

Measurements on the Turtle's Shell that Help Illuminate How the Fishes Lateral Line Function Was Replaced by the Reptilian Hearing Organ

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ABSTRACT

The acoustic sense of fish, embodied in the lateral line, no longer worked when amphibians ventured onto the land. The new acoustic environment where sound traveled in the thin medium of air rather than the relatively dense medium of water presented a major challenge. The multiple sensors of the lateral line were replaced by one gross sensor, the tympanic membrane or eardrum. We show acoustical measurements on the turtle shell that can suggest a possible explanation of how the turtle dealt with the issue of sensing the directionality of incoming sounds.

1. INTRODUCTION

The transition from fish living in aquatic space to vertebrates living in air required several adjustments. Mobility, for example, involved the morphing of fins into limbs. Morphing, however, did not suffice when it came to converting the aquatic acoustic sense realized by the fishes lateral line [1], to a terrestrial hearing organ. A hearing organ that allowed the early reptile to sense the airborne acoustic space it now lived in was essential to its survival. Hearing in the air required the development of a new acoustic computation paradigm and a new hearing organ to carry out the task of sensing the spatial origin of incoming sounds. We will show that the reflectivity of textural singularities of the turtle shell can be considered part of the turtles hearing system [2]. The main novelty and new contribution of this work lies in considering acoustic reflections from turtle shell to be an important part of the turtles interaction with its environment.

2. BACKGROUND

Before considering how amphibians and reptilians may have evolved the equipment to sense and process airborne sounds, we must understand how fish detect and process aquatic acoustic sounds with the lateral line. A description of the fishes lateral line from reference [1] describes the starting point of the

evolution of reptilian hearing:

In daylight the eye informs the fish about its surroundings. However, at night, the fish monitors its sound field just as humans listen in the dark to sense surrounding space acoustically. While humans use our ears to keep track of the sounds around us, the fish senses the surrounding acoustic space with its Lateral Line. The lateral line is a row of vibration sensors spaced along each side of the fish from the head to the tail. These sensors, each composed of groups of vibration sensing hair cells, monitor the vibrations in the water surrounding the fish. Each lateral line sensor, called a stitch, is represented by a dot in **Figure 1**.

If the direction of arrival of the vibration is at right angles to the body of the fish, all the individual lateral line sensors will be stimulated simultaneously. If the vibration comes from a position near the front of the fish the sensors at the front of the fish are stimulated first. The stimulation then sweeps from the front to the back. If the vibration comes from a position near the rear end of the fish the stimulation sweeps from the rear to the front of the fish. The lateral line, with its array of simultaneous detectors, provides a panoramic acoustic image of surrounding activity [1].

In the fish, each of the dots on the lateral line, called a “stitch”, is an individual sensor that is picking up the aquatic sound wave, or waterborne vibration, as it sweeps along the lateral line. Each lateral line sensor sends a fiber to the fishes brain. In the brain, the relative arrival time of vibrations contains the information needed to solve for the direction of arrival.

2.1. The Medium

Amphibians and Reptiles lost the functions of the lateral line when they left the sea. The vibrations in the water were able to stimulate the individual sensors of the lateral line. However, the vibrations in air were not able to couple to the small surface of the individual lateral line sensors. Water is a dense medium when compared with air. Vibrations in water are able to move the small sensing surface of the individual sensors of the lateral line. In order for vibrations in air to couple to a sensor, the sensor surface exposed to the vibrations, the eardrum, must be much larger than the tiny surface of the individual lateral line sensors.

2.2. The Sensor

The need to couple the acoustic vibrations in air to an array of hair cell sensors in the inner ear of amphibians and reptiles led to the development of a relatively large surface exposed to the air-born acoustic vibrations. This surface, the tympanum, that we call an “eardrum”, is then attached to a plunger in the fluid of the labyrinth. This produces a vibration in the fluid medium in which the vibration sensors, the hair cells, are designed to operate [3].

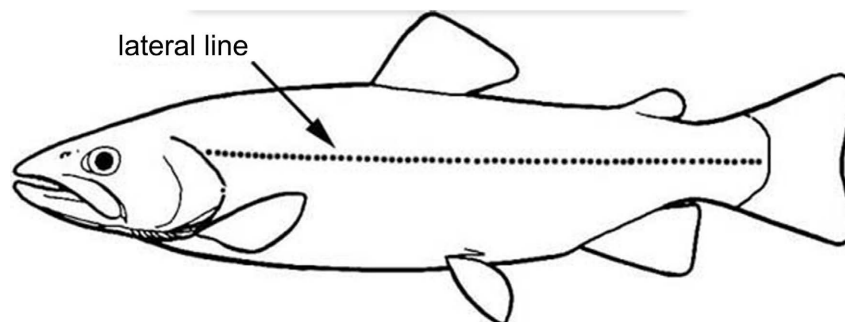


Figure 1. Image of a fishes lateral line (https://en.wikipedia.org/wiki/Lateral_line). Each of the dots on the lateral line is an individual sensor that is picking up the aquatic sound wave, or water-born vibration, as it sweeps along the lateral line. Each lateral line sensor sends a fiber to the fishes brain. In the brain, the relative arrival time of vibrations contains the information needed to solve the direction of arrival, but so far, we don't know how the fish does this.

What is new in Reptiles and Amphibians is the development of a new group, or cluster, of Hair Cell sensors placed in a long row in the labyrinth adjacent to the Utricle (Figure 2). This row of sensors is arranged in the path of the fluid vibrations produced by the plunger driven by the eardrum. These vibrations, which produce a traveling wave, contain reflections originating at different parts of the body with different delays based on the distance of the reflecting surface to the eardrum. The particular sound that is received at the eardrum is the sum of the original wave and the reflections from prominent reflecting surfaces on the animal's body. We begin by exploring the relative timing of reflections from different parts of the body in the turtle.

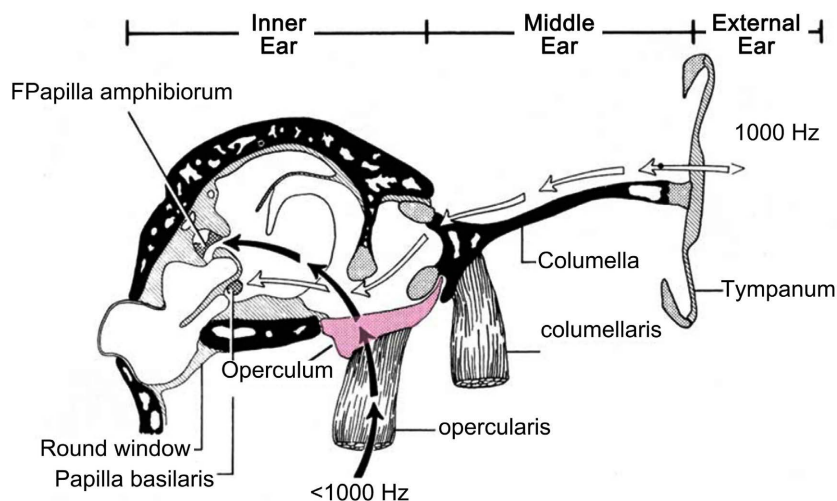


Figure 2. A Schematic representation of a primitive amphibian ear. Airborne vibrations couple to the ear drum [tympanum] and are transferred through the columella to the inner ear fluids. There the vibrations in the inner ear fluids activate the papilla basilaris which is composed of a new row of vibration sensing hair cells next to the utricle. (Holtz, T. R., & Merck, J. W. (2021, January 15). Vertebrate Paleobiology. Geol431 - vertebrate paleobiology. Retrieved from <https://www.geol.umd.edu/~jmerck/geol431/>).

3. MATERIALS AND METHODS

Measurements were made on a photographic image of a 200 m year fossilized turtle which carries the same shell structure as present day turtles. Distances from an incoming sound wavefront, through reflection shell singularities, to the tympanum were measured with a ruler calibrated in mm.

Subtracting the wavefront to tympanum distance from the reflective measurements exposes the echo timing as a function of the direction of sound arrival.

4. MEASUREMENT AND COMPUTATION

A sound source, as it travels away from the source, expands spherically on its way to its destination. For example, a sound source one meter away from a turtle will present an incoming wavefront that is part of the circumference of a two-meter diameter circle. Since the part of this spherical wave that interacts with the turtle is only about 10 cm in the present case, the incoming sound wavefront is approximated by a straight line in the example that follows. The sounds that are reflected from bumps on the turtle shell travel to the ear with a delay that depends on the distance traveled from the incoming wavefront to the ear. This travel distance was measured on the image of the turtle shell in mm, and then converted to a time delay using the speed of sound in air of 343 m/s. This computation was performed for two different angles of incidence. The 60 deg computation shows a sound coming from the left-front of the animal. The 120 deg computation is from a sound source at the right-rear of the animal (Figure 3).

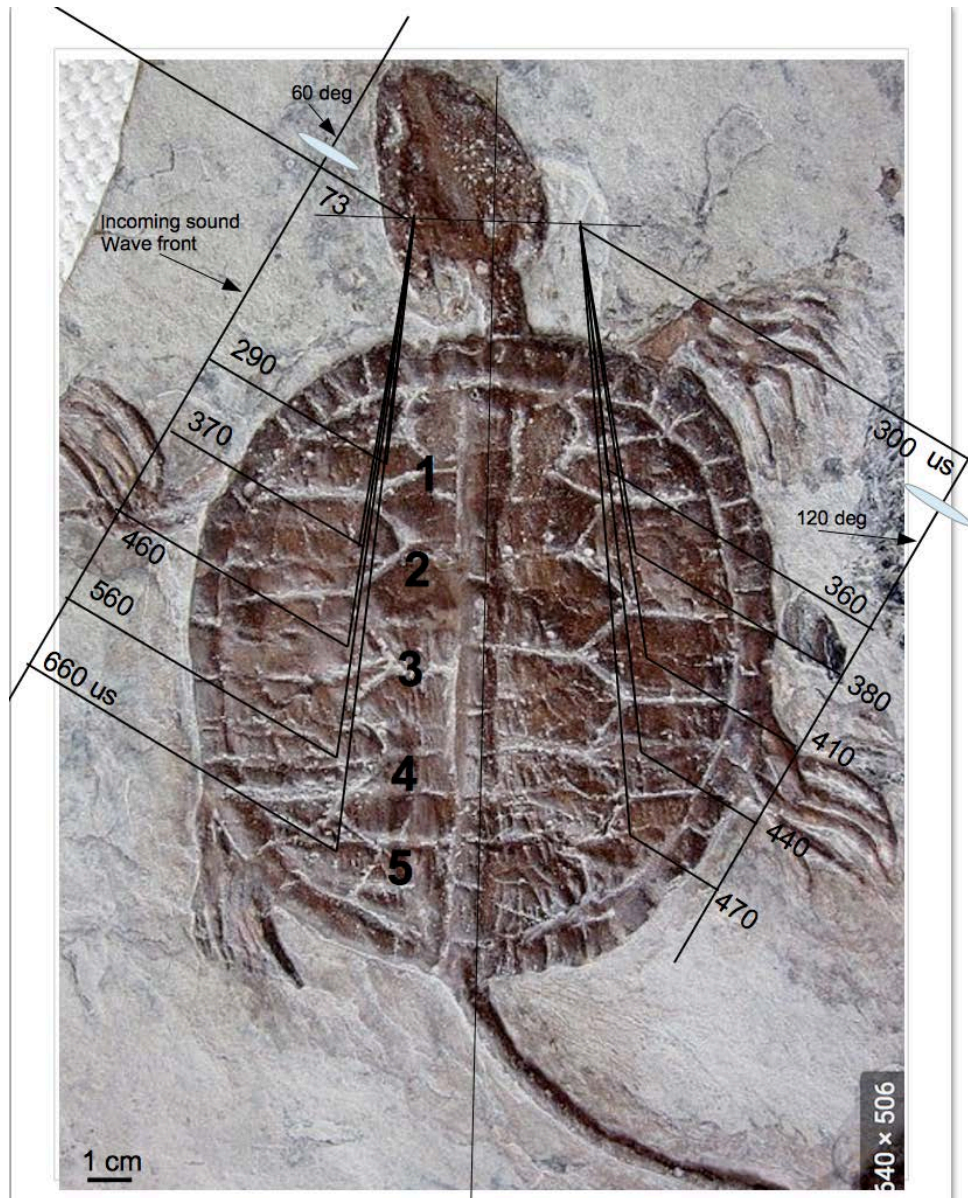


Figure 3. The relative delays of the direct signal and shell reflections from the singularities [bumps] on the shell of the turtle are shown for two angles of incidence relative to the central axis of the turtle shell. The delays were determined by measuring the distances traveled by each echo from the incoming wavefront to the ear. Measurements were made in mm and converted to time delays using the speed of sound in air of 343 m/s.

Measured delays are plotted on a linear time axis in [Figure 4](#) to illustrate how the timing of the echoes is directly related to the angle of the sound source relative to the central axis of the shell.

It would be easy to write a computer program to decode the data plotted in [Figure 4](#). The periodicity seen in the echoes is a higher frequency than the kilocycle hearing of the turtle. This opens the question: does the turtle listen to each individual echo, or does she perceive the group, together, as a single reflection centered in the group of echoes? If the group of echoes is sensed as a single reflection the decoding problem remains the same. The delay between this single reflection and the direct signal needs to be transformed into a sensation of directionality.

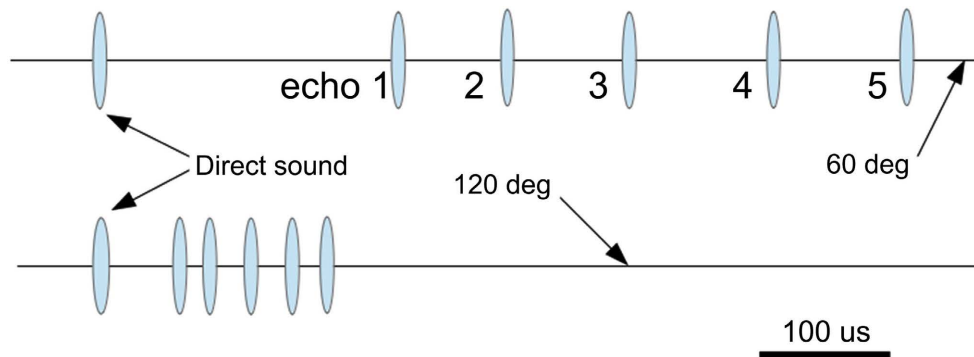


Figure 4. Showing the relative times of arrival at the turtle's ear of the direct signal and the sequence of echoes reflected from the singularities of the shell for two angels of incidence, 60 deg and 120 deg.

5. CONCLUSION

In order for a land-based fauna to flourish, it was necessary for early amphibians and reptilians to develop a new system of hearing to replace the lateral line which no longer was functional in the relatively thin air of the new environment. We have shown measurements that illustrate how the relative timing of an incoming acoustic signal and the reflections from prominent singularities on its shell contain the information needed for the turtle to locate a sound source. We have shown that both the lateral line and the new reptilian mode of hearing required that the delay between different components of the incoming signal be measured and converted to a sensation of directionality in the animal.



Figure 5. Haeckel's illustration of a variety of turtles in their environment, though slightly exaggerated, shows how varied and ubiquitous are the reflective structures on their shells.

The study of the evolution of the turtle carapace has focused on morphologic shifts of vertebrae and ribs with no consideration of how the hard surfaces of the carapace function as reflectors of sound [4]. Hard surfaces on an animal's body have been shown to reflect and concentrate sounds relevant to important life activities of the Moose and the Sambar Deer [5]. In the turtle reflections from the bumps on the shell mix with directly received sound to the ear to generate a sound compounded with its echoes.

Although the hard surfaces of antlers [5] and the hard surface of the turtle shell have long been thought to be either designed for fighting, defense, or decoration, we can now contemplate a new role for hard, acoustically reflective appendages on an animal's body: as a part of an animal's hearing system.

These considerations tempt us to reconsider the function of the hard surfaces found on other animals. Hard acoustically reflective appendages are found on elephants, rhinos, walruses, wild pigs, and mountain goats, to name a few.

At the beginning of the 20th century, Ernst Haeckel's book "Art Forms in Nature" presented, in **Figure 5**, an artist's take on the gestalts of the earthy realm of turtles [6].

Haeckel's drawings remind us that artists often see and express underlying truths of natural phenomena without scientifically understanding them.

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CONFLICTS OF INTEREST

The author declares no conflicts of interest regarding the publication of this paper.

REFERENCES

1. Rossetto, M. (2018) The Role of the Cupola in the Static and Dynamic Functioning of a Lateral Line Stitch: Natures Non-Linear Application of Hooke's Law. *Communicative & Integrative Biology*, **11**, e1542256. <https://doi.org/10.1080/19420889.2018.1542256>
2. Cordero, G.A. (2017) The Turtle's Shell. *Current Biology*, **27**, R168-R169. <https://doi.org/10.1016/j.cub.2016.12.040>
3. Pfaff, C., Schultz, J.A. and Schellhorn, R. (2019) The Vertebrate Middle and Inner Ear: A Short Overview. *Journal of Morphology*, **280**, 1098-1105. <https://doi.org/10.1002/jmor.20880>
4. Hirasawa, T., Pascual-Anaya, J., Kamezaki, N., Taniguchi, M., Mine, K. and Kuratani, S. (2015) The Evolutionary Origin of the Turtle Shell and Its Dependence on the Axial Arrest of the Embryonic Rib Cage. *Journal of Experimental Zoology Part B, Molecular and Developmental Evolution*, **324**, 194-207. <https://doi.org/10.1002/jez.b.2257>
5. Rossetto, M. (2021) Antlers Are Shaped as Elements of Concave Surfaces that Reflect and Concentrate Incoming Sounds. *Natural Science*, **13**, 469-473. <https://doi.org/10.4236/ns.2021.1311039>
6. Haeckel, E., Briedbach, O., Eibl-Eibesfeldt, I. and Hartmann, R.P. (1998) *Art Forms in Nature: The Prints of Ernst Haeckel*. Prestel, Munich.