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Derleme Makale
Review Article

The importance of auditory function in terrestrial life forms for advancing biomimicry research

Biyomimetik araştırmalarını ilerletmede karasal yaşam formlarında işitsel işlevin önemi

Hatice Mehtap Buluklu[1*], Özgül Akın Şenkal[2], Ercan Köse[3], Filiz Bal Koçyiğit[4], Cafer Erkin Koyuncu[5]

[1]Tarsus University, Production Engineering ABD, PhD Graduate, Mersin, Türkiye
[2]Tarsus University, Faculty of Health Sciences, Department of Speech and Language Therapy, Tarsus/ Mersin, Türkiye
[3]Tarsus University, Faculty of Engineering, Electrical-Electronics Engineering, Tarsus/ Mersin, Türkiye
[4]Atılım University, Faculty of Fine Art Design and Architecture, Department of Architecture, Ankara, Turkey, Türkiye
[5]Mersin University, Faculty of Fisheries, Department of Diseases, Mersin, Türkiye

Abstract: Terrestrial animals perceive a wide range of frequencies, with auditory functions varying depending on the frequency. This study examines the auditory capabilities of terrestrial animals, focusing on hearing frequency ranges, hearing thresholds (in Watt/cm^2), and spontaneous otoacoustic emissions (SOAEs), which provide insights into auditory processing. Anatomical differences significantly influence hearing abilities. For instance, although mice have relatively small ears, they require higher intensity levels for auditory processing. The auditory thresholds of mice correspond to their ear anatomy, necessitating greater acoustic energy for hearing compared to many other terrestrial animals. A model was developed to illustrate how SOAEs contribute to the mouse's auditory function. In biomimicry, these findings can inspire innovative technologies by replicating auditory mechanisms. For example, the energy conversion capabilities of auditory structures can enhance acoustic sensor efficiency. A detailed modelling study can further refine this concept by focusing on a specific species and incorporating numerous parameters based on empirical data. Future research should integrate ear modelling to improve our understanding of terrestrial animal communication and facilitate biomimetic applications. Such studies will contribute to advancements in auditory science and technology, leading to improved acoustic designs inspired by natural hearing mechanisms.
Keywords: Terrestrial animals, Auditory awareness, Auditory energy, Ear anatomy, Hearing threshold

Özet: Karasal hayvanlar geniş bir frekans aralığını algılar ve işitsel işlevler frekansa bağlı olarak değişir. Bu çalışma, karasal hayvanların işitme yeteneklerini; işitme frekans aralıkları, işitme eşikleri (Watt/cm^2 cinsinden) ve işitsel işlemlemeye dair içgörüler sağlayan spontan otoakustik emisyonlar (SOAE'ler) bağlamında incelemektedir. Anatomik farklılıklar işitme yetilerini önemli ölçüde etkiler. Örneğin, farelerin kulakları görece küçük olmasına rağmen işitsel işlemleme için daha yüksek şiddet düzeylerine ihtiyaç duyarlar. Farelerin işitme eşikleri kulak anatomileriyle uyumludur; birçok diğer karasal hayvana kıyasla işitme için daha fazla akustik enerji gerektirir. SOAE'lerin farenin işitsel işlevine nasıl katkıda bulunduğunu göstermek üzere bir model geliştirilmiştir. Biyomimetikte bu bulgular, işitsel mekanizmaların taklit edilmesiyle yenilikçi teknolojilere ilham verebilir. Örneğin, işitsel yapıların enerji dönüşüm yetenekleri akustik sensör verimliliğini artırabilir. Ayrıntılı bir modelleme çalışması, belirli bir türe odaklanarak ve ampirik verilere dayalı çok sayıda parametreyi dâhil ederek bu kavramı daha da geliştirebilir. Gelecekteki araştırmalar, karasal hayvan iletişimini daha iyi anlamak ve biyomimetik uygulamaları kolaylaştırmak için kulak modellemesini entegre etmelidir. Bu tür çalışmalar, işitsel bilim ve teknolojide ilerlemelere katkı sağlayacak; doğal işitme mekanizmalarından esinlenen daha iyi akustik tasarımlara yol açacaktır.
Anahtar Kelimeler: Karasal hayvanlar, İşitsel farkındalık, İşitsel enerji, Kulak anatomisi, İşitme eşiği

1. Introduction

Auditory function encompasses the ability of an organism to perceive sound, which is crucial for detecting potential threats, locating food, and communicating with others of the same species. Understanding the role of auditory function is essential for gaining insights into the behavior and ecology of terrestrial life forms (Schwartzkopff, 1977). The aim is to investigate the diverse mechanisms and adaptations that enable different species to process auditory signals in their environment, including the challenges and opportunities presented. Furthermore, we will examine the distinctive challenges and

*İletişim Yazarı / *Corresponding author*. Eposta/*Email* : mehtapbuluklu@gmail.com
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opportunities presented by studying auditory function in various terrestrial animals which will contribute to the advancement of biomimicry research. This will shed light on the remarkable diversity of auditory adaptations observed across different groups of organisms. (Ladich and Winkler, 2017).

Terrestrial animals can perceive a broad range of frequencies, with their auditory functions varying according to the specific frequency in question (Heffner, 2004). The application of research methods, both behavioral and physiological, enables the determination of the range of hearing frequencies that animals can detect, the energy required at each frequency, and their most sensitive frequencies. The auditory functions of terrestrial animals provide insight into their acoustic environment and the evolution of hearing across different species. It is noteworthy that certain species, including microchiropteran bats, some shrews, and oilbirds, have developed echolocation abilities. In contrast, some insects have evolved acute hearing to evade echolocating predators (Fletcher, 2004). We know little about auditory functions in terrestrial animals which is crucial for communication needs. Ten Cate and Spierings (2019) reviewed that the auditory processing mechanism of non-human animals can reveal similarities to humans. This review is concerned with the auditory functions of terrestrial animals, to elucidate the correlation between their hearing frequency ranges, hearing thresholds (acoustic energy), and spontaneous otoacoustic emissions (SOAEs) they encounter. This review encompasses the following topics:

I. Comparing the ear's anatomical structures and auditory functions between humans and terrestrial animals.

II. Analyzing the hearing thresholds (dB SPL) in the hearing frequency range of humans and terrestrial animals.

III. Assessing differences in hearing thresholds across frequency ranges in terms of Watt/cm^2.

IV. Theoretically calculating and interpreting the patterns of energy production in the ears of different terrestrial animals.

2. Methods

This study gathered studies from all databases to examine the auditory functions of terrestrial animals based on their auditory functions (Databases: Web of Science core collection (1900-present), BIOSIS Citation Index (1926-present), BIOSIS Previews (1969-present), Current Contents Connect (1998-present), Data Citation Index (1900-present), Derwent Innovations Index (1963-present), MEDLINE® (1950-present), Turkish Citation Index (2008-present), SciELO Citation Index (2002-present)) and by searching in the bibliographies of the papers we found. The keywords used for the search were "auditory function", "hearing", "terrestrial animals,", "spontaneous otoacoustic emissions in animals" and "hearing thresholds in animals". In the analysis of the data, the study investigated anatomical and physiological distinctions in the ears of terrestrial animals and humans, as well as hearing ranges, hearing thresholds, and spontaneous otoacoustic emission values. Within the scope of the study; 150 studies examining the auditory functions of terrestrial animals were searched and 68 studies were selected. According to the data obtained, 39 of them examine the anatomical and physiological differences of the

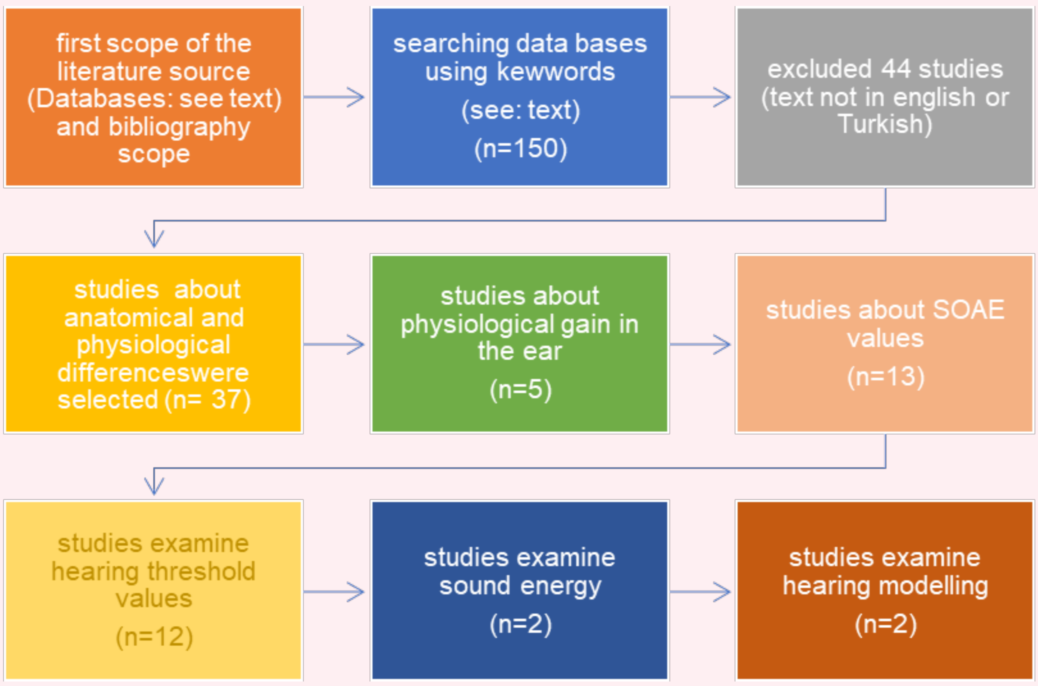


Figure 1. Data collection chart

ears of animals, 13 of them examine SOAE values, 12 of them examine hearing threshold values according to the hearing range, 2 of them examine sound energy and 2 of them examine hearing modelling. Following the aim of the study, the following comparisons and analyses were made with the information obtained from the studies in the literature (▶**Figure 1**).

Initial data were obtained to compare the anatomical structures and behavioural hearing characteristics of the ears of humans and terrestrial animals. Secondly, hearing frequency ranges of terrestrial animals were gathered from relevant literature and compared. The hearing frequency ranges graphs are arranged according to frequency ranges of 500 Hz. and below (low), 500-4000 Hz. (medium), and 4000 Hz. and above (high), taken from references. The graphs are organized according to low-, middle-, and high-frequency ranges to compare levels of processing required for auditory function. Thirdly, hearing threshold values were converted to Watt/cm^2 to detect levels of energy required for auditory functions. This conversion helps to assess the level of sound processing and potential function of the auditory system. Finally, hearing system modelling for terrestrial animals was developed based on adaptive Spontaneous Otoacoustic Emissions (SOAE) factors to reflect nonlinear processing in the inner ear and show functions to increase sensitivity to low-level sounds (McFadden et al., 2022).

3. Results

In this section, we present the comparison results of the ear's anatomical structures and auditory functions, analyzing the hearing frequency range, and assessing differences in hearing thresholds across frequency ranges regarding Watt/cm^2 of humans and terrestrial animals. We theoretically calculated and interpreted the patterns of energy production in the ears of different terrestrial animal species.

3.1. The anatomical and physiological auditory functions

Differences in the anatomical structures of terrestrial an-

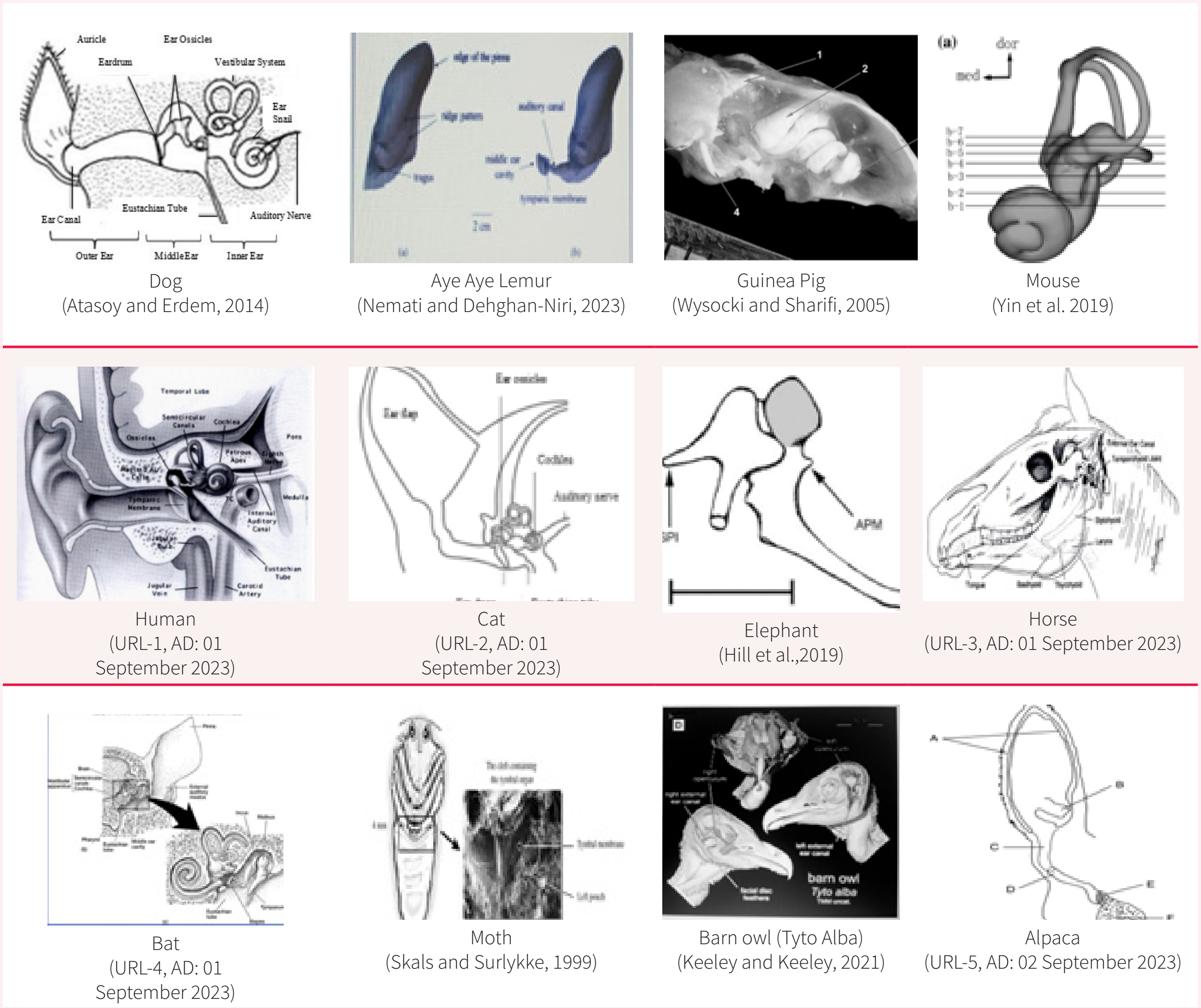


Figure 2. Ear structures of some terrestrial animals

imals' ears are specialized for auditory functions (Vater and Kössl, 2011). Due to the skull size and anatomical structure of ears in animals, the movement of the head at different angles depends on the amount of muscle in the auricles, and in this case, the amount of interaural attenuation varies (Manley, 2017; Mohanta, 2018). Sound waves coming from the atmosphere hit the head and are reflected and refracted. Depending on the direction the sound is coming from, the sound pressure increases on the side of the ear where the sound waves hit, while the

Figure 3. Hearing thresholds of different animals

pressure decreases on the other side of the ear. This creates a difference of 0.6 msec between the sounds reaching the two ears, allowing the direction of sound arrival. The ear canal in cats and dogs is deeper and thinner than that in humans, the auricle can deliver sound to the eardrum like a funnel (Gotthelf, 2004). It is crucial to acknowledge that dogs and cats exhibit considerable variation in size and morphology. Consequently, comparisons with humans should be meticulously evaluated to ascertain their relevance at the species level versus specific morphological traits within dogs (Barber et al., 2020). In this way, the sound waves collected with the help of the auricle are also more distant, and since high-frequency sounds are about 4 times higher than those of humans, cats and dogs can communicate even from kilometers away (Malkemper et al., 2020). Additionally, bats utilize echolocation (Cao et al., 2022). The capacity for environmental adaptation is reflected in the echolocation signalling utilized for navigation, foraging, and communication. Nevertheless, the extent and drivers of echolocation plasticity remain poorly understood (Montauban et al., 2021). In addition to bats, moths exhibit a distinct phenomenon. It has been demonstrated that they are capable of locating objects through the use of both acoustic and tactile energy, a process commonly referred to as sonar radar. Similar to echolocation bats, many moth species also use ultrasonic sound waves (Barber et al., 2022). The auditory system of Aye-Aye Lemurs differs from that of other terrestrial animals. The Aye-Aye lemur forages tactilely by tapping on tree bark and has infrasonic hearing features called "tactile scanning" (▶**Figure 2**). The ear canal of the aye-aye (Daubentonia madagascariensis) is notable for its capacity to enhance auditory signals. A study has also demonstrated that the Aye-Aye's outer ear has evolved to filter out low frequencies by shifting the center frequency in hearing, a change that takes the form of a "sound field beam" so that higher-frequency sounds can be heard more effectively (Nemati and Dehghan-Niri, 2022). However, when the auditory system of the mouse was examined, it was found that they exhibited a strong response to sudden noises within the auditory frequency ranges (Patel et al., 2020).

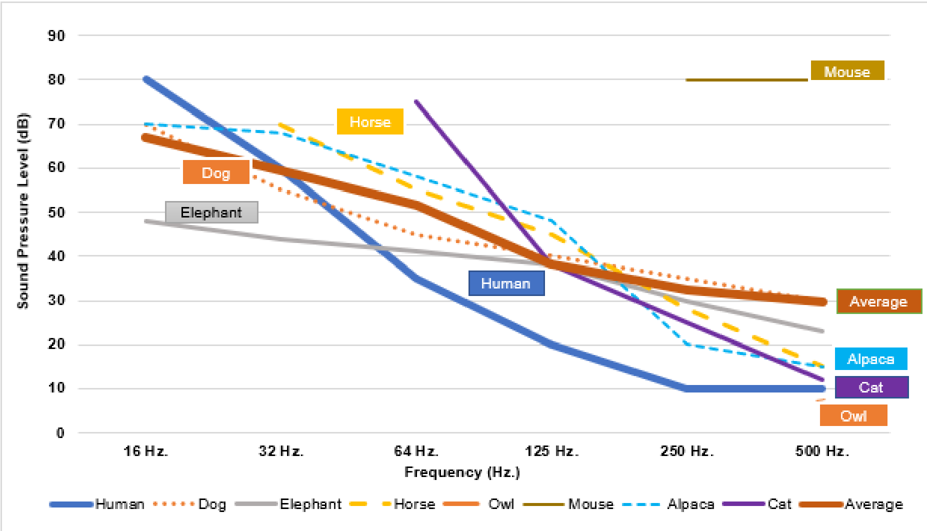
It has been observed that the ear structures of animals such as the Guinea Pig, cat, Aye-Aye Lemur, mouse, cat, elephant, horse, bat, moth, barn owl, and alpaca have common anatomical features (Sundar et al., 2021; O'Connell et al., 2024). In cats, one of the species that can turn their ears toward sound, the maximum gain value is 9.6 dB at 16.4 kHz (Tollin and Koka, 2009). In the auricle of the mouse, it is 5-12 dB at 20-35 kHz. Recent studies also indicate 27 dB at 19.1 kHz (Heuser and Tenkova, 2020). The acoustic gain values of owls are 20 dB at 3-9 kHz. in the outer ear and start to decrease after 10 kHz. The values may vary because of the curvature of the outer ear structure (Jaworski and Peake, 2020). In horses, the auricle has an acoustic gain of 10-20 dB above a few kHz. The auricle of horses provides an acoustic gain of 10-20 dB (Rørvang et al., 2020).

3.2. Hearing Threshold Values

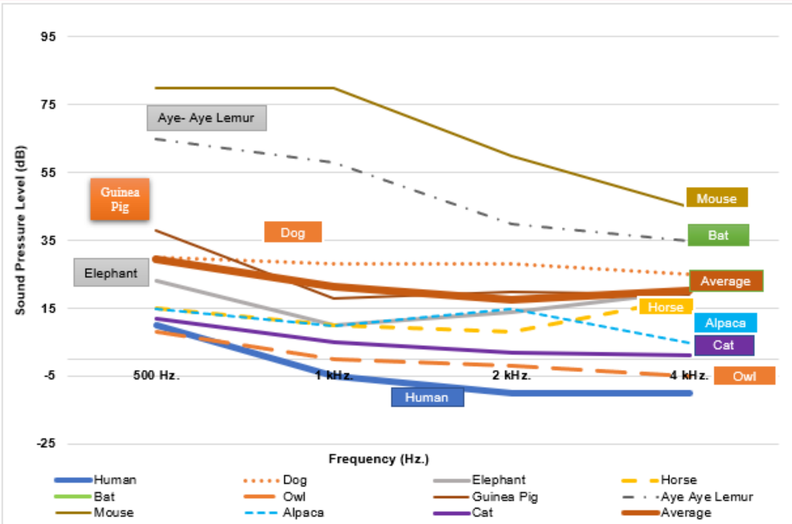
It is also important to note that the threshold values for hearing may differ depending on the auditory functions of the animal in question. This is because physiological methods do not require a behavioural response from the animal that indicates the sound was perceived. As a result, these tests are considered to be tests of "auditory function" rather than "hearing" per se. Depending on auditory function, they show sensitivity to infrasound or ultrasound sounds (▶**Figure 3**). For example, many terrestrial animals, such as dogs, can hear frequencies in the ultrasonic range (above 20 kHz.). Dog whistles in the 23–54 kHz. range used to train dogs can be heard by many animals but not by humans (Barber et al., 2020). Humans are known to be the best species at 1000–5000 Hz hearing frequency range. In this frequency range, humans and elephants can hear sounds of lower intensity than horses, rats, cows, dogs, and cats. Birds and fish generally cannot hear very low-intensity sounds (below 50 dBA), although they can hear in a narrower frequency range than other animals (Brinkløv et al., 2022). Humans hear in the frequency range of 20 Hz.-20 kHz., cats 60–60 kHz., and dogs 15–50 kHz. (Ubiema et al., 2022). Some animals can hear at lower frequencies than humans. Elephants can hear sounds between 16 Hz. and 12 kHz. It is known that horses are sensitive to auditory stimuli in the approximate range of 55 Hz.-33.3 kHz. (Ubiema et al., 2022). The frequency range of hearing sensitivity is 85 kHz.-110 kHz. Bats in *Eskisehir* have echolocation features of 30–100 kHz. in some species (Barlas, 2016). Hearing frequency range in owls is 200–10 kHz., 20–50 kHz. in eared moths, 1–15 kHz. in Guinea Pig, and 2.8–22.6 kHz. in Aye-Aye Lemur (Daubentonia madagascariensis), and 250–80 kHz. in mice (Wysocki and Sharifi, 2005; Ashida, 2015; Escabi et al., 2019; Nemati and Dehghan-Niri, 2020; Neil and Holderied, 2021).

▶**Figure 3** illustrates that the graphs of the horse, mouse, and alpaca are highly similar. Similarly, the graphs of the Guinea Pig and moth exhibit high similarity. However, the graph of the aye-aye lemur is strikingly different. When we examine terrestrial animals in general, it is seen that hearing frequency ranges are different regarding auditory functions. In determining hearing levels within the hearing range, hearing thresholds obtained with physiological methods may underestimate or overestimate behavioural thresholds. The sound pressure level (dB SPL) and the frequencies at which hearing can occur for each terrestrial animal shown in ▶ **Figure 3** are analysed in ▶**Figure 4**. The data shown in ▶**Figure 3** is taken from previous studies in literature (Heffner and Heffner 2007; Strain 2017; Heffner and Heffner 1994; (URL-6, AD: 02 September 2023); Heffner and Heffner 1983; Koay et al., 2003; Krumm et al., 2017; Nakano et al., 2015; Naert et al., 2019; Koay et al., 2014; Reynolds et al., 2010; Heffner and Heffner 2014).

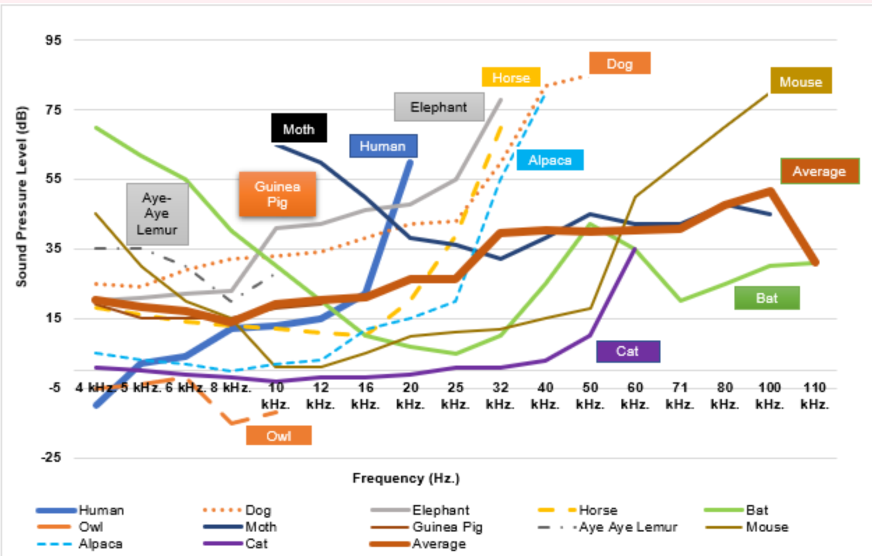
Three different frequency ranges were considered in organizing the graphs in ▶**Figure 4**. The graphs are arranged according to the frequency ranges of 500 Hz.



500 Hz. and under 500 Hz.



500- 4000 Hz. frequency range



4000 Hz. and above 4000 Hz.

Figure 4. Hearing thresholds in a limited hearing range

Table 1. Hearing threshold values of different terrestrial animals and humans (dB SPL)

Frequency	16 Hz.	32 Hz.	64 Hz.	125 Hz.	250 Hz.	500 Hz.	1 kHz.	2 kHz.	4 kHz.	5 kHz.	6 kHz.	8 kHz.	10 kHz.	12 kHz.	16 kHz.	20 kHz.	25 kHz.	32 kHz.	40 kHz.	50 kHz.	60 kHz.	71 kHz.	80 kHz.	100 kHz.	110 kHz.
Human	80	60	35	20	10	10	-5	-10	-10	2	4	12	13	15	22	60									
Dog	70	55	45	40	35	30	28	28	25	24	29	32	33	34	38	42	43	60	82	85					
Elephant	48	44	41	38	30	23	10	14	20	21	22	23	41	42	46	48	55	78							
Horse		70	55	45	28	15	10	8	18	16	14	13	12	11	10	20	39	70							
Bat									70	62	55	40	30	20	10	7	5	10	25	42	35	20	25	30	31
Owl						8	0	-2	-5	-4	-2	-15	-12												
Moth													65	60	50	38	36	32	38	45	42	42	48	45	
Guinea Pig						38	18	20	19	15	15	15	18	19											
Aye Aye Lemur						65	58	40	35	35	30	20	28												
Mouse					80	80	80	60	45	30	20	15	1	1	5	10	11	12	15	18	50	60	70	80	
Alpaca	70	68	58	48	20	15	10	15	5	3	2	0	2	3	12	15	20	55	80						
Cat			75	38	25	12	5	2	1	0	-1	-2	-3	-2	-2	-1	1	1	3	10	35				

Table 2. Hearing Thresholds Values (Watt/cm2)

Frequency	16 Hz.	32 Hz.	64 Hz.	125 Hz.	250 Hz.	500 Hz.	1 kHz.	2 kHz.	4 kHz.	5 kHz.	6 kHz.	8 kHz.	10 kHz.	12 kHz.	16 kHz.	20 kHz.	25 kHz.	32 kHz.	40 kHz.	50 kHz.	60 kHz.	71 kHz.	80 kHz.	100 kHz.	110 kHz.	Average	Number of octave bands
Human	10^{-8}	10^{-10}	10^{-12}	10^{-12}	10^{-15}	10^{-15}	10^{-17}	10^{-17}	10^{-17}	10^{-16}	10^{-16}	10^{-15}	10^{-15}	10^{-14}	10^{-14}	10^{-10}										6,37E-10	16
Dog	10^{-9}	10^{-10}	10^{-11}	10^{-12}	10^{-12}	10^{-13}	10^{-13}	10^{-13}	10^{-13}	10^{-14}	10^{-13}	10^{-13}	10^{-13}	10^{-13}	10^{-12}	10^{-12}	10^{-12}	10^{-10}	10^{-8}	10^{-7}						5,56E-9	20
Elephant	10^{-11}	10^{-12}	10^{-12}	10^{-12}	10^{-13}	10^{-14}	10^{-15}	10^{-15}	10^{-14}	10^{-14}	10^{-14}	10^{-14}	10^{-12}	10^{-12}	10^{-11}	10^{-11}	10^{-10}	10^{-8}								5,63E-10	18
Horse		10^{-9}	10^{-10}	10^{-11}	10^{-13}	10^{-14}	10^{-15}	10^{-15}	10^{-14}	10^{-14}	10^{-15}	10^{-15}	10^{-15}	10^{-15}	10^{-15}	10^{-14}	10^{-12}	10^{-9}								1,24E-10	17
Bat									10^{-9}	10^{-10}	10^{-10}	10^{-12}	10^{-13}	10^{-14}	10^{-15}	10^{-15}	10^{-15}	10^{-15}	10^{-13}	10^{-12}	10^{-12}	10^{-14}	10^{-13}	10^{-13}	10^{-13}	7,08E-11	17
Owl						10^{-15}	10^{-16}	10^{-16}	10^{-17}	10^{-16}	10^{-16}	10^{-18}	10^{-17}													1,77E-16	8
Moth													10^{-9}	10^{-10}	10^{-11}	10^{-12}	10^{-12}	10^{-13}	10^{-12}	10^{-11}	10^{-12}	10^{-12}	10^{-11}	10^{-11}		9,54E-11	12
Guinea Pig						10^{-12}	10^{-14}	10^{-14}	10^{-14}	10^{-14}	10^{-14}	10^{-14}	10^{-14}	10^{-14}												1,2E-13	8
Aye Aye Lemur						10^{-9}	10^{-10}	10^{-12}	10^{-12}	10^{-12}	10^{-13}	10^{-14}	10^{-13}													1,3E-10	8
Mouse					10^{-8}	10^{-8}	10^{-8}	10^{-10}	10^{-11}	10^{-13}	10^{-14}	10^{-14}	10^{-14}	10^{-16}	10^{-16}	10^{-15}	10^{-15}	10^{-15}	10^{-14}	10^{-14}	10^{-11}	10^{-10}	10^{-9}	10^{-8}		2E-9	20
Alpaca	10^{-9}	10^{-9}	10^{-10}	10^{-11}	10^{-14}	10^{-14}	10^{-15}	10^{-14}	10^{-15}	10^{-16}	10^{-16}	10^{-16}	10^{-16}	10^{-16}	10^{-15}	10^{-14}	10^{-14}	10^{-10}	10^{-8}							6,42E-10	19
Cat			10^{-8}	10^{-12}	10^{-13}	10^{-15}	10^{-15}	10^{-16}	10^{-16}	10^{-16}	10^{-16}	10^{-16}	10^{-16}	10^{-16}	10^{-16}	10^{-16}	10^{-16}	10^{-16}	10^{-16}	10^{-15}	10^{-12}					5,26E-10	19

and below (low), 500-4000 Hz. (medium), and 4000 Hz. and above (high). A comparison of the mouse and alpaca reveals that their values are very similar. Nevertheless, when contrasted with the Aye-Aye Lemur, it becomes evident that they exhibit strikingly disparate characteristics at these frequencies. A comparison of the mouse and alpaca with the owl reveals that they are valuable at the following frequencies.

3.3. Hearing threshold differences in hearing frequency ranges (Watt/cm²)

The relationship between sound intensity, wave size and the number of vibrations is well established. Sound intensity is defined as the amount of sound energy passing through a unit surface in a unit of time (Brixen, 2020). The energy of sound is a function of both its amplitude and frequency. As amplitude and frequency increase, so does the energy level of the sound. Eq. (1) provides a means for determining the sound intensity. It is cumbersome to measure the incredibly small amounts of power that are associated with the enormous range of intensities that the ear is capable of hearing (Valente et al., 2011).

$$\beta = 10.\log(E/Eo)\,(dB) \quad (1)$$

β: Sound Intensity (dB)
E: Energy of sound per unit area
Eo: Energy of the weakest audible sound (10^{-12} W/m²)

If E <Eo no sound audible (β = 0 dB)
• E= 10^{-11} W/m² whispers (β = 10 dB)
• E= 10^{-7} W/m² conversational speaking (β = 50 dB)
• E= 1 W/m² pain (β = 120 dB)

Hearing threshold values for different terrestrial animals are provided in Table 1, following the results obtained from ▶Figure 2. These values replace β in equation (1), enabling the calculation of sound energies per unit area per species, expressed in Watt/cm² as shown in Table 2.

The sound energy per unit area values, calculated using the data in ▶Table 1, are converted to Watt/cm2 for comparison with the data in ▶ Table 3. The results are presented in ▶ Table 2.

Yellow cells in ▶ Table 2 indicate the frequencies at which no hearing occurs and green cells indicate the highest sound levels. In general, according to the theoretical and approximate hearing threshold levels, the highest value belongs to the mouse at the frequencies of 250 Hz.-1kHz. and 100 kHz. Although the size of a mouse's ears is relatively small compared to other terrestrial animals, the mouse's ears need higher intensity levels to process hearing.

Based on the overall intensity level averages, mouse and dogs are ranked 1st, humans, elephants, horses, aye-aye lemur, alpaca, and cats are ranked 2nd, and Guinea Pig, moth, and owl are ranked 3rd. Additionally, the number of octave bands was included in the analysis, besides the average values.

Table 3. The relationship between SPL and Watt/cm²

	Watt/cm²	Decibels SPL	Example sound
Softer Louder	10^{-2}	140 dB	Pain
	10^{-3}	130 dB	
	10^{-4}	120 dB	Discomfort
	10^{-5}	110 dB	Jackhammers and rock concerts
	10^{-6}	100 dB	
	10^{-7}	90 dB	OSHA limit for industrial noise
	10^{-8}	80 dB	
	10^{-9}	70 dB	
	10^{-10}	60 dB	Normal conversation
	10^{-11}	50 dB	
	10^{-12}	40 dB	Weakest audible at 100 Hertz
	10^{-13}	30 dB	
	10^{-14}	20 dB	Weakest audible at 10 kHz
	10^{-15}	10 dB	
	10^{-16}	0 dB	Weakest audible at 3 kHz
	10^{-17}	-10 dB	
	10^{-18}	-20 dB	

The frequency ranges to be analysed are defined as octave bands. There are a large number of frequencies in each octave band. As low-frequency properties change frequently, the number of frequencies in low-frequency octave bands is less than those in high-frequency octave bands. However, this number increases from low frequencies to high frequencies. Based on the data in ▶Table 2, the average sound energy values show that the mouse has the highest value at 2E-9, and both the dog and mouse have an octave bandwidth of 20. Following this, the alpaca and cat have a bandwidth of 19, the elephant with 18, and finally the horse and bat with 17. Therefore, it can be said that the highest value belongs to the mouse.

The data shown in ▶Figure 5 in hearing threshold values (Watt/cm²) indicate that the amount of energy for the hearing threshold is relatively high in the range of 10^{-10}-10^{-8} and intense in the range of 10^{-8}-10^{-10} (80-60 dB SPL) at frequencies of 16 Hz. to 2 kHz. The bat and moth have relatively no auditory function in this range. The lowest values of the hearing thresholds for humans are 10^{-17} Watt/cm² at 1-4 kHz., and for owls 10^{-8} Watt/cm² at 8 kHz. and 10^{-9} Watt/cm² at 4 kHz. at frequencies of 20 kHz. The measurement of hearing threshold values in Watt/cm² provides a precise quantification of auditory sensitivity, allowing for detailed comparisons across different species. This approach enhances our understanding of the variations in auditory functions among terrestrial animals, shedding light on the evolutionary adaptations that contribute to their survival and communication capabilities.

3.4. Auditory Function Modelling for Terrestrial Animals Based on Adaptive SOAE Factor

The cochlea is a transducer that converts the acoustic energy of sound into electrical conduction and serves as a frequency analyser that distinguishes acoustic components. In the cochlea, frequency mapping of sound is based on spectral analysis, and cochlear amplification is performed (van der Heijden & Versteegh, 2015). Re-

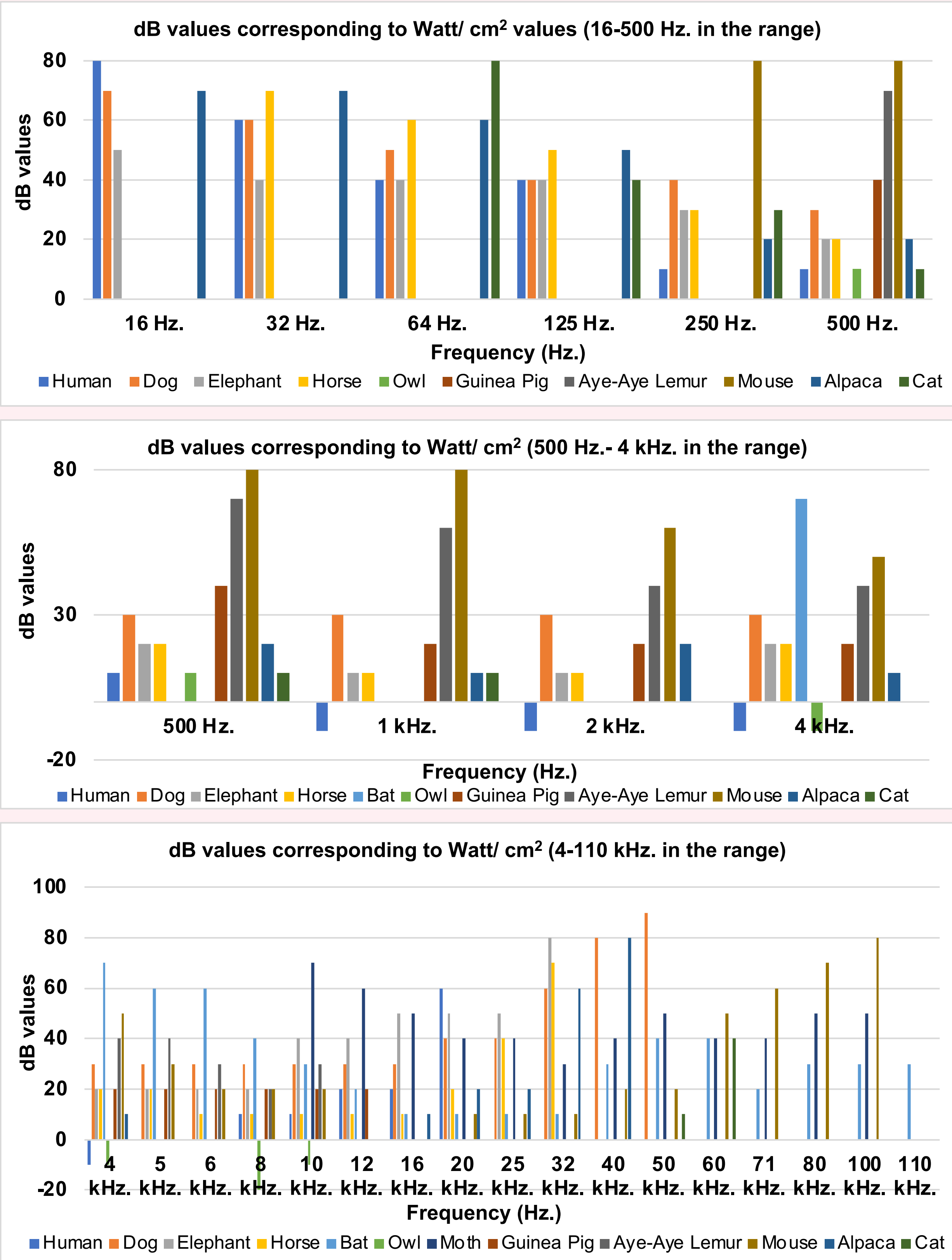


Figure 5. Terrestrial animals hearing threshold values (Watt/ cm²)

Table 4. SOAE Values in Terrestrial Animals

Number	Species	SOAE
1	Human (Kumar et al., 2020)	250 Hz.- 4 kHz. 15 dB and lower
2	Owl (Engler et al., 2020)	3,4-10,2 kHz. Peak level at 20 dB a spectral width of 200 Hz. (Tyoto Alba)
3	Guinea Pig (Nuttall et al., 2004)	14,6 kHz. 15 dB.
4	Dog (Ruggero et al., 1984)	Bilaterally 59 dB SOAE. App. 9100 Hz very small band SOAE (< 4 Hz.)
5	Mouse (Cheatham, 2021B)	12.9±4.9 kHz. 13.3±8.1 dB SPL
6	Cat (URL-7, AD: 02 September 2023)	No SOAE measurement
7	Horse (McBrearty et al., 2013)	No SOAE measurement
8	Elephant (Chen and Wiens, 2020)	No SOAE measurement
9	Bat	No SOAE measurement
10	Moth	No SOAE measurement
11	Aye- Aye Lemur	No SOAE measurement
12	Alpaca	No SOAE measurement

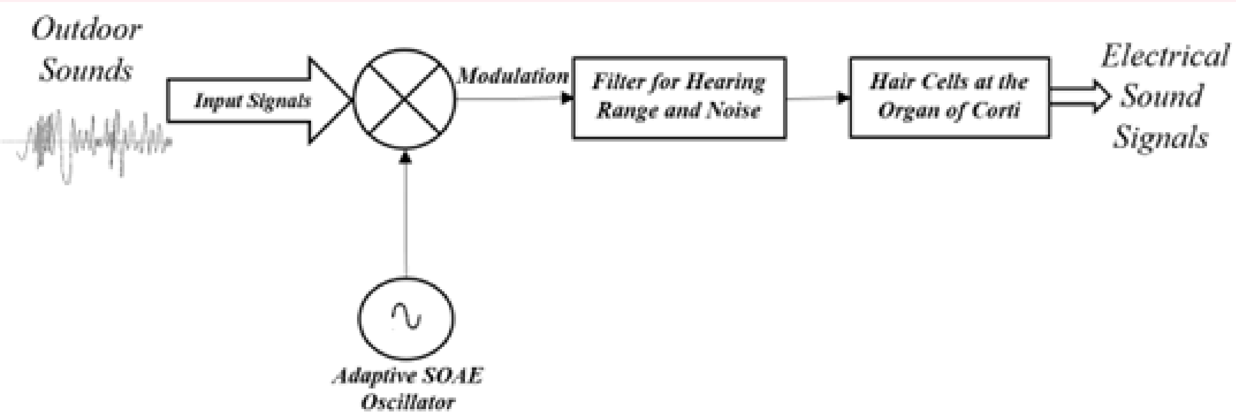


Figure 6. Hearing system modelling of land animals based on adaptive SOAE factor

markably, the cochlea itself produces sound. This sound energy in the cochlea is called otoacoustic emission. Otoacoustic emissions can be spontaneous (spontaneous otoacoustic emissions- SOAEs) or evoked by external acoustic stimulation (evoked otoacoustic emissions). Otoacoustic emissions (OAEs) are small sound waves that can be recorded in the external ear canal. SOAEs are an indicator of auditory mechanical sensitivity and active processing of frequency selectivity in the inner ear (Hudspeth et al., 2010). Therefore, it is important to consider SOAEs when comparing auditory function. SOAEs are auditory energies that can be detected in approximately 40-50% of normal hearing ears, and their amplitudes are approximately -10 to +20 dB SPL (Hudspeth, Jülicher & Martin, 2010). SOAEs could not be measured in many laboratory animals. However, SOAEs are indicative of active cochlear operation (Cheatham, 2021A). Nevertheless, the biophysical mechanism in the cochlea is still unexplained. The different SOAE values in different terrestrial animals suggest that auditory functions are used for different purposes in terrestrial animals;

- the ability to adapt to the environment to survive,
- to communicate,
- to locate and lateralize their hunting.

In the global framework, SOAEs exist because the outer hair cells in the organ of Corti continue to oscillate and provide energy according to the travelling wave theory. Animals without a basilar membrane use a different cochlear mechanism, while those that use outer hair cell electromotility and those that use travelling waves perform auditory processing with a different cochlear mechanism. For example, although the mouse ear produces SOAEs with the standing wave theory, cochlear-damaged ears can still produce SOAEs with an adaptive mechanism. It has been proposed that SOAE values may be associated with hearing frequency range (Moulin et al., 1993).

Humans' SOAEs are typically 15 dB or less at 250 Hz.- 4 kHz. The use of spontaneous emissions in humans is limited by the inability to measure them in all normal ears (Bright et al., 2007). Barn owls' SOAEs are between 3.4 and 10.2 and the Peak level is at 20 dB with a spectral width of 200 Hz. Whilst owls' SOAEs are between -5.8 and 10.3 dB at 2.3 to 10.5 kHz. and guinea pigs are 15 dB at 14.6 kHz. It is important to note that SOAE values are not reachable in cats due to limited studies in the literature (McBrearty and Penderis, 2011). Studies measuring SOAE values in non-mammalian and large animals are sparse. Nevertheless, it has been suggested that if conducted, these measurements could potentially produce results similar to those of terrestrial animals (Manley, 2022). It can be demonstrated that emissions are produced by active hair-cell mechanisms that are themselves dependent upon comparable nonlinear cellular processes. The observed differences, such as the width of spontaneous emission peaks and the delay times between peaks, should provide insights into the coupling of hair-cell activity within the organ and its partial routing out into the middle ear (Manley, 2022).

Modelling the auditory function of a terrestrial animal from the anatomy of its ear is a complex process due to the large number of variables involved and the dynamic behaviour of many of these variables. Some information from anatomy, electrophysiology and mathematical modelling may need to be combined (Borisyuk et al., 2005). In attempting to derive a model for a terrestrial animal examined in this study, the major variables are environmental adaptability for the environment, ambient temperature, and interaural attenuation. It may also be necessary to consider variables specific to each terrestrial animal. Furthermore, SOAE emerges as an important factor in this modelling.

SOAEs may be a side effect of the inner ear's active process that increases the auditory function (Manley, 2024). Some studies in the literature have recorded SOAEs simultaneously in both ears of the animal. It is remarkable that some SOAEs occur at the same frequency in both ears and are synchronized. The generation of SOAE depends on many factors, including the structure of the eardrum, the outer hair cells in the organ of Corti, and the acoustic pathway between the ears (Roongthumskul et al., 2019).

It is known from the literature that terrestrial animals perform adaptive auditory functions and that environmental sounds produce a frequency modulation in the animal's hearing frequency range. This modulation is facilitated by an oscillator that acts as an adaptive and asynchronous oscillation, which serves as the basic carrier. In addition, there is a filter structure that operates in the same range of hearing frequencies, allowing for conversion to electrical sound signals or energy. **▶Figure 6** depicts the modelling structure that incorporates these descriptions.

Mathematical modelling can be complex, but a basic framework can be established. This model demonstrates the impact of SOAEs on the adaptive auditory system (Fruth, 2014). Mathematical expressions for the model shown in **▶Figure 6** can be based on acoustic energy values, hearing thresholds, and SOAE frequencies.

3.5. SOAE Production

In adding the adaptive production of SOAEs to the model, Eq. (2) can be used for a simple oscillator model.

$$x(t) = A \cdot \sin(2\pi f t + \emptyset) \qquad (2)$$

Where:

- $x(t)$, SOAE signal,
- A, amplitude,
- f, SOAE frequency,
- $\emptyset$, represents phase.

This model represents a basic sinusoidal oscillator that can be used when modelling SOAEs.

3.6. Hearing Threshold and Sound Energy:

Eq. (3) is used to express the relationship between hearing threshold *(α)* and sound energy *(E).*

$$\alpha = 10.\log\,(\mathrm{E/Eo}) \qquad (3)$$

Where:

- α is the hearing threshold,
- E is the energy of sound coming into the unit area,
- E_0 represents the energy of the weakest sound that can be heard

3.7. Adaptive Hearing

To model the adaptive hearing mechanism, Eq. (4) can be added for the effect of SOAEs on hearing threshold (Liu, 2020).

$$\alpha_{adaptif} = \alpha_{normal} + k \cdot \alpha_{SOAE} \qquad (4)$$

Where;

- $\alpha_{adaptive}$, adaptive hearing threshold,
- $\alpha_{normal,}$ normal hearing threshold,
- α_{SOAE}, additional hearing threshold resulting from the effect of SOAEs,
- k is a parameter representing the strength of the influence of SOAEs.
- This model simply represents the adaptive effect of SOAEs on the auditory system. A real modelling study can be more complex and focus on a specific living species. This may require determining various parameters based on experimental data.

For example, it is given that a living thing's SOAE frequency is f =1000 Hz., its amplitude $A = 0.1$, hearing threshold $\alpha_{normal} = 20$ dB and sound energy $E = 10^{-10}\ \mathrm{W/m^2}$.

If Eq. (5) is used for the sinusoidal oscillator model for

SOAE,

$$\alpha_{normal} = 10 \cdot \log_{10}\left(\frac{10^{-10}}{10^{-12}}\right) = 20 \text{ dB} \quad (5)$$

If the adaptive effect of SOAE is added to the system for adaptive hearing, Eq. (6).

$$\alpha_{adaptif} = 20 + k \cdot 0.1\cos(2\pi \cdot 1000 \cdot t)$$

$$\alpha_{adaptif} = 20 + k \cdot 0.1\cos(2\pi \cdot 1000 \cdot t) \quad (6)$$

Where k parameter represents the power factor of the SOAE effect.

Frequency Modulation (FM) is a technique used to modulate audio signals. We can add a simple FM modulation to model adaptive SOAEs. The frequency of SOAE represents a time-varying transport frequency.

For example, the following formula Eq. (7) can be used to add FM modulation.

$$y(t) = A\sin[2\pi f_c + \beta\sin(2\pi f_m t)] \quad (7)$$

Where: $y(t)$ are the parameters representing the FM modulated SOAE signal, A is the amplitude, f_c is the transport frequency, β is the modulation index, f_m is the modulation frequency.

This formula; enables the SOAE frequency to be modulated at the *fm* frequency around the f_c transport frequency.

This formula is combined with the previous SOAE formula, the resulting Eq. (8):

$$\alpha_{adaptif} = \alpha_{normal} + k \cdot A\sin[2\pi f_c + \beta\sin(2\pi f_m t)] \quad (8)$$

This formula would have modified the adaptive hearing threshold with FM modulation. To determine f_m and β parameters should be done based on experimental data to check the properties of this modulation. This is especially true for a particular species, as these parameters can vary according to living species.

There are very few studies in the literature on ear anatomy, auditory functions and hearing thresholds of humans and land animals. However, no data on hearing energy could be found. Therefore, the hearing energy of land animals based on the differences between their ear anatomy and frequency-based hearing thresholds was theoretically calculated and interpreted. It is anticipated that the study will contribute to the development of terrestrial animal communication understanding and ear modelling research while pioneering acoustic designs.

4. Conclusion

In the present era, biomimicry research endeavours to facilitate the development of novel technologies by emulating the survival strategies employed by living organisms. In a world where energy demands are on the rise, this approach opens new avenues and illuminates the potential for leveraging the acoustic energy conversion capabilities of diverse acoustic functions, such as those observed in animals (Ersanlı and Ersanlı, 2023).

This study provides a comprehensive review of the auditory functions in terrestrial animals, focusing on their hearing frequency ranges, hearing thresholds in Watt/cm^2, and spontaneous otoacoustic emissions (SOAEs). The anatomical structures of terrestrial animals' ears are specialized for their specific auditory functions, and these structural differences significantly impact their hearing frequency ranges and thresholds.

Auditory function is fundamental across species such as humans, birds, frogs, and crocodiles. As far as auditory function is concerned, terrestrial animals seem to have better high-frequency hearing than humans (Ekdale, 2016). Our findings indicate that hearing thresholds vary widely among different species, with mice requiring the highest intensity levels to process hearing, particularly at frequencies of 250 Hz. to 1 kHz. and 100 kHz. This suggests that despite the relatively small size of their ears, mice need higher acoustic energy levels for auditory function compared to many other terrestrial animals. In this study, we found that hearing thresholds in frequency ranges differed between terrestrial animals (Heffner, 2004; Heffner &Heffner, 2007).

Heffner and Heffner (2007) explain that small mammals require high-frequency hearing to locate sounds better. This situation has also been observed in all terrestrial animals. Heffner and Heffner (2007) report that mammals demonstrate reduced low-frequency hearing sensitivity compared to humans. Some animals, specifically elephants, are believed to have a broader range of low-frequency hearing because they use high-frequency sounds as a form of masking to facilitate sound localization. Although some terrestrial animals, such as domestic cats, have a wider hearing range, others, such as mouse and hamsters, have a narrow hearing range. This is believed to be due to the anatomy of the pinna and external auditory canal. Nevertheless, it must be noted that the animal's positioning may also influence this phenomenon during the measurements.

In terrestrial animals other than humans, the pinna's orientation and the effect of the ear muscles can increase or decrease sound by up to 21 dB. These findings highlight the complexity of auditory processing in terrestrial animals and suggest that further research is needed to fully understand the interplay between anatomical structures, positioning, and hearing capabilities. Such insights can inform the development of more accurate models of auditory function and improve our ability to protect and support the hearing health of various species.

A comparison of the ear anatomy of humans and other terrestrial animals reveals that differences in the anatomy of the ears of terrestrial animals could affect how much sound energy is transmitted to the ear (Barber et al., 2020). According to the hearing threshold values (dB SPL) calculated with the help of available data, the highest acoustical energy value (Watt/cm^2) belongs to the mice. The mice exhibits the highest values of 12.9±4.9 kHz. and 13.3±8.1 dB SPL. The auditory functions of mice are well studied. Recent findings highlight the unique auditory capabilities of mice, underscoring the importance of anatomical differences in the ear structures of various terrestrial animals in determining their hearing sensitivity and efficiency.

Auditory function adapts to differences in anatomical structures and, therefore, to differences in interaural attenuation regarding skull size. In terrestrial animals, auditory function is better at low frequencies but worse at high frequencies, and conversely, it is better at high frequencies but worse at low frequencies. The proximity of the ear canal entrances (small skull size) increases the energy of low-frequency hearing thresholds (increased interaural attenuation). However, this is controlled by the inner ear system. The detection of this control is evidenced by the frequency modulation of spontaneous otoacoustic emissions produced by the outer hair cells (see ▶**Figure 6**). Therefore, it was felt that spontaneous otoacoustic emissions should also be evaluated, and energy levels interpreted. Furthermore, it was observed that SOAE values could not be measured for various reasons, such as the anatomically large size of the ear structures of some species and the complexity of the anatomical structure of the ears. The phenomenon of SOAEs in many terrestrial animals has been the locus of limited investigation in the current literature (Manley, 2024).

We also explored the role of SOAEs in auditory processing. SOAEs, which are spontaneous sounds produced by the cochlea, are indicative of the active processes within the inner ear. They vary among species and play a role in enhancing auditory sensitivity and frequency selectivity. For instance, SOAEs in humans typically fall below 15 dB at frequencies between 250 Hz. and 4 kHz., while in owls, they can reach up to 20 dB with a spectral width of 200 Hz.

The adaptive auditory functions of terrestrial animals are critical for their survival and communication. These functions are influenced by environmental factors, anatomical structures, and the presence of SOAEs. Modelling the adaptive auditory system of terrestrial animals revealed that SOAEs can significantly affect hearing thresholds, demonstrating the complex interplay between anatomy, physiology, and environmental adaptation.

This study demonstrates that the auditory functions of terrestrial animals remain a popular subject of ongoing research. In particular, the ears of mouse from terrestrial animals are more suitable for researching auditory functions. In conclusion, the findings underscore the importance of considering both anatomical and physiological factors in understanding auditory functions. Future research should focus on detailed modelling of the auditory systems of specific species, incorporating experimental data to further elucidate the adaptive mechanisms underlying their auditory processing. This approach will enhance our understanding of the evolutionary adaptations that contribute to the survival and communication capabilities of terrestrial animals.

Research Ethics

In the article, comparative analyzes of the ear structures of humans and land animals based on research results are included. No experimental studies have been conducted on the subject. Therefore, ethical approval was not required.

Author Contributions

Conceptualization: [HMB, ÖAŞ, EK, FBK, CEK], Metthodology: [HMB, ÖAŞ, EK, FBK, CEK], Formal Analysis: [HMB, ÖAŞ, EK, FBK, CEK], Investigation: [HMB, ÖAŞ, EK, FBK, CEK], Resources : [HMB, ÖAŞ, EK, FBK, CEK], Data Curation: [HMB, ÖAŞ, EK, FBK, CEK], Writing- Original Draft Preparation: [HMB, ÖAŞ, EK, FBK, CEK], Writing- Review & Editing: [HMB, ÖAŞ, EK, FBK, CEK], Visualization: [HMB, ÖAŞ, EK, FBK, CEK], Supervision: [HMB, ÖAŞ, EK, FBK, CEK], Project Administration: [HMB, ÖAŞ, EK, FBK, CEK], Funding Acquisition: [-].

Competing Interests

The authors states no conflict of interest.

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Data Availability

The data that support the findings of this study are available on request from the corresponding author. No new data were created or analysed in this study. Data sharing does not apply to this study.

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Orcid

Hatice Mehtap Buluklu https://orcid.org/0000-0002-1912-9598
Özgül Akın Şenkal https://orcid.org/0000-0002-3554-8274
Ercan Köse https://orcid.org/0000-0001-9814-6339
Filiz Bal Koçyiğit https://orcid.org/0000-0003-4191-0724
Cafer Erkin Koyuncu https://orcid.org/0000-0002-5264-7055

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