamic meanings is perhaps the most constructive in phonosemantics today, and various marine animal sounds have clear phonosemantic characteristics. (Fitch, 2020). The study of marine phonosemantics holds the promise of advancing the understanding of animal cognition, marine behavior, and the marine conservation of these intelligent species. (Jain and Kapoor, 2021). This philosophical framework seeks to examine the phonosemantics of marine animals to study the inter-acoustic structures of their social interactions and their sounds in the context of social integration. The study proposes the first marine phonosemantics, aiming to apply a philosophical inquiry framework to the study of marine animal communication. (Hebets *et al.*, 2016). The study seeks to bring sustainable marine phonosemantics to explore the intelligence and communication of marine organisms.

Problem Statement

In bioacoustics research, the communication patterns of marine species, especially cetaceans and pinnipeds, remain poorly understood. Much of the current study centers on the

vocal characteristics of marine species and on the measurement of physical attributes, such as sound frequencies and durations. Studies focus on measuring sounds and not their potential meanings, cognitive functions, or of a possible underlying structure. Such disconnected scholarship has led to the understanding that the communication of marine mammals is an elaborate array of sounds, rather than a system. Because the study has not taken an integrated approach to philology and audio signals, communication among marine mammals has been studied mainly as a disconnected collection of sounds. Such a lack of a cohesive approach makes communicating with marine mammals feel like an unsolved riddle. This functions to limits scholarship in relation to the marine mammals, and the marine mammals, and human relationship. This ignorance functions in a void of the desires of modern scholarship, conservation efforts, and of the cognition of the marine species.

Key Contribution

- Development of an interdisciplinary framework combining philology and acoustic signal analysis to decode marine animal communication systems.
- Application of linguistic principles to identify semantic and syntactic structures within acoustic signals, beyond traditional bioacoustic analysis.
- Uncovering cognitive processes behind marine animal vocalizations, providing deeper insights into their communication and social dynamics.
- Enhanced understanding of communication functions, contributing to more accurate interpretations of marine animal behavior and interactions.
- Improved conservation strategies by better understanding the role of communication in ecological interactions and species preservation.

Literature Review

The field of animal communication has mostly been dominated by research on vertebrates, especially marine mammals, like cetaceans and pinnipeds, where there have been documented vocalizations and their social functions. There has been research on social vocalizations in cetaceans and pinnipeds, even detailing possible functions for some vocalizations, while others remain purely speculative, leaving some social functions undocumented. At first, marine animal communication was purely speculative, based on patterns observed in their vocal characteristics and geometric shapes. Communication, especially, is vital for marine mammals because they can communicate over long distances, and their vocalizations can travel for miles. (Radhakrishnan and Chandrasekharan, 2025). Bioacoustic research has been quite successful in analyzing and cataloging marine mammals' vocalizations; however, much work remains to be done in understanding the social contexts of communication. Most works center on the signal's pattern and frequency structure, with little attention to the potential meanings and sentence structure of these communications. **(**Kostov and Alexandrova, 2009).

The incorporation of deep learning models and sophisticated signal processing technologies into the design of marine monitoring technologies has changed the way marine species sound collection and analysis. There is a value in recording marine mammals' sounds over long time periods. (Ayas, Çiftçi and Tanış, 2023). It helps to understand vocalization patterns and the contexts in which they occur. Unfortunately, even with recording technologies and machine learning tools for vocalization analysis, we are still unable to interpret the meaning of the sounds. That is why the literature calls for combining bioacoustic research with other disciplines, in particular marine vocalizations and language research. While philology is a discipline focused on human language, it provides tools for analyzing animal communication across the components of syntax, semantics, and pragmatics. For some reason, its application in bioacoustic research has been almost completely ignored. (Sebeok, 1965).

Environmental and anthropogenic noise complicates how marine creatures use sound to function within their environments. Absorption of noise can interfere with all levels, from basic signal transmission to higher levels of organized signal communication. (Kaplan, 2014). This disparity has to be addressed in any study of the construction and emission of signals. This has to be discussed explicitly: the way signals are organized and the underlying intent that could be lost in mere signal isolation. Such disparity crystallizes the focal explanation of advanced thought, social structures, and the function of communication. To that end, an intermix of philology with signal processing would go to the heart of the communication scaffold of marine species, their social interrelationship, and bolster the marine conservation database, and ultimately marine cognition. (Kanakidis *et al.*, 2006).

Research Gap

The existing literature on animal behavior provides little to no analysis of marine animal communication. Initial marine behavioral studies focused on the structure of signals rather than their meaning. Interdisciplinary studies of philology, bioacoustic signals, and their meanings are largely untapped. Environmental and anthropogenic noise are primarily seen as disruptors rather than modifiers of communication. Voices of communication have been described and cataloged. Unfortunately, much of the communication is not fully understood. Finally, systematic studies of cross-species and within cognitive and social structure of communication have been poorly documented. As well as the studies of technology in the analysis of communication, and gaps in the documentation of signals within noise. The gaps in the studies of communication of marine animals are well documented and thus leave the field open for research.

Methods And Materials

The engineering methodologies and materials in Table 1 combine bioacoustics with elements of language theory to track and decode the communicative behavior of certain marine species. The initial step is a form of passive listening termed “acoustic monitoring,” in which the researcher uses hydrophones to sample underwater vocalizations as marine organisms occupy their natural

behavioral milieu. Secondary analysis of the recording encompasses the use of amplification and software routines to visualize the vocal sample and extract relevant signal features (e.g., frequency, duration, amplitude) using MATLAB, R, or Python.

Table 1: Methods and materials for decoding complex communication systems of marine animals.

Method	Description	Materials/Tools
Data Collection: Acoustic Monitoring	Implement passive acoustic monitoring systems to capture marine animal vocalizations in their natural habitat.	Hydrophones, underwater microphones, data loggers, acoustic recorders.
Signal Processing and Classification	Apply signal processing methods to extract essential features such as frequency, duration, and amplitude from acoustic data signals.	MATLAB, R, Python (Librosa, PyAudio, SciPy), signal processing software.
Linguistic Analysis (Philology)	Use linguistic principles—syntax, semantics, and pragmatics—to examine the structure and possible meanings of vocalizations.	Linguistic analysis software (e.g., Praat, ELAN), coding frameworks.
Contextual Analysis	Examine the circumstances surrounding particular vocalizations, covering social, environmental, and behavioral factors.	Video recordings, behavioral observation logs, GPS, and environmental data.
Cross-Species Comparative Analysis	Compare vocalizations among various marine species to identify common structures or communication patterns.	Acoustic datasets from different species, cross-species analysis software.

Next, a Praat and ELAN analysis focuses on the potential use of the marine vocalizations as units of expression each with syntactical arrangement, meaning, or use in a communicative exchange; i.e., were the signals structured in any way, and if so, is there a possibility they are meaningful or meaningful as part of a broader discourse? The use of termed contextual analysis from the visual and behavioral logs of the subjects and the environment of the recording, often termed a focal video, provides behavioral insights into the probable social, geographic, and ecological stimuli or changes that prompted a marine organism to vocalize. The contextual analysis is enriched by incorporating a behavioral data log of cross-species data, seeking to identify other marine voices that exhibit a similar pattern of vocalization and to explain the synergistic use of ecological data in behavioral systems and the vocalizations utilized by specialized marine software. Collectively, a fusion of approaches identifies the primary elements of the features of marine life vocalizations and the potential range of cognitive, social, and/or linguistic features of vocal systems.

Research Methodology

Conceptual Framework for Integrating Philology with Acoustic Signal Analysis for Decoding Complex Communication Systems of Marine Animals

In Figure 1 of this interdisciplinary approach, framed architecture addressing the Decoding of Marine Animal Communications presents an excellent step-by-step process. We start the flow of the process with Data Collection employing passive monitoring of hydrophones, underwater microphones and data loggers to record the sounds marine animals make and monitor their activities.

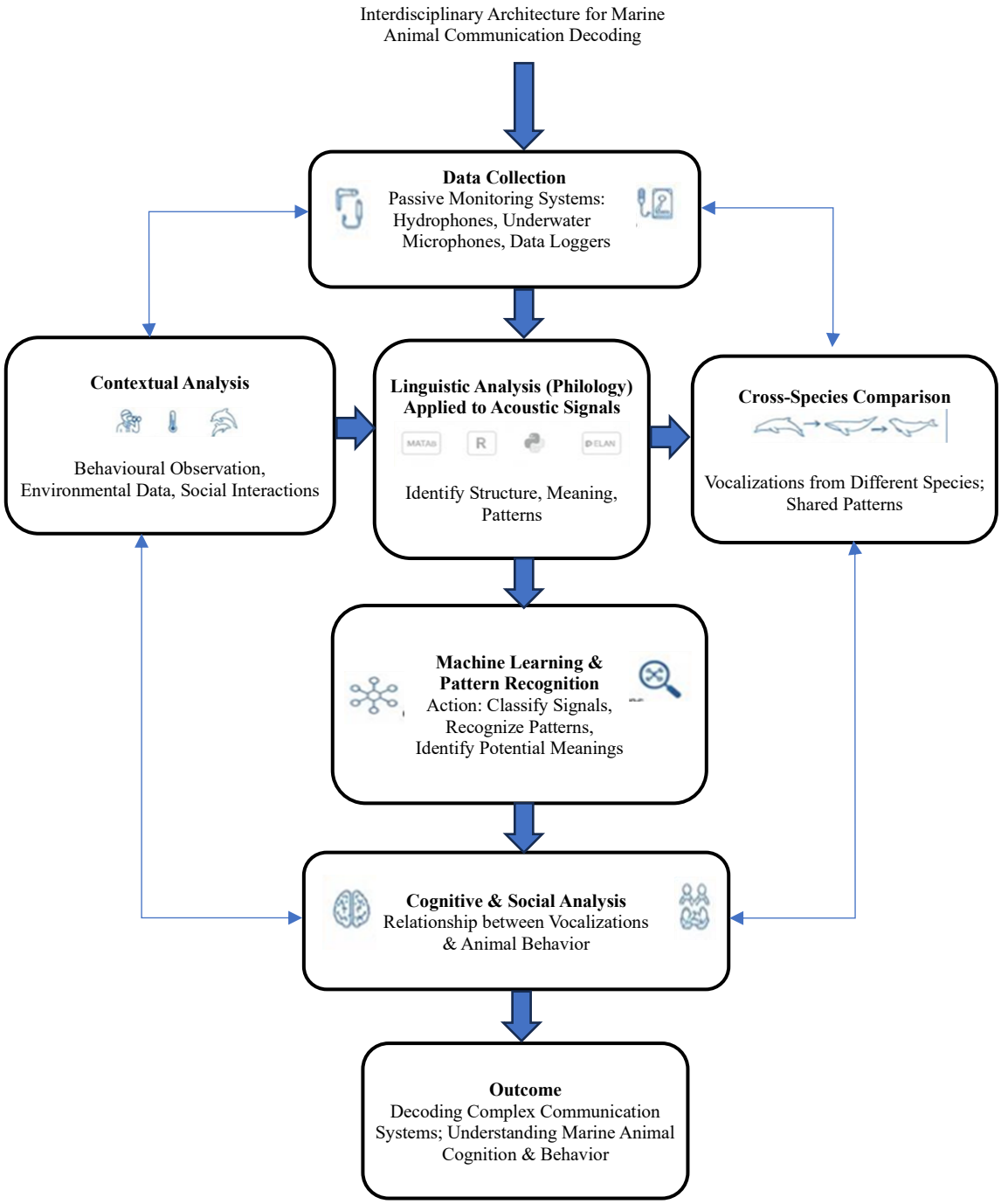

Figure 1: Interdisciplinary architecture for maine animal communication decoding.

Following this step, we perform Linguistic Analysis (Philology) of the recorded audio employing an assortment of software such as MATLAB. R, and ELAN to isolate and identify the pattern of structure and possible meaning of the phonations. We then incorporate Contextual Analysis, which includes cross-monitoring of behavior and the environment, as well as social interactions, to provide the necessary structure for understanding the signal(s). In addition, we perform Cross-Species Comparison to identify common patterns of phonation across various marine animals, thereby providing a broader view of communication across different aquatic animals. The next step is the

Machine learning & Pattern Recognition, wherein the algorithms sort the signals, pattern creation is done, and the prediction of the possible meaning of the phonation(s) is attained. Once this step is complete, we perform a Cognitive & Social Analysis to examine the animal's phonation(s) and thus its social and cognitive behavior. The last anticipated result constitutes the deciphering of complex communication systems. These results primarily advance understanding of marine animals' cognition and behavioral systems. This result combines the fields of bioacoustics, linguistics, and machine learning and serves an integrated approach to the study of the systems of communication of marine animals.

Results And Discussion

Dataset Description

The dataset, designed to facilitate the integration of acoustic signal analysis and philology to decipher the intricate communication systems of marine creatures, is constructed to provide complete information about the creatures' voices. It consists of acoustic information collected through passive monitoring systems, such as hydrophones and underwater microphones, which capture and record the vocalizations of various marine species. The data is further augmented with time stamps, frequency range, signal strength, and species classification. Linguistic tools such as MATLAB, R, and ELAN are used to devise syntax to enable analyses of the recordings using philological techniques, in which the tapes are detailed with phonetic transcription, syntactic organization, and possible semantics. In addition, contextual information is to enable the descriptions to be more encompassing of the spatial and social aspects of the vocalization's occurrences. The dataset also provides information from other species, allowing the analyst to compare vocalizations to identify and record shared structures, along with specific species information in the metadata. To develop classification systems that can discern and suggest possible interpretations of different forms of vocalizations, machine learning features are computed from the audio signals. Cognitive social data connect vocalizations and social behavior, linking to social groupings and aiding in determining the role of communication in social structures and relationships. Raw acoustic data, speech analytics, behavioral patterns, and machine learning combine to form a detailed study of the communication systems of marine species.

Distribution of Data Points in Different Analysis Categories

Table 2: Distribution of data points in different analysis categories.

Analysis Category	Number of Data Points
Acoustic Analysis	6
Contextual Analysis	5
Linguistic Analysis	7
Machine Learning	4

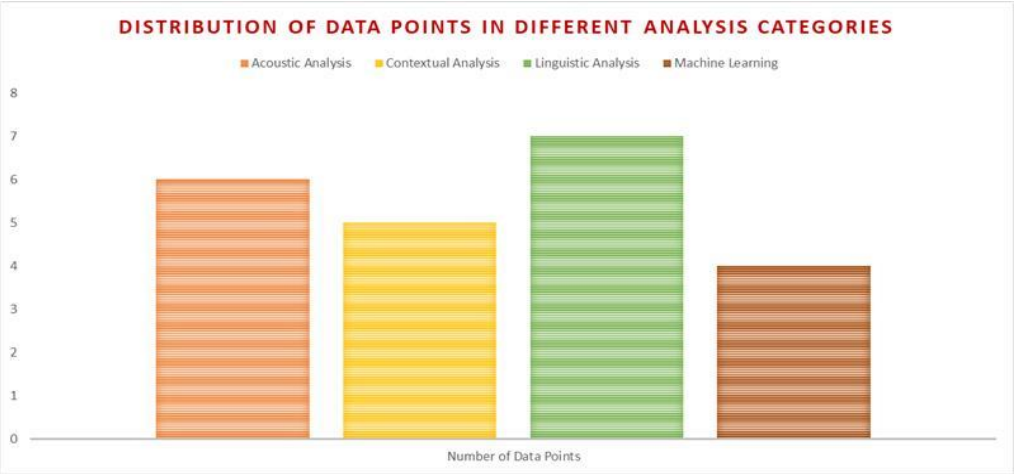

Figure 2: Distribution of data points in different analysis categories.

Data points are distributed across four categories of analysis (Table 2 and figure 2) in marine animal communication systems. As shown in the first row of Table 2, in the Linguistic Analysis section, the most data points were assigned, 7 in total. This shows that the analysis focusses heavily on the structural, semantic, and systemic patterns within the vocalizations. The next highest total (6) was found in the Acoustic Analysis row, which indicates that the analysis devoted considerable effort to the study of the signals in terms of their basic acoustic characteristics such as the frequency, duration, and amplitude. The next highest allocation of data points (5) was in the Contextual Analysis row, where analysts consider the significance of the deaf environment and the behaviors for which the vocalizations are intently examined. The row with the fewest data points (4) indicates that in Machine Learning, although the use of automated algorithms to classify patterns within the vocalizations was probably more than marginal, it was probably more than marginal. Thus, the table shows the dominated analysis being linguistic and acoustic. Except for the machine learning, it was contextual analysis that was more other than linguistic and acoustic research in the study of marine animal communication.

Discussion

The combination of philology and analyses of marine mammal communication is a new and different way of examining animal communication. For a long time, aquatic bioacoustics focused only on the science of sound - features like frequencies, amplitude, and duration of sound. Studies in this area have made essential contributions to our understanding of the science of sound that marine animals produce. However, these studies have usually ignored the fact that human vocalizations can and do utilize structured, linguistic patterns in their communication. The aim of this study is to begin to fill this knowledge gap by using philology, the study of language, its structure, and its meanings, in analyses of the vocalizations of marine mammals. Fax silva in human studies is most concerned with the identification of syntax, meaning of units of communication, and the pragmatics, or

the context and situation in which the language is used. Using these aspects of language to study marine mammal communication can provide evidence that their vocalizations do indeed achieve a certain complexity or structure. Through the fusion of philology and bioacoustics, we can capture and analyze the marine creatures' words and sentences and the particular messages they wish to pass through their conversations.' We can also investigate the potential of these 'conversations' to possess meaning that is variable with heterogenous social and ecological settings, the structure and order of these 'conversations' syntactically, and the possible usages of these 'conversations.' The primary value of philology and bioacoustics fusion is that it enhances understanding about the communication systems and the particular functions vocalizations serve. A raw acoustic analysis can show a soundscape laden with a multitude of calls, what is absent, is the understanding of those calls and their communication systems. Philology provides the tools critical to the understanding of communication systems and the multiple functions that vocalizations serve, fundamental to what a communication system is. The integration of a contextual analysis that takes into account the behaviors and ecological factors provide inferences on the particular calls and behaviors they are used to signal, and the systems of calls used.

A further central consideration of the interdisciplinary method is the integration of machine learning and pattern recognition to differ and explain vocalizations. In particular, the employment of packs of neural networks to dissect large swathes of acoustic data, the employment of machine learning to dissect large swathes of acoustic data, is inspiring, and these data may not be evident to human designers. They are also able to assist in the automation of classifying and differentiating acoustic vocalizations, removing the bottlenecks to the analysis of enormous volumes of field data brought home. Together with the other strands of linguistics, machine learning is of help in the analytic processes when the focus is on vocalizations to discern the nuances that may have differential meaning/intention in the context of the communication models be that the abstraction levels are relatively high. However, this configuration is not without its challenges. Some of the most important of the challenges, is the diversity and intricacy of marine animals vocalizations. These animals generate a diversity of sounds, and a single vocalization, is hypothesized to be polygamous in meaning in correlation with the class of the organism, the environment, and even the unique individual. Marine settings are also problematic for deep learning systems since the background noise in these environments can amplify distortion, creating problems for deep learning systems. While challenges do exist, improvements in machine learning helps to analyze high quality data more efficiently, while advancements in processing techniques and acoustic monitoring technology continue to help collect high quality data sets.

Besides, communicating with marine animals philologically entails considering that language is not uniform

across all species. As much as human communication and language is structured around symbols and grammar, and is complex, animals in the sea communicate in ways that do not resemble language in human form. One does not, for instance, rule out the possibility that the sounds whales and dolphins utter, though they do not comply with the structures of syntax, are meaningful in the patterns and repetitions that they produce. For this reason, a marine communication study is philologically flexible with the understanding of some "language" to be the only form of communication in some species. Ultimately, marine communication, opening philology with acoustic signal analysis, is complex and may be construed as enabling the hypotheses that marine animals, like humans, are capable of layered, complex vocalizations for multiple uses including social and navigation purposes. It is this framework that will guide the study of marine and acoustic signal. Presumably, marine communication in animals, like all other communication, is complex. It provides signals for social interactions, navigation and is layered. This study is interdisciplinary. By analysing acoustic signals with some linguistic principles, new aspects of communication are brought to light, and, with this, new avenues of animal cognition, social behaviors, and communication systems are trodden. This study will also provide new aspects of animal behaviours to animal behaviour and it will aid in conservation and other management systems around wildlife. The mechanisms underlying the communication systems of marine organisms help to shape conservation strategies due to the ability to recognize and prioritize fundamental activities, social interactions, and ecological functions that warrant safeguarding. In addition, the impacts of human activities, particularly shipping-related noise and underwater building, which interfere with the communication systems of marine organisms, are mitigated to the extent that communication systems are understood.

Conclusion

In summation, integrating the discipline of philology with the analysis of acoustic signals presents new horizons in the study of the communication systems of marine animals. Considering the structure, meaning, and context of a marine mammal's vocalizations alongside bioacoustic methods, this interdisciplinary paradigm opens new avenues for studying meaning and the multifunctionality of these sounds. Whether to structure a social system or to help the marine animal maneuver through its surroundings, the sounds produced are multifunctional and highly valuable. Under the guise of background noise, the challenges posed by acoustic signals of varying complexity can be addressed through the marriage of machine learning and language analysis. The study of animal communication will be advanced, and with this knowledge the cognition and behavior of marine animals will be better understood. The insights gained will aid in the conservation of aquatic ecosystems and will address the negative ramifications of human endeavors.

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