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Optimized structures for vibration attenuation and sound control in Nature: a review

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Abstract:

Nature has engineered complex designs to achieve advanced properties and functionalities through evolution, over millions of years. Many organisms have adapted to their living environment producing extremely efficient materials and structures exhibiting optimized mechanical, thermal, optical properties, which current technology is often unable to reproduce. These properties are often achieved using hierarchical structures spanning macro, meso, micro and nanoscales, widely observed in many natural materials like wood, bone, spider silk and sponges. Thus far, bioinspired approaches have been successful in identifying optimized structures in terms of quasi-static mechanical properties, such as strength, toughness, adhesion, but comparatively little work has been done as far as dynamic ones are concerned (e.g. vibration damping, noise insulation, sound amplification, etc.). In particular, relatively limited knowledge currently exists on how hierarchical structure can play a role in the optimization of natural structures, although concurrent length scales no doubt allow to address multiple frequency ranges. Here, we review the main work that has been done in the

field of structural optimization for dynamic mechanical properties, highlighting some common traits and strategies in different biological systems. We also discuss the relevance to bioinspired materials, in particular in the field of phononic crystals and metamaterials, and the potential of exploiting natural designs for technological applications.

1. Introduction

It is well known that engineering materials such as metals or fibre-reinforced plastics are characterized by high stiffness at the expense of toughness. In particular, these materials do not efficiently dissipate energy via vibration damping. On the other hand, particularly compliant materials, such as rubbers and soft polymers, perform well as dampers, but lack in stiffness [1][2]. In this context, biological natural materials such as wood, bone, and seashells, to cite a few examples, represent excellent examples of composite materials possessing both high stiffness and high damping, and thus combine properties that are generally mutually exclusive. This exceptional behaviour derives from an evolutionary optimization process over millions of years, driven towards specific functionalities, where the natural rule of survival of the fittest has led to the continuous improvement of biological structure and organization. For instance, spider silk, bone, enamel, limpet teeth are examples of materials that combine high specific strength and stiffness with outstanding toughness and flaw resistance [3–8]. In these examples, a hierarchical architecture has often been proved to be the responsible for many energy dissipation and crack deflection mechanisms over various size scales, simultaneously contributing to exceptional toughness[2]. Given these numerous examples and the related interesting properties, the rich research field of biomimetics has emerged, with the aim of drawing inspiration from natural structures and implementing them in artificial systems, to bring progress to many technological domains.

However, studies in biomechanics and biomimetics linking material structure to function have mainly been limited to the quasistatic regime, while the dynamic properties of these materials have been somewhat less investigated, although notable examples of impact tolerance (e.g., the bombardier beetle's explosion chamber [9]) or vibration damping (e.g., the woodpecker skull [10]) have been studied. In fact, the first attempt to analyse biological

vibration isolation mechanisms in the woodpecker date as far back as 1959, when Sielmann [7] found, through dissection and observation, that the cartilage in sutures in its skull have the effect of buffering and absorbing vibration [11].

As confirmed by these examples, it is reasonable to assume that biological structures whose main function is vibration and impact damping, sound filtering and focusing, transmission of vibrations, etc., have also been optimized through evolution, and that it is possible to look for inspiration in nature for technological applications based on these properties. Based on this assumption, a growing interest in the superior vibrating attenuation properties of biological systems has emerged, and nowadays, applications such as bio-inspired dampers are beginning to be used in the protection of precision equipment and the improvement of product comfort [12]. Motivated by this emerging field of research, we provide here a review of some of the main biological systems of interest for their dynamic properties, focusing on the role of structural architecture for the achievement of superior properties.

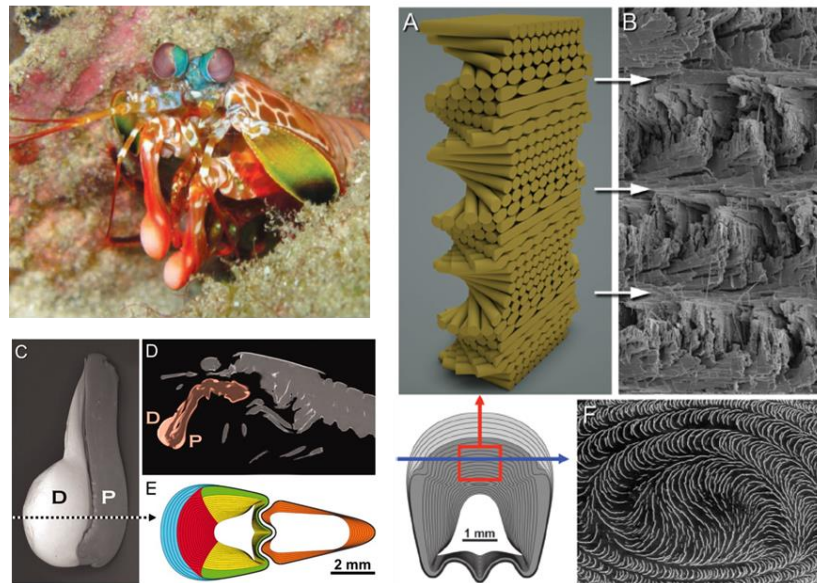
2. Impact resistant structures

2.1 Mantis shrimp

Probably the most well-known example of impact resistant structure in Nature is the stomatopod dactyl club. The mantis shrimp (*Odontodactylus scyllarus*) is a crustacean with a hammer-like club that can smash prey (mainly shells) with very high velocity impacts [13–15], reaching accelerations of up to 10000 g, and even generating cavitation in the water [16]. To sustain repeated impacts without failing, the claw requires extreme stiffness, toughness and impact damping, and has emerged as one of the main biological systems that epitomizes biological optimization for impact damage tolerance [17].

The exceptional impact tolerance is obtained thanks to the graded multiphase composition and structural organization of three different regions in the claw (Figure 1). The impact region, or striking surface, is dominated by oriented mineral crystals (hydroxyapatite), arranged so that they form pillars perpendicular to the striking surface. A second region called the “periodic region” backs up the impact zone and is mainly constituted by chitosan. This area, which lies just beneath the impact zone, is stacked at different (helical) orientations, generating crack stopping and deviation. Thus, the structure consists of a multiphase composite of oriented stiff (crystalline hydroxyapatite) and soft (amorphous calcium phosphate and carbonate), with a highly expanded helical organization of the fibrillar chitinous organic matrix, leading to effective damping of high-energy loading events [17][18]. The impact surface region of the dactyl club also exhibits a quasi-plastic contact response due to interfacial sliding and rotation of fluorapatite nanorods, leading to localized yielding and enhanced energy damping [19].

Interestingly, it has been found that the mantis shrimp also displays another highly efficient impact damping structure, since it has evolved a specialized shield in its tail segment called a telson that absorbs the blows from other shrimps during ritualized fighting[20]. The telson is a multiscale structure with a concave macromorphology, ridges on the outside and a well-defined pitch-graded helical fibrous micro-architecture on the inside, which also provides optimized damage tolerance [21,22].



*Figure 1: Morphological features of the stomatopod dactyl club. (A) A generalized stomatopod body plan and (B) a magnified view of the anterior end of *O. Scyllarus*. The arrows denote the location of the dactyl club's impact surface. (C) Backscattered scanning electron micrograph of the club's external morphology and (D) a microcomputed tomographic longitudinal section through the anterior half of a complete specimen showing the constituent dactyl (D) and propodus (P) segments, revealing their differences in electron density (the second thoracic appendage with its terminal dactyl club modification is highlighted in red). (E) Cross-sectional analysis of the club illustrates the three distinct structural domains: (i) The impact region (blue), (ii) the periodic region [further subdivided into two discrete zones: medial (red) and lateral (yellow)], and (iii) the striated region (green). The periodic region of the propodus is shown in orange (reproduced from [17], authorization pending).*

2.2 Woodpecker skull

Another well-known example in nature of a highly impact resistant system is that of the woodpecker skull and beak, which repeatedly impacts wooden surfaces in trees at a

frequency of about 20 Hz, a speed of up to 7 m/s, and can reach accelerations of the order of 1200 *g*, while avoiding brain injury [10,23]. This structure has been widely studied to draw inspiration for impact-attenuation and shock-absorbing applications and biomimetic isolators [12]. Limiting our observations to the head, and neglecting the body, feathers, and feet (which could also play a role), the woodpecker emerges as a very complex and rich system, from the mechanical and structural point of view at different spatial scales: macro-, micro- and nanoscale. The head is mainly formed by the beak, hyoid bone, skull, muscles, ligaments, and brain [24].

Several groups have investigated the mechanical behaviour of the woodpecker using finite element analysis [24–30]. Generally, the models are based on the images obtained by X-ray computed tomography (CT) scans. The stress distribution due to the impacts due to pecking, is investigated. In some of these studies, the results are also compared with *in vivo* experiments, where the pecking force is measured by using force sensors and compared with that in other birds [25]. Zhu et al. [29] measured the Young’s modulus on the skull, finding a periodic change in space, as reported in Figure 2a. Moreover, they performed a modal analysis on the skull by using a finite element model (Figure 2b), based on CT scan images, and determining the first ten natural frequencies, as shown in Figure 2c. The largest amplitude frequency components appear at 100 Hz and 8 kHz, which are well separated from the working frequency (around 20 Hz) and the natural frequencies (as derived in simulations), thus ensuring protection of the brain from injury.

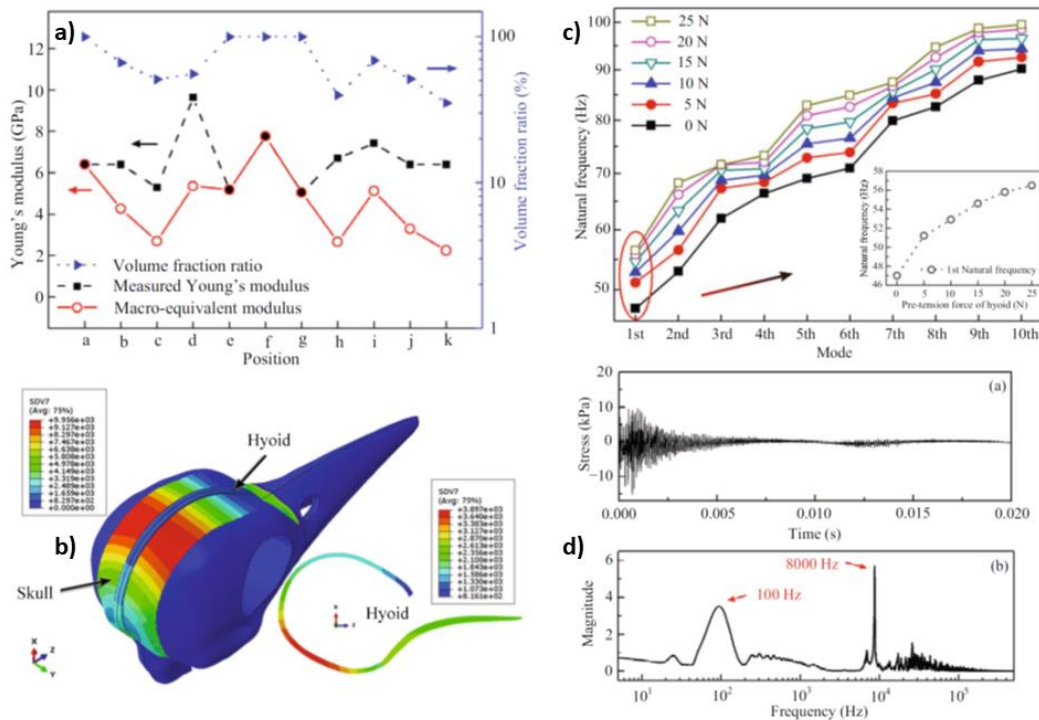


Figure 2 : Vibration attenuation in the woodpecker skull (adapted from [29]). (a): Volume fraction ratio of skull bone, local measured modulus, and macro-equivalent modulus around the skull. (b): 3D finite-element model of the skull and hyoid bone. Note that the Young's modulus on the skull is not uniform. (c): first ten modes of the skull under a pre-tension on the hyoid in the range 0-25 N. (d), upper panel: stress wave at a brain location under impact direction. (d), lower panel: stress spectrum in the frequency domain obtained by FFT.

Although the results from different groups are not always in agreement, most researchers conclude that the shape of the skull, its microstructure and chemical composition are all relevant for the exceptional impact-attenuation properties in woodpeckers [10]. In particular, a grading in the bone porosity and mechanical properties is particularly important in damping high frequency vibrations, which can be particularly harmful [31]. Many papers also point out the importance of the hyoid bone, very peculiar in woodpeckers, in the shock-absorption

capability [32]. The hyoid is much longer than in other birds and wraps the skull until the eye sockets, forming a sort of safety belt around the skull. A specific study of the hyoid bone has been carried out by Jung et al. [32] who performed a macro- and micro-structural analysis of the hyoid apparatus and hyoid bones. The authors developed a 3D model of the hyoid which they showed to be formed by four main parts connected by three joints. Interestingly, by performing nanoindentation measurements, they also showed that it features a stiffer, internal region surrounded by a softer, porous outer region which could play an important role in dissipating the energy during pecking. Another important issue is the relative contribution of the upper and lower beaks in the stress wave dissipation [25,33] which is most probably dissipated through the body [30].

Yoon and Park [10] showed that simple allometric scaling is not sufficient to explain the shock-absorbing properties of the woodpecker. Furthermore, they investigated its behaviour by using a lumped element model including masses, springs, and dampers, as shown in Figure 3a. The complexity of the sponge-like bone within the skull makes it too hard to model it by lumped elements. Thus, the authors characterized its behaviour by using an empirical method consisting of close-packed SiO₂ microglasses of different diameter (Figure 3b). The vibration transmissibility shows that the porous structure absorbs excitations with a higher frequency than a cut-off frequency which is determined by the diameter of the glass microspheres, as reported in Figure 3c.

Lee et al. [31] reported a detailed analysis on the mechanical properties of the beak, showing that the keratin scales are more elongated than in other birds and the waviness of the sutures between them is also higher than for other birds (1 for woodpecker, 0.3 for chicken and 0.05 for toucan), most probably to favour energy dissipation due to the impact. Raut et al. [34] designed flexural waveguides with a sinusoidal depth variation inspired by the suture geometry of the woodpecker beak which were tested by finite element analysis. The suture

geometry helps reducing the group speeds of the elastic wave propagation whereas the presence of a viscoelastic material, as is the case for collagen in the beak sutures, significantly attenuates the wave amplitudes, suggesting a promising structure for applications in impact mitigation. Garland et al. [35] took inspiration from the same mechanism of the sliding keratin scales in the beak to design friction metamaterials for energy adsorption.

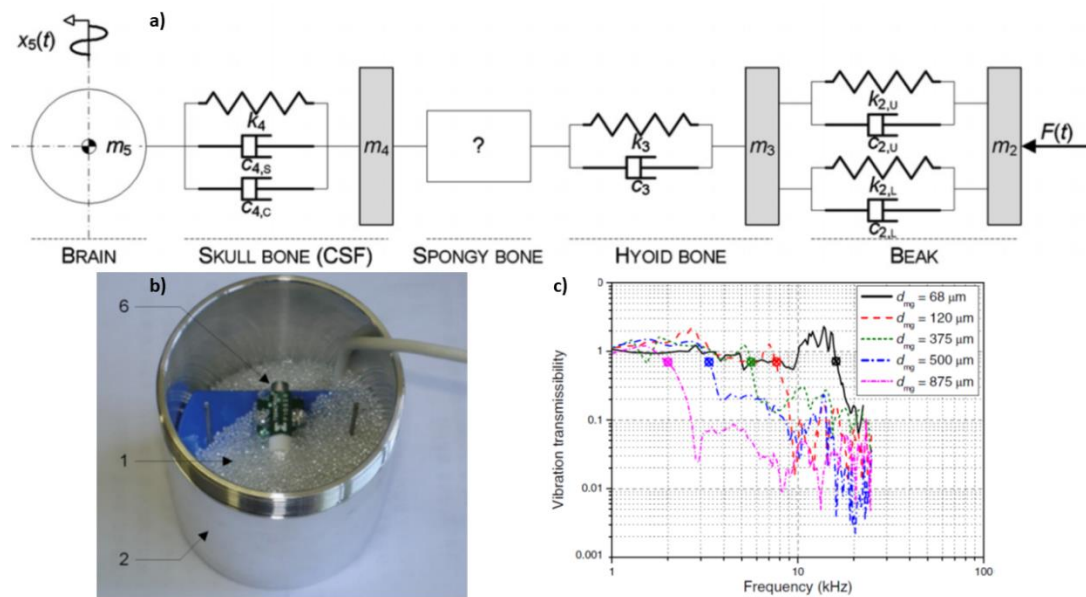


Figure 3 : Modelling of vibration attenuation in the woodpecker skull (adapted from [10]).
 (a): lumped-elements model of the head of a woodpecker. (b): empirical model of the spongy bone by means of an aluminium enclosure filled with glass microspheres. (c): vibration transmissibility as a function of frequency for different diameters of the SiO₂ microspheres.

2.3 Seashells

Seashells are rigid biological structures that are considered to be ideally designed for mechanical protection, and they are now viewed as a source of inspiration in biomimetics [36,37]. A seashell is essentially a hard ceramic layer that covers the delicate tissues of

molluscs. Many gastropod and bivalve shells have two layers: a calcite outer layer and an iridescent nacre inner layer. Calcite is a prismatic ceramic material composed of strong yet brittle calcium carbonate (CaCO_3). Nacre, on the other hand, is a tough and pliable substance that deforms significantly before collapsing [38]. It is considered that a protective structure that combines a hard layer on the surface with a tougher, more ductile layer on the interior optimizes the impact damping properties [37–39]. When a seashell is exposed to a concentrated stress, such as a predator's bite, the hard ceramic covering resists penetration while the interior layer absorbs mechanical deformation energy. Overloading can cause the brittle calcite layer to fracture, causing cracks to spread into the soft tissue of the mollusc. Experiments have demonstrated that the thick nacreous layer can slow and eventually halt such fractures, delaying ultimate shell collapse. Although a significant amount of research has been performed on the structure and characteristics of nacre and calcite, there has been little research done on how these two materials interact in real shells. While there is evidence that nacre is tuned for toughness and energy absorption, little is known about how the shell structure fully utilizes its basic constituents, calcite, and nacre.

One method employed to analyse the geometry of the shell at the macroscale, while accounting for the micromechanics of the nacreous layer, was to adopt multiscale modelling and optimization [37]. Different failure modes are possible depending on the geometry of the shell. On the other hand, according to optimization procedures, when two failure modes in different layers coincide, the shell performs best in avoiding sharp penetration. To reduce stress concentrations, the shell construction in this example fully leverages the material's capabilities and distributes stress over two different zones. Furthermore, instead of convergent to a single point, all parameters converged to a restricted range inside the design space.

According to the experiments done on the two red abalone shells [37,40] the actual seashell arranges its microstructure design to fully utilize its materials and delay failure, a result that is also obtained through optimization. The crack propagated over the thickness of the shell in three different failure situations. Furthermore, the seashell, which is constructed of standard ceramic material, can resist up to 1900 N when loaded with a sharp indenter, which is an impressive load level given its size and structure.

2.4 Suture joints

Suture joints with different geometries are commonly found in biology from the micro to the macro length scales (Figure 4). Examples include the carapace of the turtle [41,42], the woodpecker beak [31], the armoured carapace of the box fish [8,43], the cranium [44], the seedcoat of the *Portulaca oleracea* [45] and *Panicum miliaceum* [46], the diatom *Ellerbeckia arenaria* [47] and the ammonite fossil shells [48], among others.

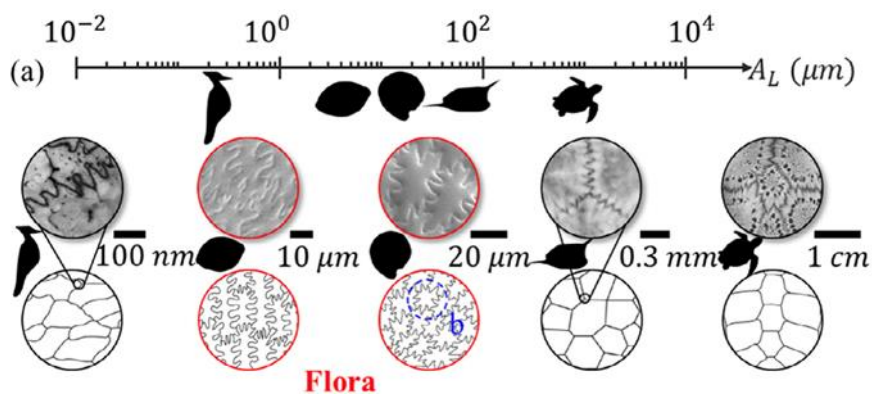


Figure 4: Biological systems with suture tessellation (reproduced from [49], authorization pending).

In the aforementioned systems, the suture joint architecture, where different interdigitating stiff components, i.e., the teeth, are joined by a thin compliant seam, i.e., the interface layer, allows a high level of flexibility and is the key factor for the accomplishment of biological vital functions such as respiration, growth, locomotion and predatory protection [50–52]. Also, from a mechanical point of view, it has been demonstrated computationally and/or experimentally that this particular configuration allows an excellent balance of stiffness, strength, toughness, energy dissipation and a more efficient way to bear and transmit loads [49,52–55].

Several existing studies confirm this aspect. Among others [51,56], where, in the case of cranial sutures, it emerges that an increased level of interdigitation, found among different mammalian species, leads to an increase in the suture’s bending strength and energy storage. Emblematic is the case of the leatherback sea turtle (Figure 5), a unique specie of sea turtle having the capacity to dive to a depth of 1200 m [57]. This is due to the particular design of the turtle’s carapace, where an assemblage of bony plates interconnected with collagen fibres in a suture-like arrangement is covered by a soft and stretchable skin. As reported in [57], the combination of these two elements provides a significant amount of flexibility under high hydrostatic pressure as well as exceptional mechanical functionality in terms of stiffness, strength and toughness, the collagenous interfaces being an efficient crack arrester.

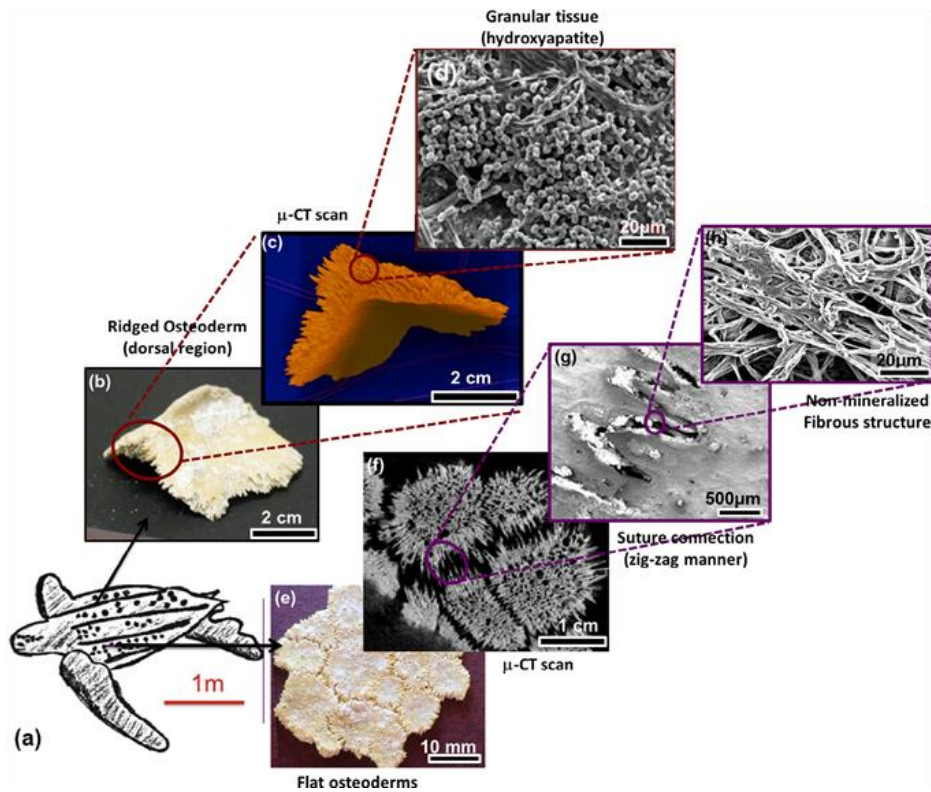


Figure 5 : Multi-scale hierarchical structure of the leatherback turtle shell (reproduced from [57], authorization pending).

In addition, the study in [58] explained not only how the high sinuosity and complexity of the suture lines in ammonites (Figure 6) are the result of an evolutionary response to the hydrostatic pressure, but also that the stress, displacements and deformations significantly decrease with the level of complexity. A similar result is also obtained in [59], which seeks to clarify the functional significance of the complex suture pattern in ammonites.

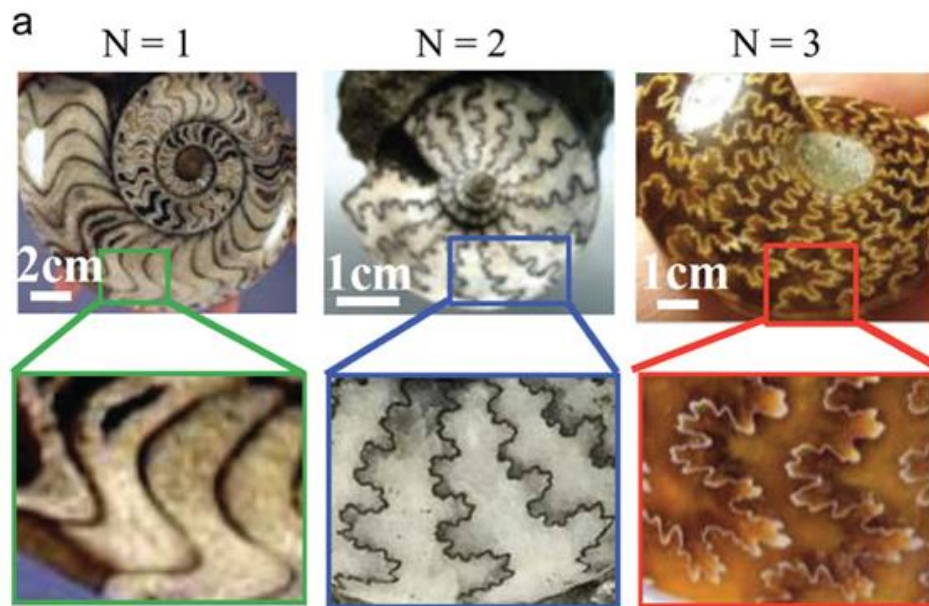


Figure 6: Hierarchical sutures of increasing complexity found in ammonites (reproduced from [60], authorization pending).

2.5 Bone

Bone's trabecular structure offers unmatched tensile strength, anisotropy, self-healing and lightness when compared to traditional engineered materials [61,62]. This is precisely what is required in most current mechanical and civil engineering applications. So far, bio-inspiration from cancellous bone has been exploited to enhance static properties, strength and toughness above all [63], but very little has been done in dynamics, with only a handful of studies in ultrasonics [64,65] focused on non-destructive evaluation of the bone structure.

The same can be said about 3D frame structures [66], where most of the work has addressed static properties [67] and only a few recent articles have addressed wave propagation [68,69]. Frame structures offer a convenient way to approximate trabecula using truss-like structures, inspired by the well-known Bravais lattices [70]. The implementation of such lattices paves the way to a simplified model of the bone structure, where the joints can be collapsed to points-like connections and the number of degrees of freedom can be drastically reduced.

2.6 Attenuation of surface gravity waves by aquatic plants

If one considers damping of low frequency vibrations over long timescales, one can look to natural barriers that allow to prevent or delay coastal erosion, and the destruction of the corresponding habitats. One such example is the *Posidonia Oceanica*, a flowering aquatic plant endemic of the Mediterranean Sea which aggregates in large meadows forming a mediterranean climax community. This macrophyte has evolved by angiosperms typical of the intertidal zone and displays features similar to that of terrestrial plants: it has roots and very flexible and thin leaves of about 1mm thickness and 1cm width without significant shape variations along the leaf length. The anchoring to sandy bottoms is provided by the horizontal growth of the rhizomes, which also grow in vertical. The leaves length varies throughout a year due to the seasonal cycle and the marine-climatic conditions and can vary as much as 0.3m in winter and 1m in summer.

The effects of seagrasses on unidirectional flows are well studied at different scales in the field and in laboratory flumes and in numerical studies while much less is known about the interaction between seagrass and waves. Wave attenuation due to *Posidonia* and flow conditions over and within vegetation fields have been investigated experimentally (see [71]) and numerically (see [72]) . There, it was found that the *Posidonia* is a good natural candidate for dissipating surface gravity waves in coastal regions. The study assessed quantitatively the physical value of the seagrass ecosystem restoration in this area, also opening new routes of actions towards a resilient, efficient, and sustainable solution to coastal erosion.

3. Sensing and predation

3.1 Spider webs

Of all the natural structures that inspire and fascinate humankind, spider orb webs play a particularly central role and have been a source of interest and inspiration since ancient times [73]. Spiders are able to make an extraordinary use of different types of silks to build webs which are the result of evolutionary adaptation and can deliver a compromise between many distinct requirements [74], such as enabling trapping and localizing prey, detecting the presence of potential predators, and serving as channels for intraspecific communication [75]. The variety of structures, compositions, and functions has led to the development of a large amount of literature on spider silks and webs [75–77] and their possible bio-inspired artificial counterparts [78–80].

The overall mechanical properties of spider orb webs emerge from the interaction between at least five types of silk [3,81], each with a distinct function in the web. The most important vibration-transmitting elements are made from the strong radial silk [82,83], which also absorbs the kinetic energy of prey [84,85] while sticky spiral threads, covered with glue, are used to provide adhesion to retain the prey [86,87]. Moreover, junctions within the webs can be composed of two different types of silk [81]: the strong and stiff piriform silk that provides strength to the anchorages [88–90] (Figure 1a-b), and the aggregate silk that minimizes damage after impacts [5,81] (Figure 1c). The mechanical synergy of such systems is therefore due to the mechanical response of the junctions [91], the constitutive laws of different types of silks, and the geometry of the webs [5]. The richness of these features, which are still the subject of many studies, have already inspired technologies with different goals in various scientific fields [92–94].

Spider orb webs are able to stop prey while minimizing the damage after impacts, thus maintaining their functionality [5], partially exploiting the coupling with aerodynamic damping that follows prey impacts [85]. This makes orb webs efficient structures for capturing fast-moving prey [95], whose location can then be detected due to the vibrational properties of the orb web. Efficiency in detecting prey by the spider is mediated by the transmission of signals in the webs, which needs to carry sufficient information for the prey to be located [96]. Using laser vibrometry, it has been demonstrated that the radial threads are less prone to attenuating the propagation of the vibrations compared to the spirals [74], due to their stiffer nature [97], allowing them to efficiently transmit the entire frequency range from 1 to 10 kHz.

Spiral threads can undergo several types of motion, including: (i) transverse (perpendicular to both the thread and the plane of the web) (ii) lateral (perpendicular to the thread but in the plane of the web), and (iii) longitudinal (along with the thread axis), thus yielding complex frequency response characteristics [98–100]. Distinct wave speeds are also associated with each type of vibration, i.e., transverse wave speed is determined by string tension and mass density, while longitudinal wave speed is linked to mass density and stiffness [101]. The addition of more reinforcing threads due to the multiple lifeline addition by the spider, the orb webs appears to maintain signal transmission fidelity [102]. This provides further evidence of the impressive optimization achieved in these natural structures, which balance the trade-offs between structural and sensory functions.

The sonic properties of spider orb webs can also be significantly influenced by pre-stressing, as demonstrated in the study conducted by Mortimer et al. [103]. Wirth and Barth [104] have shown that silk thread pre-stress increases with the mass of the spider, considering both inter and intra-specific variations, and may be used to facilitate the sensing of smaller prey [105].

The pre-tension in webs can also be strongly influenced by large amplitude vibrations, as demonstrated by numerical analysis [106]. This dependence has been shown to be stronger if the structure is damaged, especially in the radial threads [107].

Investigations on the vibration transmission properties of silk have been conducted by accessing its high-rate stress-strain behaviour using ballistic impacts using *Bombyx mori* silk (which can be partially compared to spider silk) [108]. Some studies indicated that the capability of transmitting vibrations is relatively independent of environmental conditions such as humidity [109,110], but in general it is expected that they affect the silk Young's modulus and the pre-stress level on the fibres, and therefore the speed of sound (i.e., wave propagation speed) in the material [111–113]. This dependence is one of the reasons why the measurement of the speed of sound in silk has not produced homogeneous data [99,114,115], and could provide a possible degree of freedom for spiders in tuning the vibrational properties of their webs [103,114].

Spider orb webs have proven to be one of the most inspiring systems to design novel structures able to manipulate elastic waves. Although many types of webs can be extremely efficient in detecting and stopping prey [116,117], plane structures tend to be preferred when it comes to bio-inspired systems, due to their simplicity. Metamaterials can be designed exploiting the rich dynamic response and wave attenuation mechanism of orb webs [118], based on locally resonant mechanisms to achieve band gaps in desired frequency ranges [119], and further optimized to achieve advanced functionalities [120]. The possibility of designing low-frequency sound attenuators is also regarded as a common objective in metamaterials design, and spider web-inspired structures seem to be able to provide lightweight solutions to achieve this goal [121,122].

3.2 Spider sensing

Although many spiders have poor sight, remarkable sensors that make them capable of interacting with their surroundings have evolved [123], including hair-shaped air movement detectors, tactile sensors, and thousands of extremely efficient strain detectors (lyriform organs such as slit sensilla) capable of transducing mechanical loads into nervous signals embedded in their exoskeleton [124–126]. Air flow sensors, named trichobothria (Figure 1d), seem to be specifically designed to perceive small air fluctuations induced by flying prey, which are detectable at a distance of several centimetres [127]. Spiders can process these signals in milliseconds and jump to catch the prey using only the information about air flow [128]. Although this could be sufficient to guide the detection of the prey using trichobothria, it could be that different hair-like structures undergo viscosity-mediated coupling that affects the perception efficiency. Interestingly, in the range of biologically relevant frequencies (30–300 Hz), viscous coupling of such hair-like structures is very small [129]. It seems, in particular, that the distance at which two structures do not interact is about 20 to 50 hair diameters, which is commonly found in Nature [129,130]. Spiders are also equipped with strain sensors (lyriform organs), which are slits that occur isolated or in groups (Figure 1e) with a remarkable sensory threshold in terms of displacement (from 1.4 nm to 30 nm) and corresponding force stimulus (0.01 mN). Moreover, many of such organs have an exponential stiffening response to stimuli, which makes them suitable to detect a wide range of vibration amplitudes and frequencies. These organs act as filters with a typical high-pass behaviour [131] to screen the environmental noise found in nature. Despite their remarkable capability in detecting vibration patterns (in frequencies between 0.1 Hz and several kHz), it is not yet clear how low-frequency signals are transmitted [132].

The sensing capabilities of spiders have driven the design of bio-inspired solutions in terms of sensor technology. Materials scientists have designed bio-inspired hair sensors realized to work both in air [133,134] and water [135]. Furthermore, the lyriform organs have inspired

crack-based strain sensors [136][137], eventually coupled with the mechanical robustness of spider silk [136]. Interestingly, these two types of structures (crack and hair sensors) may be combined in a multi-functional sensor. Results for such a spider-inspired ultrasensitive flexible vibration sensor demonstrated a sensitivity that outperforms many commercial counterparts [137].

Spider silk threads are also capable of detecting airflows by means of their fluctuation [138], providing an incredibly wide range of detectable frequencies, from 1 Hz to 50 kHz. Thus, by modifying these materials (e.g., making them conductive) it may be possible to produce devices able to expand the range of human hearing. It is clear, however, that many difficulties remain to be resolved to scale and fully optimize such bio-inspired solutions. Firstly, the reduction of the exposed surface can be large due to electronics. Secondly, wearing and application of the device could mechanically deteriorate its efficiency during its lifetime. Lastly, an engineering approach is in stark contrast with biological ones. In this context, a profound breakthrough is needed to achieve high efficiency in the self-assembly materials at the submicron scale.

3.3 Scorpion sensing

Scorpions are arachnids belonging to the *Subphylum Chelicerata* family of the arthropods (which includes spiders), which have evolved sensory mechanisms specially adapted to desertic environments [139]. Once structure-borne vibrations are produced in the ground, they propagate through bulk and surface waves: while the former propagate into the soil at large speeds and cannot be perceived by surface-dwelling animals, the latter can provide a useful information propagation channel for various species [140,141]. Sand offers an especially interesting medium in this regard, since its wave speed and damping are significantly lower than in other soils, favouring time-domain discrimination and processing

[142]. Brownell [143] has shown that two types of mechanoreceptors can be observed in the *Paruroctonus Mesaensis* desert scorpion species: (i) sensory hairs on the tarsus, which sense compressional waves, and (ii) mechanoreceptors located at the slit sensilla, which sense surface waves, thus serving as the basis for the scorpion's perception of the target direction, performing a role of mechano-transduction similar to that observed in spiders [144]. Thus, these structures appear to be those responsible for vibration sensing in scorpions, even though some controversy exists regarding the use of other scorpion appendages for the same purpose [145]. Brownell and Farley have shown that this scorpion species can discriminate the vibration source direction by resolving the time difference in the activation of the slit sensilla mechano-receptors even for time intervals as small as 0.2 ms [146]. The same authors have also shown that for short distances (down to 15 cm), scorpions can discriminate not only direction but also distance and vibration signal intensities, which are means to distinguish between potential prey from potential predators [147]. Such underlying phenomena have been used to construct a computer theory that simulates prey-localizing behaviour in scorpions [148], further motivating the development of artificial mechanisms based on this approach. Microstructural investigations as the ones performed by Wang et al. [148] have demonstrated that the slit sensilla owe their micro-vibration sensing properties to their tessellated crack-shaped slits microstructure [149], further indicating that this type of microstructure can serve as a bioinspiration for the design of new mechano-sensing devices [136,150].

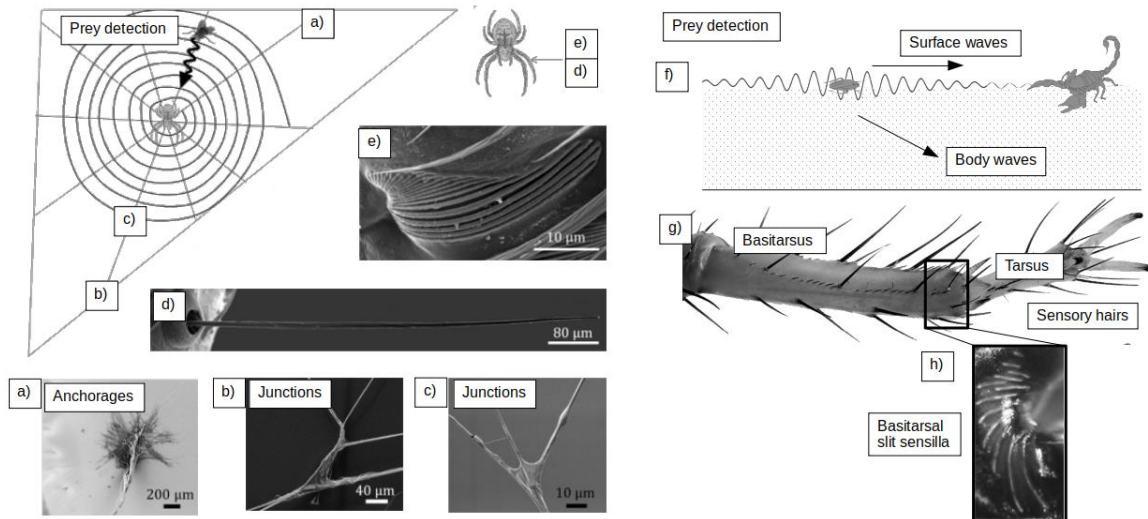


Figure 7 Prey sensing similarities in spiders and scorpions. a) web structure: a typical orb web of a spider *Nuctenea umbratica*. The web is built by means of junctions between threads and surfaces, b) junctions between radial threads, c) and junctions between radial and spiral threads. A flying prey can be eventually detected by air flow sensors, d) the trichobothria. If the prey impacts the web, the vibrational signal will be transmitted mainly by radial threads and be perceived by e) lyriform organs of the spider. Figure adapted from [81,123]. f) schematic of scorpion prey detection using surface waves; g) sensory hairs and mechanoreceptors located at the slit sensilla sense surface waves. Adapted from [151][152]

3.4 Echolocation in Odontocetes

Apart from communication purposes, toothed whales and dolphins (Odontocetes) use clicks, sounds and ultrasounds for sensing the surrounding environment, navigating and locating prey [153]. This process is similar to that adopted by terrestrial animals like bats, and is called echolocation [154–156]. The sounds are generated in special air cavities or sinuses in the head, can be emitted in a directional manner [157,158], and their reflections from objects are received through the lower jaw and directed to the middle ear of the animal [159,160]. A number of studies have adopted CT scans and FEM to simulate sound generation and

propagation in the head of dolphins or whales, demonstrating how convergent sound beams can be generated and used to direct sound energy in a controlled manner, and also how sound reception can be directed through the lower jaw to the hearing organs [161,162]. Dible et al. have even suggested that the teeth in the lower jaw can act as a periodic array of scattering elements generating angular dependent band gaps that can enhance the directional performance of the sensing process [163]. The emitted frequencies of the sounds used for echolocation are typically in the kHz range, e.g. bottlenose dolphins can produce directional, broadband clicks lasting less than a millisecond, centred between 40 to 130 kHz. Some studies have suggested that high intensity focussed sounds can even be used to disorient prey, although this remains to be confirmed [164,165]. The process of echolocation is extremely sensitive [166,167] and can provide odontocetes with a “3D view” of their surrounding environment world. This is confirmed by the fact that sonar signals employed by military vessels can confuse and distress whales and dolphins, and even lead to mass strandings [168].

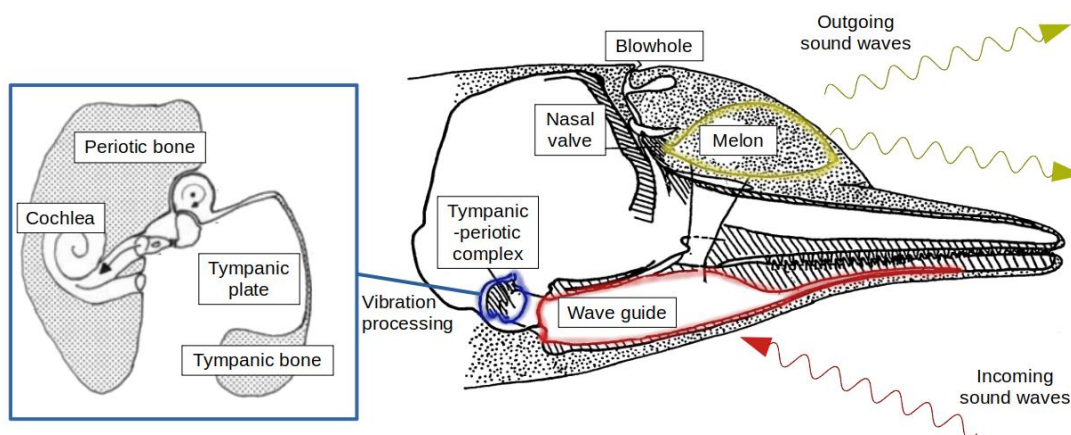


Figure 8: Structures for sound production and detection in Dolphins. Adapted from [159].

3.5 Anti-predatory structures and strategies

It is thought that the origin of many distinctive morphological and/or behavioural traits of living organisms is related to the selective pressure exerted by predators [169,170]. Generally, various defensive strategies can be adopted by organisms to reduce the probability of being attacked or, if attacked, to increase the chances of survival. The first consists in avoiding detection (i.e., *crypsis*), through camouflage, masquerade, *apostatic* selection, subterranean lifestyle or nocturnality, and deterring predators from attacking (i.e., *aposematism*) by advertising the presence of strong defences or by signalling their unpalatability by means of warning coloration, sounds or odours [171]. The second are based on overpowering, outrunning and diverting the assailants' strikes by creating sensory illusions to manipulate the predator's perception [172–174].

Despite being extremely fascinating from an engineering point of view, the effectiveness of the first type of defensive strategies is restricted mainly to visual phenomena and none of them work on non-visually oriented predators. However, although rare, a number of acoustic based deflection strategies exist in nature. Most of them are related to one of the most famous examples of non-visually oriented predators, i.e., echolocating bats (Fig. 8) that rely on echoes from their sonar cries to determine the position, size and shape of moving objects in order to avoid obstacles and intercept prey in the environment [170,175–177].

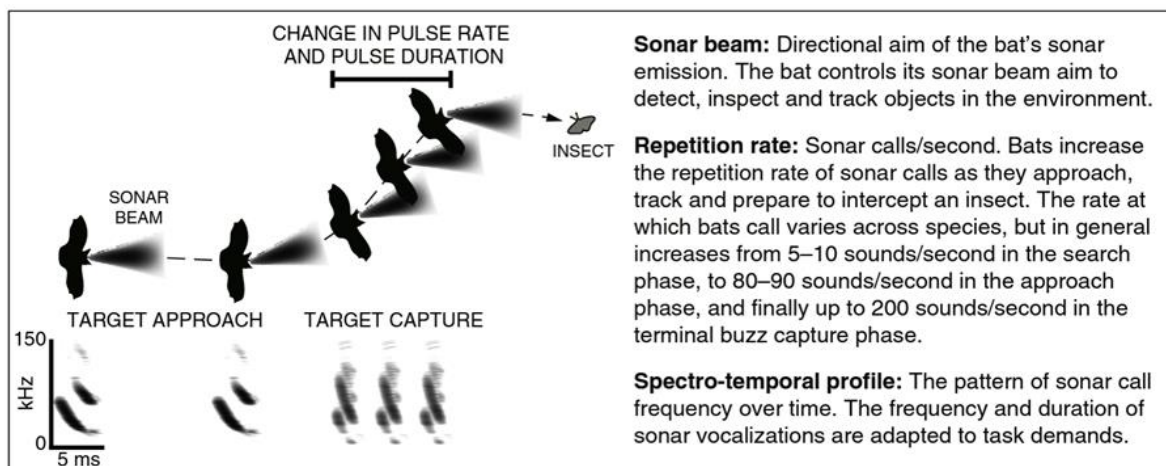
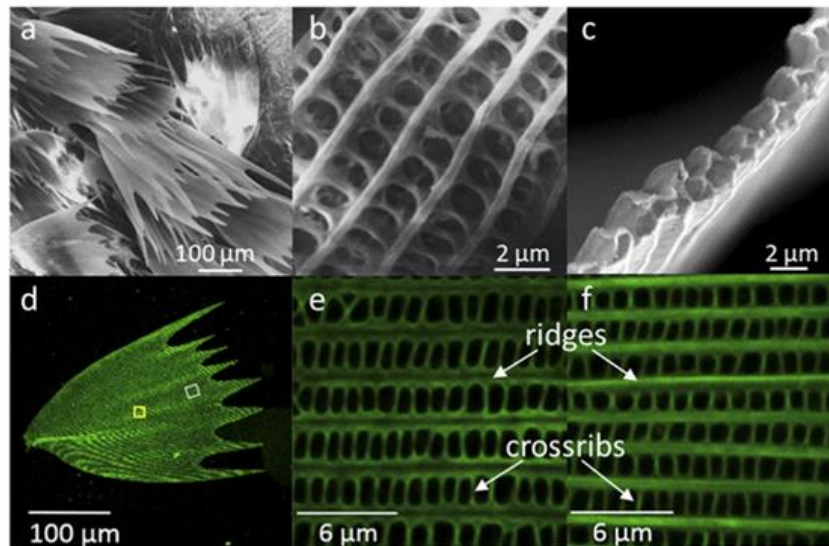


Figure 9 Bat Sonar sensing: The high-resolution 3D acoustic imaging system evolved by echolocating bats (reproduced from [176], authorization pending)

The first strategy to avoid detection by bats deals with some species of earless moth that, as a result of millions of years of evolution, developed a passive acoustic camouflage relying on a particular configuration of both the thorax and the wings. In particular, differently from the other species of moth which evolved ears to detect the ultrasonic frequencies of approaching bats or produce, when under attack, ultrasound clicks to startle bats and alert them to the moth's toxicity [178–180], the wings of earless moths are covered with an intricate layer of scales (Figure 9) that serve as acoustic camouflage against bat echolocation [179][181]. According to [179], each leaf-like shaped scale shows a hierarchical design, from the micro- to the nanoscale, consisting, at the larger scale, of two highly perforated laminae made of longitudinal ridges of nanometer size connected by a network of trabeculae pillars. This configuration leads to a highly porous structure which is able, because of the large proportion of interstitial honeycomb-like hollows, to absorb the ultrasound frequencies emitted by bats and thus reduce the amount of sound reflected back as echoes [182]. As a result, the moth partially disappears from the bat's biosonar and the distance at which the bat can detect the moth is reduced by 5-6% [181], representing a significant survival advantage. In addition, by exploring the vibrational behavior of a wing of a *Brunoa alcinoe* moth, researchers discovered that each scale not only behaves like a resonant ultra-sound absorber having the first three resonances in the typical echolocation frequency range of bats [179], but also that each one has a different morphology and resonates at a particular frequency, creating a synergistically broadband absorption [182]. As reported in [182], it can be thus said that the complex pattern of scales on moth wings exhibit the key features of a technological acoustic metamaterial.



*Figure 10: Moth acoustic camouflage from bat sonars. Scale arrangement and structure. (a-c) SEM images of *B. alcinoe* scales: (a) Partly disrupted tiling of scales; (b) perforated top lamina of a scale; (c) cross-section of a fractured scale revealing the intertrabecular sinus between the two laminae. (d-f) Confocal microscopy of the scale: (d) Individual scale used for further analysis. (Magnification 20 \times .) White square indicates observation area of (e) top lamina and (f) bottom lamina. (Magnification 100 \times). Reproduced from [180], authorization pending.*

As previously mentioned, the second type of passive acoustic camouflage developed by earless moths consists in having much of the thorax covered by hair-like scales (Figure 10) acting as a stealth coating against bat biosonar [183–185]. As suggested by [184,186] such thoracic scales create a dense layer of elongated piliform elements, resembling the lightweight fibrous materials used in engineering as sound insulators. Their potential as ultrasound absorbers was explored in [184] by means of tomographic echo images and an average of 67% absorption of the impinging ultrasound energy emerged. Also, to provide a more in-depth investigation, the authors employed acoustic tomography to quantify the echo strength of diurnal butterflies that are, contrary to moths, not a target for bat predation. The results were then used to establish a comparison with those derived for moths. Interestingly, the analysis revealed that the absorptive performance is highly influenced by the scale

thickness and density, with the very thin and less dense scales typical of butterflies that are able to absorb just a maximum of 20% of the impinging sound energy. Conversely, the denser and thicker moth’s thorax scales possess ideal thickness values that allow the absorption of large amounts of bat ultrasonic calls. These findings are confirmed by [185] where an extended list of references is also provided.

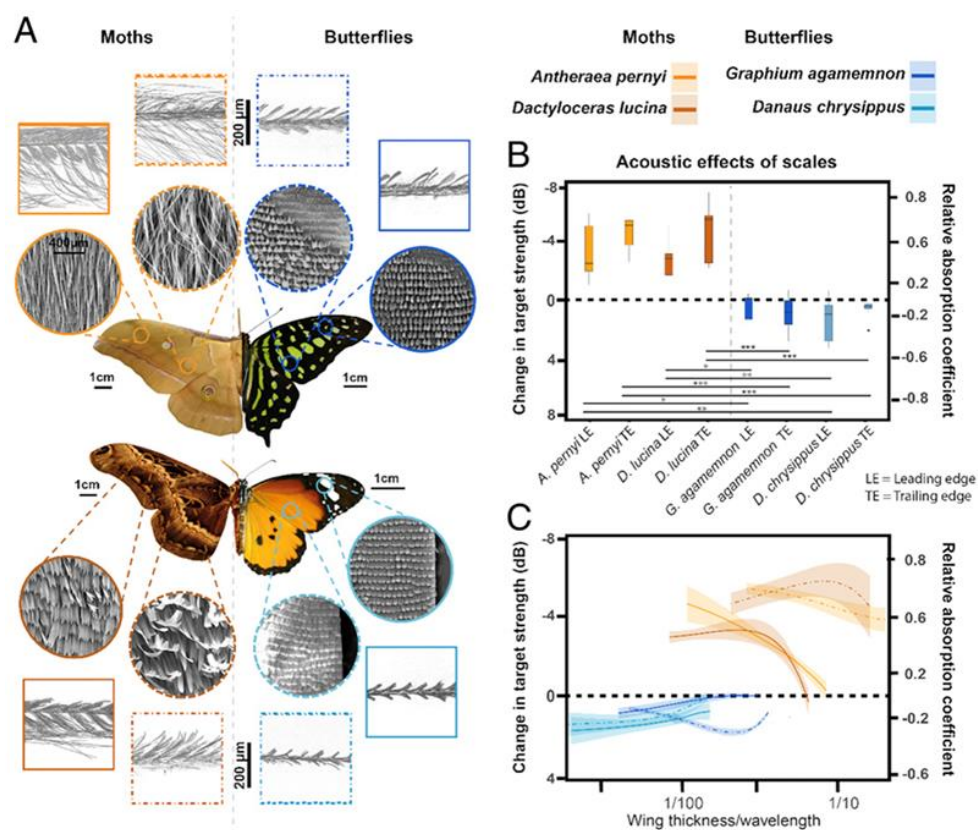


Figure 11: Tiling patterns and acoustic effects of lepidopteran scales. (A) Photographs of butterflies *Graphium agamemnon* and *Danaus chrysippus*, and moths *Dactyloceras lucina* and *Antheraea pernyi* (clockwise from Top Right). Round Insets show SEM images of dorsal surfaces, and square Insets show micro-CTs of cross sections of each wing sample. (B) Change in target strength caused by presence of scales, and equivalent intensity absorption coefficient. (C) Change in target strength caused by presence of scales, and equivalent absorption coefficient as a function of wing thickness/wavelength. Reproduced from [184], authorization pending.

The last example of an acoustically based strategy to confuse predators is the long hindwing tail (Figure 11) commonly found on luna moths (*Actias luna*). Such tail presents a twist toward the end and this distinguishing feature, as suggested in [187], is the key for how the tail creates a sort of acoustic camouflage against the echolocating bats. The tail, in particular, because of its length and twisted morphology, in reflecting the bat’s sonar calls produces two types of echoic sensory illusions [25, 24]. The first consists in deflecting the bat’s attacks from the vital parts of the body, i.e., head and thorax, to this not-essential appendage, by using high-speed infrared videography to analyse the bat-moth interactions. According to the authors, in over half of the interactions, bats directed the attack at the moth’s tail as the latter created an alternative target distracting from the principal one, i.e., the moth’s body. Also, by comparing moths with the tail and moths with the tail ablated, it emerged a survival advantage of about 47%.

The second sensory illusion provided by the twisted tail consists in inducing a misleading echoic target localization that confuses the hunting bats [172,187]. As reported in [187], the origin of this effect is the twist located at the end of the tail that creates a sequence of surfaces having different orientations so that, independently of the inclination of both the incident sound waves and the fluttering moth, the tail is able to return an echo, complicating and spatially spreading the overall echoic response of the moth. In addition, the analysis of the overall acoustic return generated by the wings, body and tail of a Luna moth, revealed an additional survival contribution of the twisted tail, consisting in a shift of the echoic target centre, i.e., the centre of the echo profile used by the bat to estimate the prey location, away from the moth’s thorax [187].

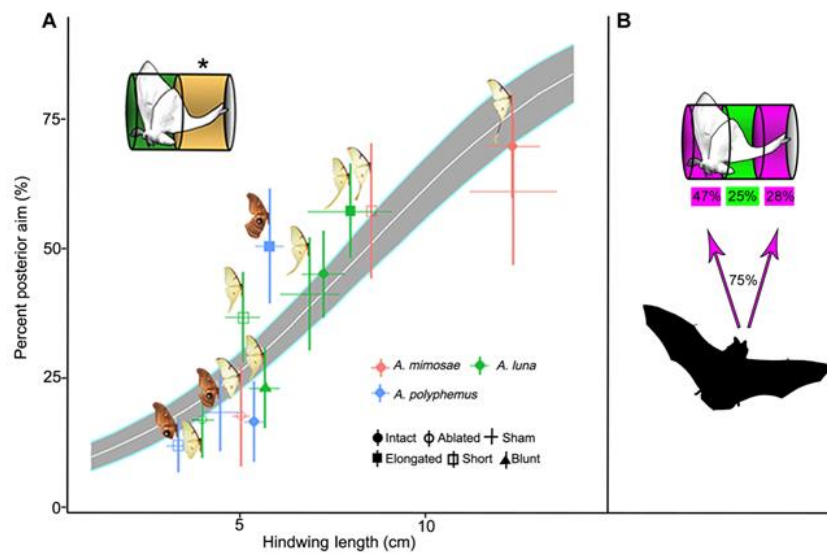


Figure 12: Moth defence against bat predation. Hindwing tails redirect bat attack against moths. Behavioural analyses reveal that (A) bats aim an increasing proportion of their attacks at the posterior half of the moth (indicated by yellow cylinder with asterisk) and that (B) bats attacked the first and third sections of tailed moths 75% of the time, providing support for the multiple-target illusion. An enlarged echo illusion would likely lead bats to target the hindwing just behind the abdomen of the moth, at the perceived echo center (highlighted in green); however, bats targeted this region only 25% of the time. (Reproduced from [173], authorization pending).

4. Sound/vibration control, focusing and amplification

4.1 Cochlea in mammals

The hearing organ in mammals has developed extraordinary capabilities from the point of view of the extension of audible frequencies and perceived intensities. The human ear (Figure 14A-C), for example, is sensitive to 8 octaves of frequencies (20Hz-20kHz) and is capable of distinguishing sounds within 12 orders of magnitude of intensity (120 dB). The evolutionary complexity of this organ has represented an obstacle to the deep understanding of all the

mechanisms involved and, even today, some aspects remain unexplained (for a review on the mechanical mechanisms involved see [188,189]). The *cochlea* (Fig.12E) is the core organ of the inner ear (in blue in Fig.12A), coiled in the form of a snail (hence its name) and enclosed by a bony shell. The cochlea is composed of two ducts (scala vestibuli (SV) and *scala tympani* (ST), see Fig.12B) filled with a liquid (perilymph) which is compressed by a membrane, hit by three miniscule bones of the middle ear (in red in Fig.12A). The pressure difference between the two ducts put in vibration the basilar membrane, which separates them, and which conducts a largely independent traveling wave for each frequency component of the input (this mechanism was proposed for the first time in Ref. [190] and then largely developed). Because the basilar membrane is graded in mass and stiffness along its length [191], however, each traveling wave grows in magnitude and decreases in wavelength until it peaks at a specific frequency-dependent position (see Fig.12F), thus allowing a spatial coding of the frequency contents. This is referred to as the tonotopic organization of the cochlea [192] and is one of the most interesting aspects for our project. The mechanical vibration of the basilar membrane is then collected and translated into an electrical impulse from the hair cells (see Fig.12D) and sent to the brain for the signal decoding.

One of the most relevant and studied characteristics of the basilar membrane is that its response to an external stimulus is highly nonlinear (i.e., not proportional to the input amplitude) and this nonlinear response is also frequency specific. Moreover, each point of the cochlea has a different nonlinear response depending on the characteristic frequency pertaining to this specific point [193,194]. These features are especially evident in in vivo measurements, underling the existence also of an active mechanism (otoacoustic emission) added to the merely mechanical ones (see e.g., [195–197]).

The mechanisms at play are complex and often more than a possible explanation can be found in literature, but different simplified models have tried to capture the basic features of the cochlea and reproduce its incredible capacity of sensing, its tonotopic and amplification behaviours (for a review see e.g., [198,199]). One of the aspects can be relevant for bioinspired applications in the propagation of elastic waves in solids, is the influence of the geometry (spiral) on the frequency attenuation/loss and on the tonotopic property of the sample, as also pointed out by some works (see [200,201]).

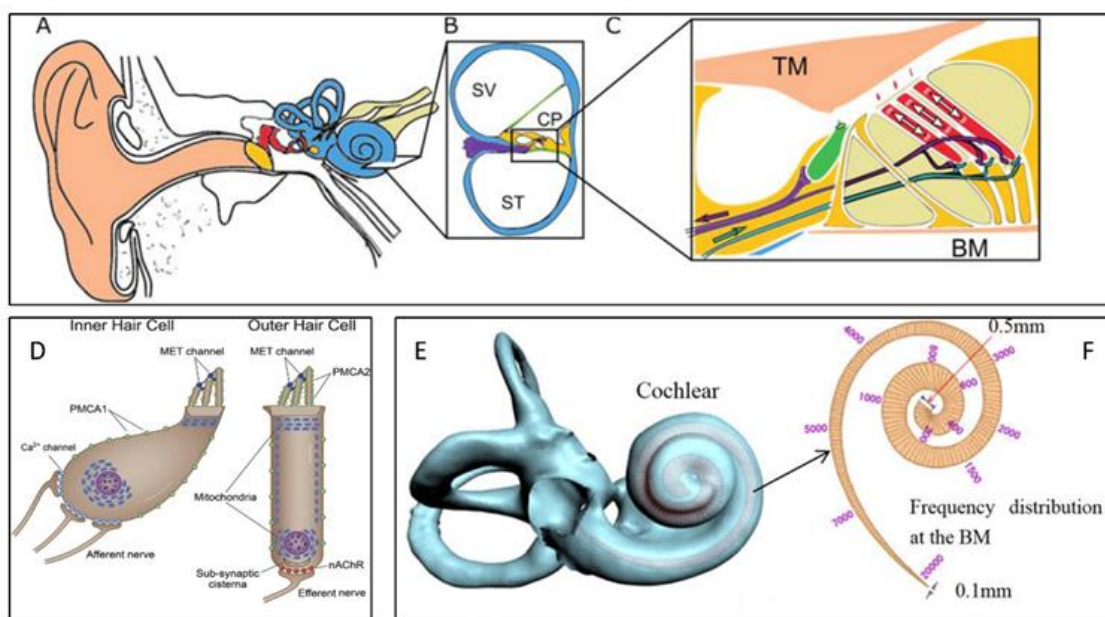


Figure 13 : Cochlea structure. (A) the outer (beige), middle (red) and inner (blue) parts of the human ear. (B) Cross-section of the cochlea showing the scala vestibuli (SV) and the scala tympani (ST), separated by the cochlear partition (CP) which contains the basilar membrane (BM) and the sensory hair cells (adapted from [202]). These cells are represented in panel C in green (inner hair cells) and red (outer hair cells) and are also reported with more details in subplot D (adapted from [203]). In panel E a 3D representation of the cochlea is reported and a schematic map of the tonotopic property of the basilar membrane reported in panel F (adapted from [204]).

All these features attracted the interest of researchers working on mechanical and elastic waves manipulation devices, e.g., in the field of structural health monitoring, sensor development, guided waves, etc. There are specific works in the literature that explicitly refer to the cochlea as a bio-inspiration for metamaterial realizations and that propose acoustic rainbow sensors, where the aim is to separate different frequency components into different physical locations along the sensor (see Fig. 15 and Refs. [202,204–206]). In particular, the tonotopy and the low amplitude amplifier is reproduced with a set of subwavelength active acoustic graded resonators, coupled to a main propagating waveguide in [202]. Similarly, based on a set of Helmholtz resonators arranged at sub-wavelength intervals along a cochlear-inspired spiral tube in [205], the authors realize an acoustic rainbow trapper, that exploits the frequency selective property of the structure to filter mechanical waves spectrally and spatially to reduce noise and interference in receivers. The tonotopy can be also obtained in a 3D model of the cochlea ([204]) by grading the mechanical parameters of an helicoidal membrane: in this case the overall cochlear is a local resonant system with the negative dynamic effective mass and stiffness.

Some of the examples of cochlea-inspiration for the design of metamaterials. In particular in panels A,B,C a gradient-index metamaterial for airborne sounds, made from 38 quarter-wavelength acoustic resonators of different heights is reproduced (from [202]). In panel D a rainbow trapper based on a set of Helmholtz resonators is described (from [205]). In panel E a modal analysis of a helix model of cochlea is reported, showing the different responses to different frequency excitations (in particular, at the top circle, the minimum natural frequency is 89.3 Hz; (c) at the medial circle is 5000.5 Hz; and at the base circle is 10097.2 Hz).

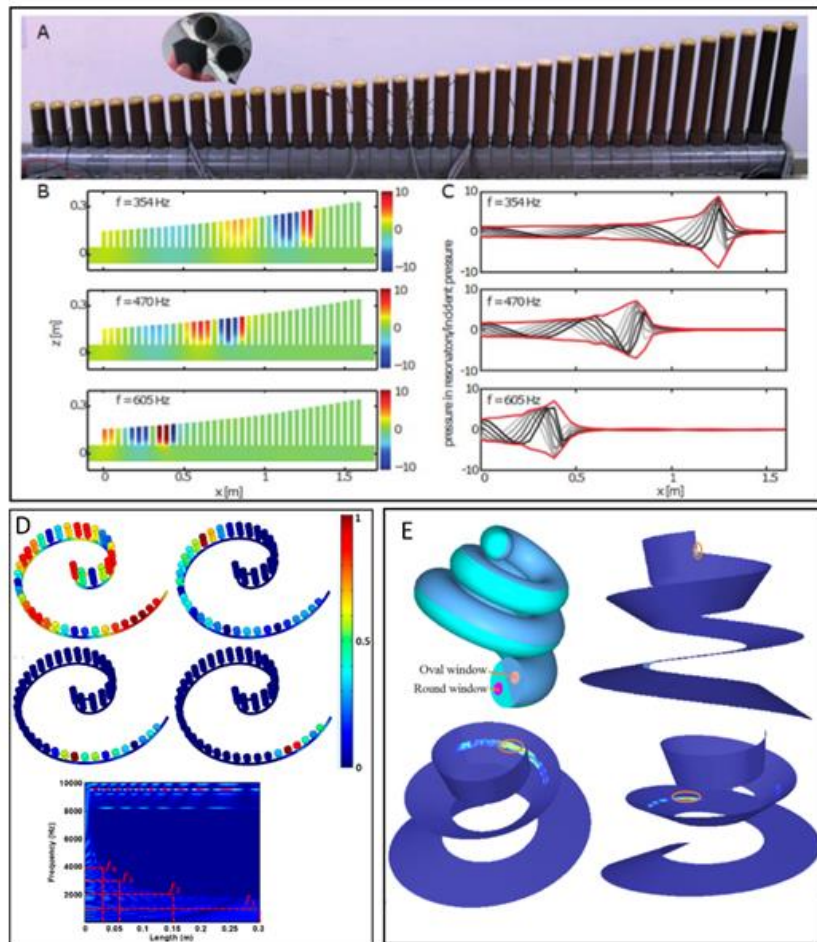


Figure 14 : Metamaterial inspired by the cochlea. Some of the examples of cochlea-inspiration for the design of metamaterials. In particular, in panels A,B,C, a gradient-index metamaterial for airborne sounds, made from 38 quarter-wavelength acoustic resonators of different heights is reproduced (adapted from [202]). In panel D, a rainbow trapper based on a set of Helmholtz resonators is described (adapted from [205]). In panel E, a modal analysis of a helix model of cochlea is reported, showing a different response to different frequency excitations.

3. Conclusions

In conclusion, we have presented a review some notable examples of biological materials exhibiting optimized non-trivial structural architectures to achieve improved vibration control or elastic wave manipulation, for many different purposes. The fields in which these features

appear are mainly impact and vibration damping and control, communication, prey detection or mimesis, and sound amplification/focusing. From the documented cases, some recurrent strategies and structural designs emerge. Among them, an important feature is hierarchical structure, which appears to be essential to enable effects at multiple scale levels, and therefore in multiple frequency ranges. Moreover, these recurrent structural features appear at very different size scales (from microns to meters), in disparate environments (terrestrial or marine) and for different functions. This is an indication that the designs are particularly resilient and effective in their purposes, which encourages the adoption of a biomimetic approach to obtain the comparable types of optimized dynamic mechanical properties in artificial structures. This is a particularly attractive proposition in the field of phononic crystals and acoustic metamaterials, which have emerged as innovative solutions for wave manipulation and control, and where a biomimetic approach to design has thus far been limited to few cases. In general, further investigations in the natural world will no doubt continue to reveal original architectures and designs and advanced functionalities, where function (or multiple functions) is/are achieved through form.

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