Nature as a model for biomimetic sensors

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ABSTRACT

Mammals, like humans, rely mainly on acoustic, visual and olfactory information. In addition, most also use tactile and thermal cues for object identification and spatial orientation. Most non-mammalian animals also possess a visual, acoustic and olfactory system. However, besides these systems they have developed a large variety of highly specialized sensors. For instance, pyrophilous insects use infrared organs for the detection of forest fires while boas, pythons and pit vipers sense the infrared radiation emitted by prey animals. All cartilaginous and bony fishes as well as some amphibians have a mechnaosensory lateral line. It is used for the detection of weak water motions and pressure gradients. For object detection and spatial orientation many species of nocturnal fish employ active electrolocation. This review describes certain aspects of the detection and processing of infrared, mechano- and electrosensory information. It will be shown that the study of these seemingly exotic sensory systems can lead to discoveries that are useful for the construction of technical sensors and artificial control systems.

Key words: biomimetics, electroreception, mechanoreception, infrared reception, lateral line, hydrodynamics, fish, insects

1 INTRODUCTION

All animals use sensory information for object detection, discrimination and localization, as well as for intraspecific communication. In addition, sensory systems provide basic cues for spatial orientation and navigation. Animals live in a wide variety of habitats and lead different life styles. For this reason, they need to extract specific kinds of sensory information from their respective environment. This is probably the main reason why such a stunning diversity of sensory systems has evolved. Whereas nearly all animals rely on mechanosensory, chemosensory and visual cues some animals in addition use infrared (IR) stimuli [1, 2] or magnetic radiation [3] for object detection and/or spatial orientation. Aquatic animals possess various types of hydodynamic sensory systems [4] and all cartilaginous as well as many teleost fish employ active or passive electrolocation [5].

For decades comparative physiologists have studied the various types of animal sensory systems. They gained insight in the uptake, transformation and transduction mechanisms these systems employ and in the computational rules used by these systems to process sensory information. In contrast to technical sensors, biological sensors are often extremely small, highly energy efficient and of utmost sensitivity. Furthermore, biological sensory systems often have hundreds of receptor organs working in parallel, each of which may contain hundreds or even thouthands of sensory cells. This parallel sampling and processing of sensory information not only helps to improve the signal-to-noise ratio (by averaging incoming information) but also reduces the likelihood of errors (due to malfunctioning or loss of singel sensory elements).

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All sensory organs are innervated by afferent nerve fibers. These fibers transmit neuronal information to primary sensory nuclei in the brain. There, sensory information usually is processed in parallel with a speed and efficiency that still beats our fastest computers. Since all sensory systems have developed to serve a particular need in each specific environment the biologists who study these systems have a good chance to uncover physical principles not yet used for the development of technical sensors. Consequently, in a multidisciplanary approach biologists and engineers have already repeatedly and successfully emulated natural sensory systems for technical applications (for recent comprehensive reviews see [6, 7]). Examples include artificial eyes [8-10], electronic noses [11] and silicon cochleae [12]. This review focuses on three types of sensory systems which so far have barely been considered by biologically inspired engineers: The mechano- and electrosensory sensory lateral line of fishes and the infrared sensory system of pyrophilous insects.

2 INFRARED SENSORY SYSTEMS

Pyrophilous beetles like *Merimna atrata*, *Acanthocnemus nigricans* and *Melanophila acuminata* (Fig. 1A-C),

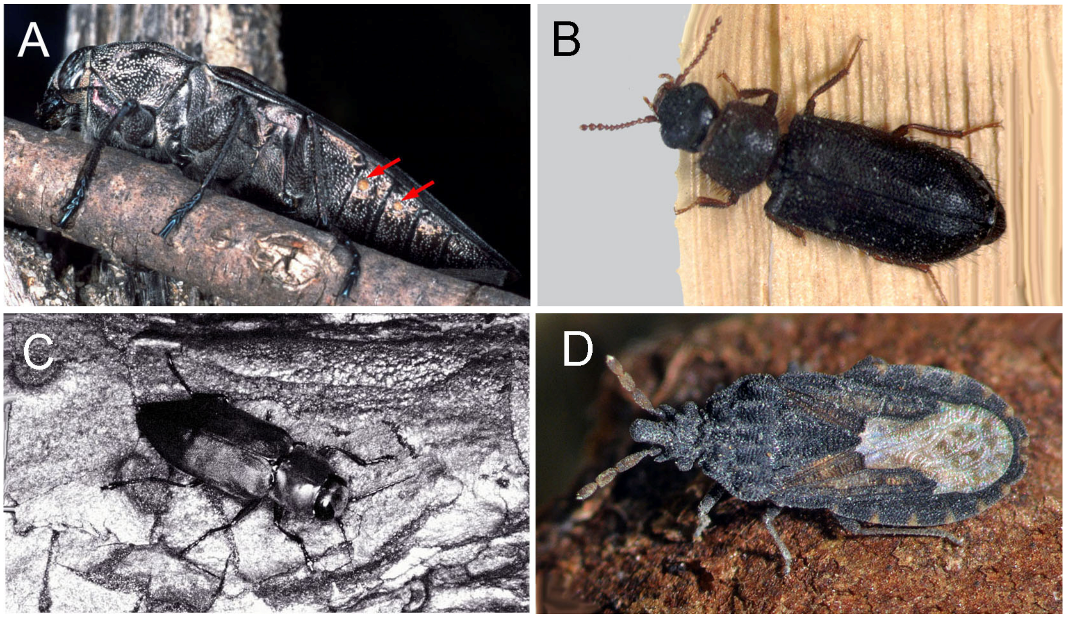

Fig. 1 A-D. A. The Australian fire-beetle *Merimna atrata* (Buprestidae, length 2 cm). Arrows point to the abdominal IR receptors.**B.** The little ash beetle *Acanthocnemus nigicans* (Acanthocnemidae, length 5 mm). The IR sensitive cuticular discs are situated on the ventral prothorax. **C**. The black pine beetle *Melanophila acuminate* (Buprestidae; length 1 cm) on the burnt bark of a pinewood log. One pair of IR organs is situated directly behind the coxae of the mesothoracic legs. **D.** The Australian flat bug *Aradus fusciornis* (Aradidae, length 4 mm). This bug has a small number of dome-shaped IR-sensilla on the prothorax. Photos were kindly provided by H.Schmitz.

approach forest fires [13, 14] from distances of many miles [15]. These beetles copulate on burned areas, followed by deposition of eggs under the bark of freshly burned trees [16, 17]. Also, pyrophilous flat bugs (Aradidae) of the genus *Aradus* can be found on freshly burnt areas after fires [18] (Fig. 1 D). The reason for this is probably that larvae of these insects depend on food sorces that become only available after a forest fire [19]. Forest fires burn with a temperature of about 500 to 1,000°C. Fires of such temperatures emitt IR-radiation in the wavelength range of 2.2 to 4 µm. Since IR-radiation of this wavelength is easily transmitted through the atmosphere [20-22], IR reception is a useful tool for the detection and localization of burning forests [22].

2.1 Microbolometer systems

The Australian “firebeetle”*Merimna atrata* has four IR receptors located on the ventrolateral sides of the second and third abdominal sternite (Fig. 1A). The center of each absorbing area is innervated by a single thermosensitive neuron [23]. Each of the two IR organs of the Australian “Little Ash beetle” *Acanthocnemus nigricans* (Fig. 1B) consists of a tiny cuticular disc which serves as the absorbing structure for IR radiation [14]. To reduce heat convection each disc is located over an air filled cavity. The outer surface of each disc contains about 90 cuticular sensilla, each of which is innervated by a single ciliary sensory cell. The IR organs of *Merimna* and *Acanthocnemus* most probably function as microbolometers, i.e. thermosensitive neurons measure the temperature of an absorbing surface that is heated by IR radiation. In IR organs that function like a microbolometer any decrease or increase in ambient temperature alters

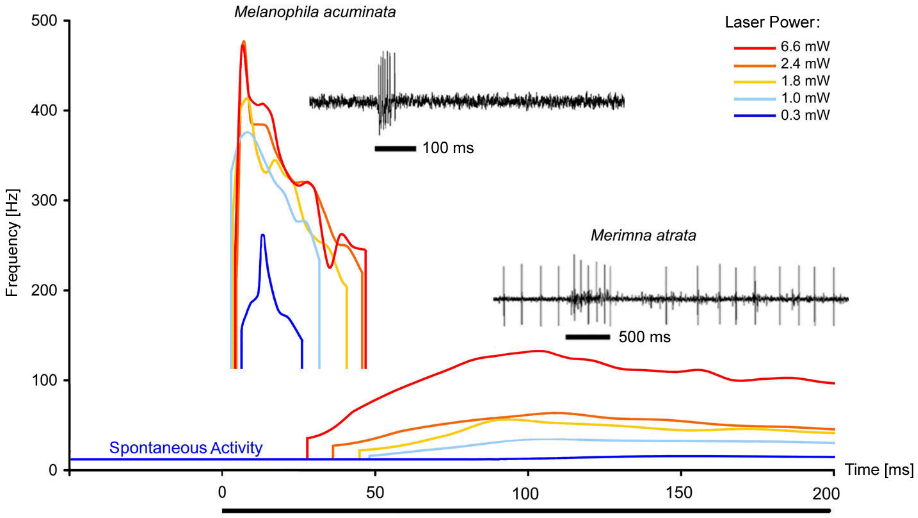

Fig. 2. Responses from an IR sensillum of *M.acuminata* (upper left traces) and from the multipolar thermoreceptive neuron of *Merimna atrata* (lower right traces). Black bar indicates onset and duration of laser irradiation. Insets show original responses to IR stimuli produced with a laser beam (adapted from [24]).

spike frequency [25, 26](Fig. 2). The majority of current uncooled technical IR sensors, especially those capable of forming infrared images, are based on a bolometer principle [27, 28], hence the IR-receptors of *Merimna* and *Acanthocnemus* will not be further discussed here.

2.2 Photomechanic systems

There are at least two examples of insects with IR-receptors that are not based on the bolometer principle. One is *Melanophila* (Fig. 1C), a beetle with a pair of IR-organs situated next to the coxal cavities of the mesothoracic legs [29]. At the bottom of each organ, 50 to 100 sensilla are bulging out with their upper hemispheres extending above the surface [30-32] (Fig. 3 A). The second example is provided by some pyrophilous members of the flat bug genus *Aradus* (e.g. the Australian species *A. fuscicornis,* Fig. 1 D). These bugs have a small number of dome-shaped IR-sensilla on the prothorax. The sensory apparatus of the sensilla of *Melanophila* consists of a sphere with a lamellated exocuticular shell reinforced by layers of chitin fibres and an inner microfluidic compartment. Each sphere is innervated by a single neuron that is anchored ventrally with the distal tip of its cylindrical and unbranched dendritic outer segment in the sphere (Fig. 3B). The dome-shaped IR-sensilla of *Aradus* are furthermore characterized by an inner compartment enclosed in a round cuticular shell [33]. The inner compartment of *A.albicornis* consists of a fluid-filled cavity sourrounding a dendritic tip.

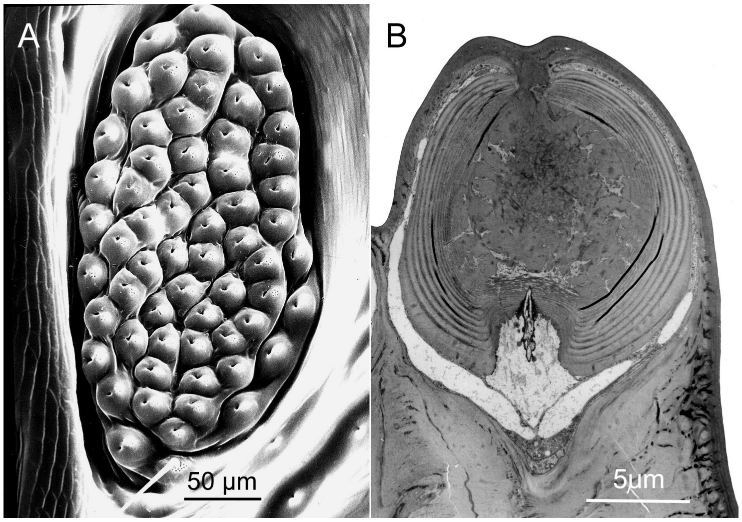

Fig. 3 **A, B.** The pit organ of *M.acuminata*. **A.** About 60 dome-shaped IR-sensilla are housed in a metathoracic pit. **B.** TEM section through an IR sensillum. Below the outer cuticle a cuticular sphere is located in an inner cavity. From below, the sphere is innervated by the single dendrite of a mechanosensitive neuron. Adapted from [31].

When the IR-organs of *Melanophila* or *Aradus* are stimulated with short wavelength IR-radiation, nerve impulses with a latency of about 3 – 7 ms can be recorded. For a stimulus lasting 30 ms the physiological threshold of the IR-organ of *Melanophila* is about 500 µW/cm^2. At higher intensities a stimulus duration of 2 ms is already sufficient to generate a nerve impulse. If exposed to a prolonged stimulus, the IR-recptors of *Melanophila* respond only to the stimulus onset, i.e. the IR-receptors of *Melanophila* are purely phasic (Fig. 2). However, if exposed to a train of short stimuli the IR receptors follow repetition rates of up to 100 Hz [32, 34]. Thus, the dome-shaped sensilla of *Melanophila* (like those of *Aradus)* are uncooled, miniaturized and fast IR-sensors. Based on receptor anatomy and physiology, the IR receptors of *Melanophila* and *Aradus* most likely function according to the following principle [33, 35]: In both species a lamellated outer mantle of the cuticular spherules ensures a high mechanical stability. In contrast, the inner less sclerotized part of the spherules is soft and thus most likely can store a small amount of fluid [36]. Ultrastructural investigations further revealed the existance of small nanocanals that extend throughout the lamellated outer mantle. In *Melanophila*, a distinct (pressure) chamber is connected with the inner part of the sphere. Probably both the cuticular components of the IR sensilla as well as the fluid inside the fluidic core function as IR absorbing materials. Especially the biopolymers of the cuticle (proteins, chitin) have stretch resonances around 3 µm [37]. A wavelength of 3 µm not only coincides with the region of lowest transmission of insect cuticle [31] but, as shown for *Melanophila*, also with the region of highest behavioural sensitivity [38, 39]. Molecules with stretch resonances in the 3 µm wave length region convert the vibrational energy within fractions of a millisecond into translational energy, i.e. heat, by nonradiative deexcitation processes. Any heating should cause a slight increase in pressure inside the fluidic core of the sensillum and thus a deformation of the dendritic tip of the receptor neuron. The nanocanals that extend throughout the outer mantle in the *Melanophila* sensilla may serve as pressure release windows thereby assuring that the IR receptors do not respond to relatively slow changes in ambient temperature. This explanation, which is not jet based on experimental evidence, is in line with the observation that the ultrastructure of the neurons that innervate individual spherules reminds one of a typical insect mechanoreceptor [31, 32].

2.3 Biologically inspired IR sensors

In contrast to the bolometers widely used in technical applications (see above), the photomechanical principle employed by *Melanophila* and *Aradus* was so far unknown to engineers [17]. In a photomechanical IR detector, a fluidic or solid absorber should be directly connected to a mechanosensor. To demonstrate the functionality of an IR sensor based on the photomechanic principle a prototype was fabricated (Fig. 4, top). This prototype detected IR radiation with an intensity of about 800 µW/cm^2 (Fig. 4, bottom). First calculations have yielded a preliminary value for the standardized detectivity (D*, the most important parameter used to specify IR sensors; Rogalski 2002) of 1 x 10^3 cm Hz ^{½} W^{-1}. This value is about five orders of magnitude below the D* values of currently available uncooled technical microbolometers. So far, efforts have been made to miniaturize the sensory elements of the technical IR sensors using Micro-Electro-Mechanical Systems (MEMS) technology. Like the prototype the MEMS sensors contain a microfluidic compartment filled with water or another fluid. Fabricating MEMS sensors will reduce the thermal mass and thereby increase the sensitivity of the sensor [40]. Miniaturization will allow the construction of multisensory arrays, a prerequisite for thermal imaging. Because the absorbing fluid can be chosen according to the IR wave lengths of interest, photomechanic IR sensors can be used in all the same ranges of applications where current IR sensors are utilized, e.g. for the detection of fires or hot surfaces as well as for the detection of animate and inanimate objects whose temperature differs from ambient temperature.

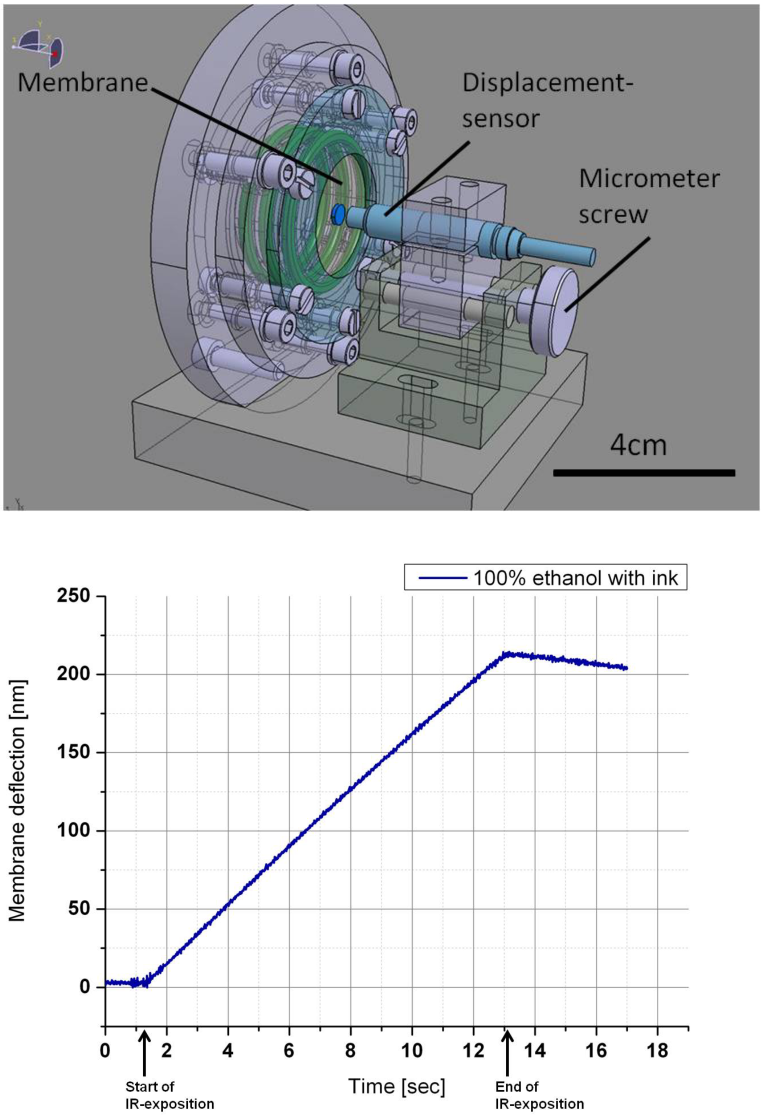

Fig. 4, top: Prototype of a photomechanical IR sensor. IR radiation is absorbed by a fluid or gas filled cavity (diameter 1.5 cm, green part). Expansion of a membrane is measured by a capacitive displacement sensor. **Bottom:** The voltage output of the sensor (blue curve) exposed to an IR stimulus (intensity 1.5 mW/cm^2). The sensitivity curve was kindly provided by H. Schmitz, the drawing of the sensor by W. Briell (Research Center Juelich, Germany).

3. The mechanosensory lateral line of fishes

All fishes can detect nearby water motions and pressure gradients with their mechanosensory lateral line. The receptive structures of the lateral line are the neuromasts which consist of up to several hundred (in some cases of up to several thousand) sensory hair cells covered by a gelatinous cupula (Fig. 5). Lateral line hair cells have a hair bundle at their apical surface comprised of up to 150 stereovilli that grow longer from one edge of the bundle to the other. Within the sensory epithelium of a neuromast the hair cells are oriented into two opposing directions that define the most sensitive axis of a neuromast [41].

In the various fish species the design of the lateral line can be quite different. However, most fish have several hundred superficial neuromasts (SN) on their head, body and tail fin [42]. Most fish also have fluid filled subepidermal canals in the head and trunk region that contain canal neuromasts (CN), each of which is located halfway between neighboring canal pores. Fish use lateral line information for prey detection, predator avoidance, schooling behavior, intraspecific communication, rheotaxis and station holding [43, 44]. The lateral line even enables fish to navigate through their environment and to detect and discriminate stationary objects [45, 46].

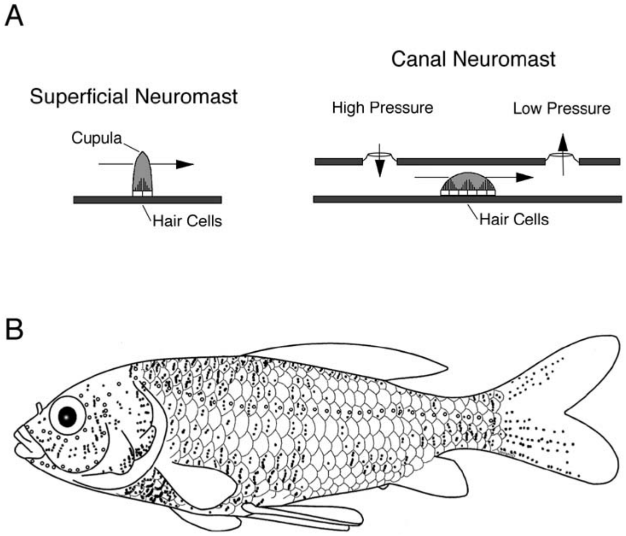

Fig. 5 A, B. Morphology of the lateral line periphery. **A**. Diagrammatical representation of a SN and a lateral line canal with a CN (redrawn from [47]). Arrows indicate direction of water flow. **B**. Distribution of SNs (dots) in the goldfish, *Carassius auratus*. Circles indicate canal pores. The drawing of the goldfish was gratefully provided by A. Grotefeld.

Lateral line neuromasts are small, robust and extremely sensitive (at 100 Hz the displacement threshold is about 0.01 μm) [48]. If stimulated with sinusoidal water motions SNs respond in proportion to water velocity (up to about 80

Hz), while CNs respond in proportion to the pressure gradient between neighboring canal pores (up to about 150 Hz), i.e. in proportion to fluid acceleration [49]. Lateral line nerve fibres also alter their discharge rate if an object passes the fish laterally [50, 51]. If stimulated with a stationary vibrating sphere or a moving object the discharge patterns reflect both the position (including distance) of the object and the direction of object motion [52]. The lateral line can also be stimulated with bulk water flow. However, neither the SNs nor the CNs respond to the DC component of the flow but only to the microfluctuations that are always superimposed on the flow [53]. The lateral line can also be stimulated with single vortices [54] and with the Kármán vortex street generated by a cylinder exposed to running water. In the latter case the vortex shedding frequency of the cylinder can be retrieved from the discharge pattern of primary lateral line afferents [55] and from the discharge pattern of higher order lateral line neurons (Winkelnkämper, Klein and Bleckmann, unpublished).

3.1 Biomimetic flow sensors

Many commercial flow sensors are based on impellers. Sensors of this type measure the DC component of flow and integrate water motions over a fairly large area (depending on the size of the impeller). Water motions can also be measured with hot-wire anemometers [56], laser doppler anemometers [57], capacitive probes and cantilever based sensors [58]. Hot wire anemometer, capacitive probe or cantilever based sensors integrate the water motions over only a small area. In contrast, with particle-image velocimetry (PIV) the two- or even three-dimensional extension of water movements can be studied [59, 60]. Most of the measuring techniques mentioned above are either expensive and/or difficult to perform. Fish have up to several thousand neuromasts distributed over their head, body and tail fin. This allows them to monitor 2D- or even 3D flow fields in real time. Due to their small size, micropillars with an optical readout or flow sensors based on MEMS Technology can also be arranged in compact arrays and thus may especially be useful for the study of complex flow fields. Große et al. [61] and Brücker et al. [60] used arrays of flexible micropillars with an optical readout to measure flow fields. Yang et al. [62] have built a monolithically linear array of 16 microfabriacted flow sensors, each of which had a size of about 50 εm. Sensor spacing was 1 mm, i.e. the artificial lateral line built by Yang et al. [62] matched the fish lateral line. Each individual sensor (threshold 200 μm/s, bandwidth 1 kHz) was based on thermal hot wire anemometry. With such an array of flow sensors the authors successfully localized a dipole source and tracked a hydrodynamic wake [62](Fig. 6).

Most bioinspired sensory hairs (neuromasts) are still one to three orders of magnitude less sensitive than the fish lateral line. One of the reasons for its high sensitivity are the cupulae which efficiently couple the sensory hair cells to the surrounding water flow by increasing the drag of the neuromasts, thereby enhancing stimulus absorption and transmission. To lower the threshold of artificial hair cell sensors, McConney and Tsukruk developed an analogue of

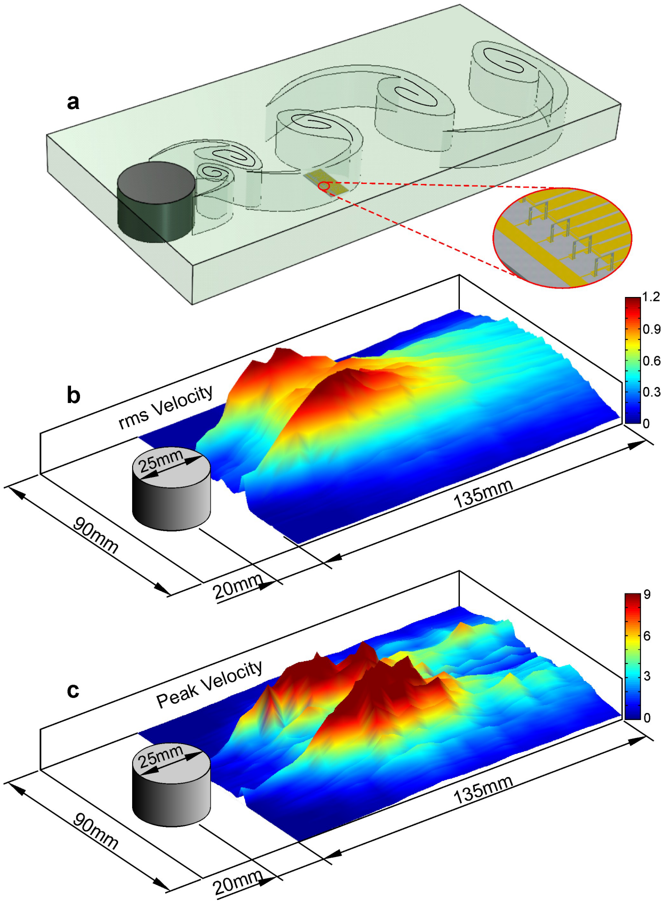

Fig. 6 A-C. Wake signatures for tracking the source of a vortex street. **A.** Kármán vortex street caused by a cylinder exposed to running water. Bulk water flow is from left to right. Inset in **A**: Four of the 16 hot wire anemometers used for the measurements. **B** and **C**. The pattern of rms water velocity and of peak water velocity in the wake of a cylinder (after [62]).

the lateral line cupula. Synthetic cupulae improved the sensitivity of artificial flow sensors by almost 40 times down to values that mached the sensitivity of the fish lateral line [63].

[64] and [65] placed microfabricated hair cell sensors in artificial lateral line canals. Using these canals, equipped with at least two sensors, bulk flow velocity could be determined. Artificial lateral line canal systems can be used to sense a Kármán vortex street and to determine the upstream position of a cylinder shedding the vortices. Because the vortex shedding frequency is a function of both bulk flow velocity and cylinder diameter, information about the size of the cylinder can also be obtained by artificial lateral line canal systems. With aid of bioinspired SNs and CNs it could be confirmed [66] that CNs are less prone to noise than superficial sensors [67].

4 ELECTROSENSORY SYSTEMS OF WEEKLY ELECTRIC FISH

Nearly all non-teleost fish and four groups of teleosts belonging to the Ostariophysi and the Osteoglossiformes possess electroreceptor organs [68, 69]. Teleost fish with electroreceptor organs belong to the Mormyriformes and Gymnotiformes, the large and world-wide order Siluriformes, and some members of the *Xenomystinae* [70]. Low frequency (ampullary) electroreceptors are used for the detection of the bioelectric fields emanating from living prey. In addition, some fish use ampullary electroreceptors to detect electric fields of geoelectric origin [71]. Besides ampullary receptor organs, Mormyriformes and Gymnotiformes possess high-frequency (tuberous) electroreceptors (e.g. Fig. 7). Fish with tuberous receptors produces weak electric fields around them with an electric organ located in the tail. In wave-type electric fish, organ discharges (EODs) are sinusoidal with frequencies of up to 1700 Hz. In contrast, pulse type electric fish produce brief (usually < 1 ms) electric pulses, separated by intervals that are much longer than pulse duration [72](Fig. 8).

Fig. 7. The weakly electric fish *Gnathonemus petersii*. The electric organ is located inside the straight part of the tail. The pores of the high-frqeuency electroreceptor organs can be seen as white dots on the dorsal and ventral sides of the body and on the head. The photo was kindly provided by G. von der Emde.

Both wave and pulse species use high-frequency electroreceptors to obtain sensory information from distortions of their own electric field, caused by objects with impedances different from that of the surrounding water. Fish detect the presence of a nearby object by measuring the amplitudes of their own EODs, which changes at the affected skin region if the resistance of

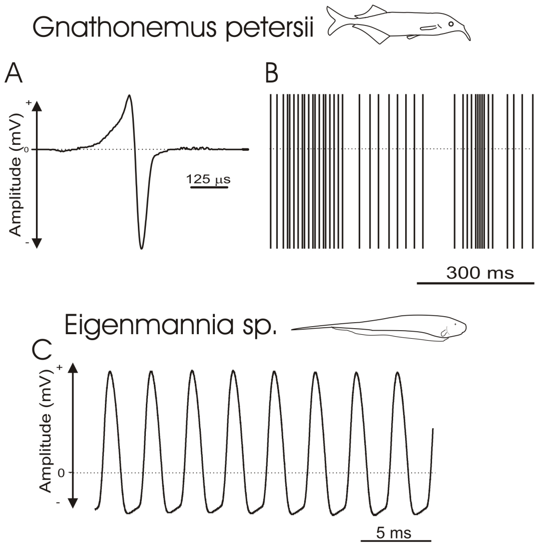

Fig. 8 A, B. Electric signals (voltage vs. time) from a pulse species (*Gnathonemus petersii*) (**A** and **B**) and a wave species (*Apteronotus albifrons*) (**C**). Note the variable pattern of pulse intervals in **B**, which is controlled by a pacemaker in the medulla. Changes in pulse intervals are used to generate different kinds of social signals. Redrawn from [73].

the object differs from that of the surrounding water. In addition to detecting an object and determining its electric resistance, weakly electric fish also recognize the material properties of the object. Animate objects such as water plants, fish, worms, or insect larvae not only have ohmic, but also capacitive properties [74]. Objects with capacitive properties not only alter the EOD amplitude, but – in addition - its waveform or phase. Mormyrids and Gymnotids can perceive the capacitive properties of an object by measuring local EOD amplitudes as well as either EOD waveform distortions (caused by phase and amplitude changes of certain spectral frequencies, Mormyridae) [75] or temporal EOD shifts (Gymnotidae) [76-78].

4.1. Receptor mechanism of phase discrimination

Mormyriformes have two types of high-frequency electroreceptor organs: the mormyromast for the detection, discrimination and localization of animate and inanimate objects and the Knollenorgans, used for intraspecific communication. Mormyromasts contain two types of morphologically distinct sensory cells. The deeper part of a mormyromast contains B receptor cells that are innervated by a single B afferent nerve fiber. The more superficial A receptor cells are innervated by A afferent fibers (Fig. 9). Both A and B afferents respond with one to about five action potentials to the animals own EOD. In both, A and B afferents, a decrease in EOD amplitude causes an increase in spike latencies and a decrease in the number of spikes elicited [79]. However, in contrast to A afferents, B afferents are highly sensitive to distortions (phase shifts) of the EOD (Fig. 10). If the amplitude and the duration of a 300 µs EOD is held constant, a distortion of the EOD that corresponds to a phase shift of only 1° already is sufficient to cause a significant decrease in first-spike latencies [79].

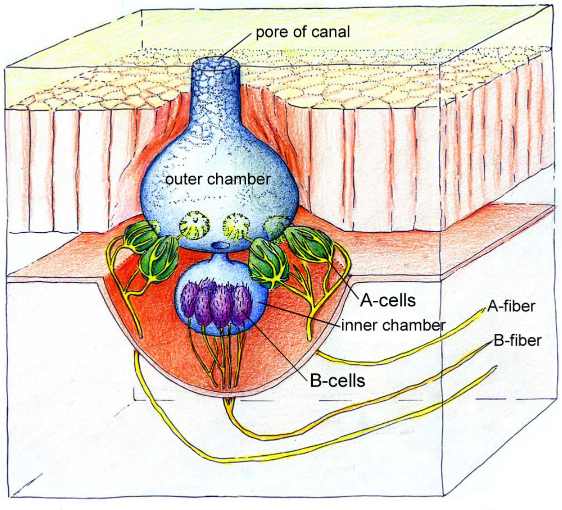

Fig. 9. A mormyromast electroreceptor organ of a *G.petersii* with. The organ opens with a canal filled with loosely packed cells to the outside water. The A-receptor cells are positioned at the outer chamber, while the B-receptor cells are located almost entirely inside the inner chamber. Both cell types are innervated by afferent nerve fibers that project to the hindbrain (modified after [80]).

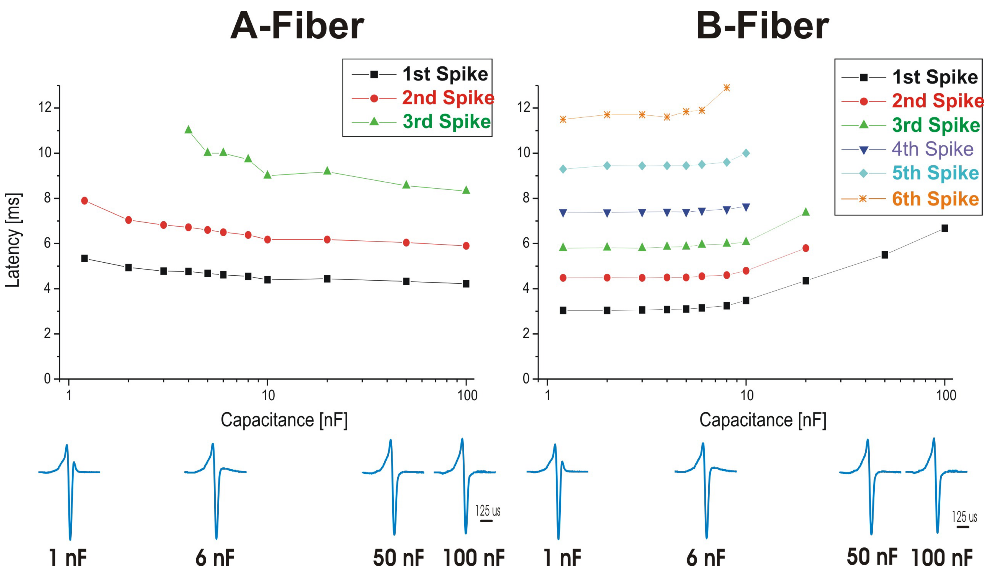

Fig. 10. Electrophysiological recordings from an A-fiber (left) and a B-fiber (right) of a mormyromast organ of a *G. petersii* while an object of variable capacitances was placed close to the pore of the organ. The latencies of the action potentials evoked by each stimulus are drawn versus the capacitive values of the object (abscissa). The peak-peak amplitude of the stimulus was held constant so that only waveform distortions varied for the different stimuli: a 1nF object causes maximum distortions, while distortions were almost absent when a 100 nF object was used. The A-fiber on the left responds slightly negative to increasing waveform distortions from right to left, i.e. spike latencies increase and spike numbers decrease. In contrast, B-fibers (right) respond strongly positive to capacitive objects: with increasing waveform distortions spike numbers increase and spike latencies decrease. The fiber shown on the right is saturated at a capacitive value of 8 nF. Redrawn from [76].

During active electrolocation, weakly electric fish acquire a precise electrical image of their surroundings and the objects within it, even in complete darkness. *G.petersii* can discriminate between an object with a fixed capacity and various resistive objects. This fish not only uses electric information to determine the 3-dimensional shape of an object but also to categorize different objects [81]. Mormyrids can localize objects in space during active electrolocation. *G.petersii* can discriminate between two objects that are placed at slightly different distances from the fish, independently of the size or electrical properties of the objects [78, 82]. Thus mormyrids possess a true sense of depth perception. An object's distance is determined by calculating the ratio of the maximal slope of an electric image to its maximal amplitude (c.f. [78]), which depends only on distance and not on the object's size or other object properties.

4.2 Artificial sensor systems for active electrolocation

Gerhard von der Emde and coworkers applied the principles of active electrolocation to technical sensory systems by building devices that produce electrical current pulses in a conducting medium and simultaneously sense local current density. Depending on the specific task the sensor was designed for, it could (i) detect an object, (ii) localize it in space, and (iii) measure certain object properties such as material properties, thickness or material faults [83]. Active electrolocation has the advantage of working under unfavorable environmental conditions, such as high pressure or temperature. In addition, electrolocation still functions in polluted environments, e.g. in murky waters, or in media containing contaminations. Thus, electrolocation sensors can be used in environments that are difficult to access by humans or where other sensors fail, such as in great depths (e.g. deep-sea mining) or blast furnaces [84].

It may also be possible to apply active electrolocation sensors to medical diagnostics. One example is the detection of plaques in blood vessels, which are the major cause for heart attacks and strokes. Von der Emde and coworkers are currently developing a catheter based microelectrode array sensor, which like the electric fish, emits electrical signals and simultaneously detects and analysis the electric field changes caused by the blood vessel wall [85]. Such a sensor has the capability to distinguish biological materials that differ in their electrical properties. Despite their astonishing capacities, artifical electrosensors are still far behind their biological counterparts. Therefore, the understanding of the sensory and computational principles governing electroreception in fish remains an ongoing goal in scientific research.

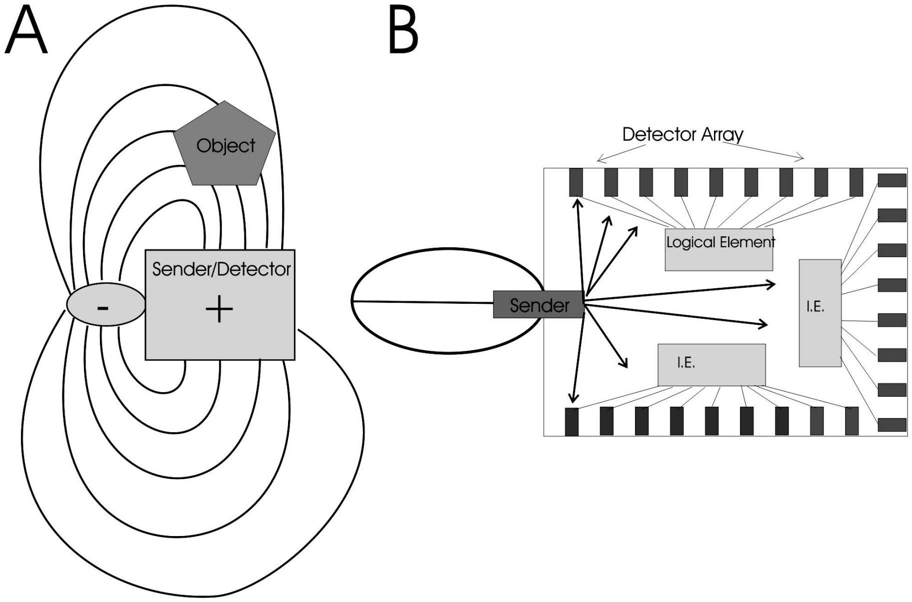

Fig. 11 A, B. Schematic drawing of a technical sensor based on the principles of active electrolocation. **A** shows an overview of a device (sender/detector) inspecting an object. The lines depict electrical current lines (field lines). In **B** a transparent close-up of the Sender/detector is shown. The Sender constitutes a non-symmetric dipole with a round and a cube like pole, respectively. The Receiver contains a 3-dimensional array of detectors (sensors) that feed their information into three logical elements which analyze the received signals and compute object parameters like distance, shape or material properties. Redrawn from [73].

Conclusions

Sensors are of essential importance for many products, systems and their manufacture. Since nature has invented an incredible variety of sensors it is not surprising that biologists can provide engineers with ideas about new types of sensors and how to miniaturize and optimize existing technical sensors. Although biomimetic sensors work according to natural principles, they usually don't copy these principles. The task of engineers and biologists developing biomimetic sensors is to understand how the biological system works and how the animal's brain analyses the information provided by the sensor. Only after the biological principles have been understood, analogous technical sensors can be built. If the transformation from nature to engineering is achieved, biomimetic sensors may offer several advantages over traditional technical sensors such as a smaller size, higher sensitivity, and last but not least uniqueness.

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