

# A robotic system emulating the adaptive orienting behavior of the barn owl

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*Abstract*— Autonomous robotic systems need to adjust their sensorimotor coordinations so as to maintain good performance in the presence of changes in their sensory and motor characteristics. Biological systems are able to adapt to large variations in their physical and functional properties. The adjustment of orienting behavior has been carefully investigated in the barn owl, a nocturnal predator with highly developed auditory capabilities. In the optic tectum of the barn owl, an area well-known to be involved in the production of orienting behavior, neural maps of space in the visual, auditory, and motor modalities are found in close alignment with each other. As a neurophysiological correlate of the adjustment of motor responses, neural maps in the tectum tend to realign if the sensory inputs are manipulated. We have recently proposed that the development and maintenance of such map alignment can be explained through a process of learning, in which plasticity is mediated by the activation of diffuse-projecting neuromodulatory systems which respond to innate or acquired salient cues. This proposal was tested using a detailed computer model of the principal neural structures involved in the process of spatial localization in the barn owl. Here we consider the application of this model to the control of the orienting behavior of a robotic system in the presence of auditory and visual stimulation. The system we consider is composed of a robotic head equipped with two lateral microphones and a camera. We show that the model produces accurate orienting behavior toward both auditory and visual stimuli during normal visual experience, after alteration of the visual inputs, and after the reestablishment of normal visual conditions. The results illustrate that an architecture specifically designed to account for biological phenomena can produce flexible and robust control of a robotic system.

## I. INTRODUCTION

Operating in the real world requires a high degree of flexibility. Real environments are unpredictable, mechanical and electronic devices may fail and their properties change over time. Autonomous systems should be able to adaptively integrate sensory and motor information, so as to tolerate noise and faults.

Nature, in the course of evolution, has faced these very problems. It has developed systems which are highly flexible in the face of variable phenotypic and environmental conditions. The understanding of the basic principles of how brains adapt to the environment and their application to the development of artificial systems is one of the major goals of modern science.

In this paper, by focusing on the specific case of orienting behavior, we show how an architecture specifically designed to account for adaptation in orienting toward visual and auditory cues in the barn owl can be directly applied to the control of a robotic system.

The barn owl is a nocturnal predator which is able to

capture mice in complete darkness, purely on the basis of auditory cues [16]. Nevertheless, visual orienting to stimuli is of primary importance in the barn owl, since vision is the most informative modality, and it is already organized in terms of space at the input stages. In other modalities, such as audition, spatial cues need first to be extracted from the input signals in order to orient correctly. These cues depend on the functional and physical characteristics of the phenotype and may change with time.

Manipulations of the sensory inputs have shown that the barn owl is able to adapt to drastic perceptual changes [13]. By simulating in a computer model the neural structures involved in the generation of orienting behavior in the owl, we have recently proposed [20] that the development and maintenance of accurate spatial localization can be explained in the context of a neurobiologically-based paradigm of reinforcement learning, which we call *value-dependent learning* [19], [6]. According to this paradigm, signals related to the saliency of sensorimotor events are broadcast by the activation of diffuse-projecting neuromodulatory systems to different parts of the brain, where they modulate synaptic changes which mediate neural plasticity. This hypothesis relies on a large body of biological evidence [4], [18]. Here we consider the application of this model to the control of the pan axis of a robotic head, in the presence of both auditory and visual stimulation. We show that the model produces accurate and robust orienting behavior in the presence of different visual conditions, and quickly recovers good performance after alterations of the sensory inputs.

In the following we briefly review the neural substrates for orienting behavior in the barn owl. We then describe a computer model of the main neural structures involved in spatial localization in the barn owl. In section IV, we consider the application of the model to the control of a robotic system. The results are discussed in the last section.

## II. ORIENTING BEHAVIOR AND THE PERCEPTION OF SPACE IN THE BARN OWL

Neural maps of extra-personal space based on different modalities are found in brains of many vertebrate species [21], [13], [7]. These maps are usually in close alignment so that neurons close to each other are activated by stimuli in different modalities originating from the same spatial locations. In several areas of the brain, sensory maps of space are also aligned with motor maps in which the activation of neurons elicit movements of the eyes and/or head

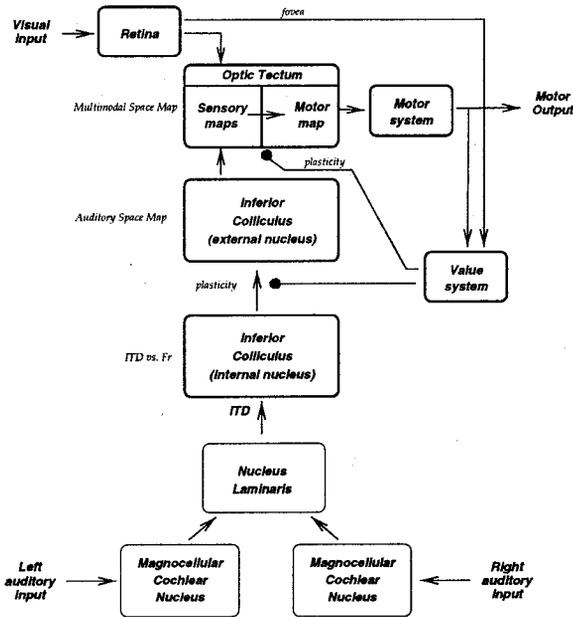


Fig. 1. Main neural stages involved in the process of azimuth localization in the barn owl: the auditory and the visual pathways converge at the level of the tectum, and project to the motor system. Thick boxes represent areas which have been included in the model. The value system replicates the presumed role of modulatory systems with diffuse projections. It is activated for salient events and modulates synaptic plasticity.

toward different locations. Such a registration among sensory and motor maps implements an economical scheme in which different modalities access a common motor output. A well-studied example of map registration is the alignment between visual, auditory and motor maps of space in the optic tectum (OT) of the barn owl [9], [15], an area well known to be involved in the production of orienting behavior. It has been shown that two separate auditory cues are used by the barn owl for localizing the azimuth and the elevation of the target: difference in the time of arrival of the sounds at the two ears (interaural time differences (ITDs)) for the azimuth, and differences in the amplitude (interaural level differences (ILDs)) for the elevation [17]. Tectal neurons are activated by ITDs and ILDs generated by sources at spatial locations that correspond to their visual receptive fields. This alignment is necessary to guide the barn owl's orienting behavior to auditory stimuli so that the source of those stimuli falls onto the fovea. Auditory spatial cues are extracted from the input signals by complex neural structures. The main sites in the pathway dedicated to azimuth localization in the barn owl are shown in Fig. 1. This pathway starts with the magnocellular cochlear nuclei, and through the nucleus laminaris and the inferior colliculus reaches the tectum, where it meets the visual pathway composed of direct retino-tectal projections. In the tectum, the sensory representation of space is aligned with the motor map which controls the activation of motoneurons.

A dramatic demonstration of the ability of the barn owl to adapt to altered sensory conditions comes from exper-

iments in which owls were raised with their visual field chronically shifted by the insertion of prisms over their eyes [12]. It has been shown that prolonged exposure in early life to a translated visual field causes the animal to calibrate a motor action, so that instead of aiming directly toward the sound source, it will gaze laterally by an extent equal to the shift introduced [14], [12]. In this way, after the execution of the motor action, the target projects on the fovea. Furthermore, if removal of the prisms occurs within 200 days of age, a barn owl is able to recover accurate sound localization [14]. The changes in the orienting behavior of the animal have a physiological correlate in the change in the sensitivities of the units in the optic tectum: the auditory receptive fields of OT units shift by an amount which accurately matches the visual displacement. In practice, neurons in the OT change their auditory sensitivity so as to respond to ITDs that correspond to the new visual locations [12]. In this way, the auditory map of space is dynamically adjusted to the visual map of space in an experience-dependent manner [11], [13]. Such a realignment seems to occur continuously during normal development to accommodate for the changes in auditory cues that follow alterations in the morphology of the head and ears.

### III. MODELING THE BARN OWL NERVOUS SYSTEM

The neural structures included in the model are shown in darker boxes in Fig. 1. Since the main focus of this work is the plasticity of multimodal spatial representations at the level of the tectum, the first stages of the auditory pathway were not included in the model. In practice, for a given stimulus position, the corresponding ITD was used to drive the units of the simulated internal nucleus of the inferior colliculus.

The modeled areas are briefly described in this section. More details can be found in [20]. Areas in the model are indicated by italic characters, using the same names that refer to the corresponding biological structures.

The activation of the units in the model was regulated by the classical leaky integrator equation

$$\frac{dy}{dt} = x(t) - \gamma y(t) \quad (1)$$

where  $y(t)$  is the unit output,  $x(t)$  is the net input to the unit and  $\gamma$  is a constant which determines the decay of activation. A noise term was superimposed on the activation of the units.

#### *Central Nucleus of the Inferior Colliculus*

In the owl, neurons in the *central nucleus of the inferior colliculus* (ICc) have narrow sensitivity to both frequency and interaural phase. They are arranged tonotopically in adjacent frequency laminae along one direction, and according to interaural phase sensitivity along the other. ICc neurons show a characteristic periodicity in their response to different ITDs, with a period determined by the neuron's best frequency.

In the model, the response of *ICc* units was designed so as to fit the physiological data as closely as possible. Unit activation was characterized by a narrow frequency range and showed a periodicity with respect to ITD. Following the anatomical organization of the *ICc*, as revealed by electrophysiological recordings, *ICc* units were arranged in the model such that their sensitivities to frequency and ITD were aligned along perpendicular directions. As result, the modeled *ICc* can be seen as a bidimensional array, where each unit is identified by a characteristic value of frequency and of ITD.

#### *External Nucleus of the Inferior Colliculus*

The *external nucleus of the inferior colliculus* (*ICx*), is the first site in the ascending pathway to the tectum where the two fundamental sound localization cues (ITD and ILD) are brought together to create an auditory representation of space. *ICx* neurons have restricted auditory receptive fields, in that they respond maximally to stimuli located at a specific position of space, and their layout gives rise to a systematic map of the auditory space. Anatomical studies have shown that space-specific *ICx* neurons receive afferents from many isofrequency laminae in *ICc*, but from a limited range of ITDs [8]. It has been shown that, in the *ICx*, the local connectivity with inhibitory neurons has a crucial role in shaping the receptive fields of *ICx* units [1].

In the model, the *ICx* contained two types of units: excitatory and inhibitory neurons. Excitatory neurons received inputs from *ICc* and projected to *OT*. They also projected to surrounding excitatory and inhibitory units in the *ICx*. Inhibitory units projected to more distant regions of the map. This pattern of local connectivity gave rise to a competition among different areas of the *ICx*, where units with higher values of activation inhibited the others. In the simulations, the decay factors of *ICx* and *ICc* units were chosen sufficiently large, so that the activated units possessed some residual activation after the execution of the saccade, at which time foveation could occur.

A coarse topographical organization existed in the connectivity between the *ICc* and the *ICx*, so that each unit in the *ICx* received projections from units in all *ICc* frequency laminae, but within a delimited range of ITD. The probability of connection between *ICc* and *ICx* units decreased exponentially with distance between the two units. This reflected the fact that, as indicated by orienting behavior in young barn owls, developmental events are sufficient to establish a neural connectivity which supports a rudimentary auditory localization [10], independent of sensorimotor experience.

#### *Optic tectum*

In the barn owl, the space map of the *ICx* is projected topographically to the *OT*, where it is combined with spatially organized inputs from other sensory modalities. Tectal cells have well-defined spatial receptive fields and are excited by stimuli located in their receptive field and inhibited by stimuli outside of it. In the barn owl, the ma-

ajority of the cells in the *OT* respond to both auditory and visual stimuli [10]. The location of the receptive field shifts systematically with the position of a cell in the tectum, giving rise to multimodal maps of space. Sharp tuning to a particular azimuth and elevation of a sound source is the result of the unit's sensitivity to specific values of ITD and ILD for dichotic stimuli. In the tectum, the auditory map of space is well aligned with the map of visual space [13].

The *OT* was modeled as two unidimensional arrays of units: a sensory map composed of bimodal units which were activated by both visual and auditory stimuli and a motor map whose units projected to the motor system. *OT* sensory neurons received visual input directly from the retinal map by means of a set of topographically organized connections (adjacent receptors of the retina are connected to adjacent areas of *OT*). They also received topographically organized connections from *ICx* excitatory units. Whereas the visual receptive field of *OT* sensory units was determined by the fixed connections from the retina, the auditory receptive fields could change location depending on plastic changes in the connections from the *ICc* to the *ICx*.

Similar to the connections between the *ICc* and the *ICx*, a coarse topographical organization also existed in the connectivity between the sensory and motor maps in the *OT*. The probability of connection between a sensory and a motor unit decreased exponentially with the distance between the two units.

#### *Motor output*

In order to determine the direction of gaze for a given pattern of activation in *OT*, a simplified motor system was implemented. *OT* units projected to two motor neurons through a set of fixed connections. The two motoneurons controlled movements to the left and right. In this way, a linear relationship was established between the position assumed by the system and the map of activation in *OT*.

#### *Plasticity*

A striking aspect of orienting behavior in barn owls is its wide range of adaptability. Even though the basic features for auditory localization (ITD and ILD) are shared by all barn owls, the actual values of these parameters depend on the morphology of the body, in particular the size of the head and the shape of the facial ruff of feathers. In the first months of life these animals undergo large physical changes, as these structures change in size and shape. Consequently, the auditory parameters also change significantly, and the nervous system must adapt to such modifications.

The origin of the visually-induced shift of the auditory receptive fields has been carefully investigated [3], and plasticity has been found to occur at the level of *ICx*, the site where the auditory map of space is first synthesized. Different experiments have also revealed that the alignment between visual and motor maps in the *OT* may be modified, even if in this case the site of plasticity has not been unequivocally determined.

In the model, the strengths of connections were allowed

to change on the basis of experience both in the projections from *ICc* to *ICx* and in the projections between sensory and motor maps in the *OT*. The strength of plastic connections was initially set to a random value.

Synaptic modifications were mediated by the activation of a modulatory system (the value system of Fig. 1), triggered by the occurrence of salient events [19], [18]. This value system functionally replicated the proposed role of neuromodulatory subcortical centers, such as monoaminergic and cholinergic nuclei. Due to the complexity of these systems and their interactions, the present model did not attempt to replicate in detail any of their individual properties, but simply represented their overall effect of modulating synaptic plasticity. For simplicity, the value system consisted of a single unit, which received afferents from both the fovea and the motoneurons. In this way, the value unit was active when a stimulus was in the center of the visual field or when a movement was executed. Due to the long time constant of units in the motor system, the value system received input throughout the duration of the saccade until the beginning of the foveation response. The time constant of the value unit was considerably smaller, such that its level of activation increased nonlinearly only if the response to motor events and foveation overlapped in time.

At each time step of the simulations, the strength of a connection  $\omega_{ik}$  between unit  $i$  and unit  $k$  was modified according to

$$\omega_{ik}(t+1) = \omega_{ik}(t) + \Phi_L(\epsilon_1 U_i U_k + \epsilon_2 V) \quad (2)$$

where  $U_i$  is the activation of unit  $i$ , and  $\Phi_L(x)$  is a linear function characterized by two thresholds  $\theta_{LTD}$  and  $\theta_{LTP}$  [2]. When the argument is lower than the first threshold  $\theta_{LTD}$  the function has a value of zero; in between the two thresholds it has a negative value, thus inducing depression of synaptic strengths; and above  $\theta_{LTP}$  it assumes positive values, thereby potentiating the connections. Typically, the values of the thresholds were selected so that potentiation occurred only for units whose activations were correlated when the activation of the value system was high. This happened after a successful saccade, which brought the stimulus onto the fovea. By contrast, when the value system was not strongly activated, such as when the system moved but did not localize the target, highly correlated units were mostly depressed. The two terms at the argument of  $\Phi_L$  have different functional implications: the first term reflects a *local* factor which may be different for different connections; the second term is a *global* factor shared by all the plastic synapses. The relative contribution of these two terms is set by the values of the parameters  $\epsilon_1$  and  $\epsilon_2$ .

#### IV. APPLICATION TO THE CONTROL OF A ROBOTIC SYSTEM

The model described above was tested in a series of computer simulations [20]. They have shown that the model can account for the development of a spatial regis-

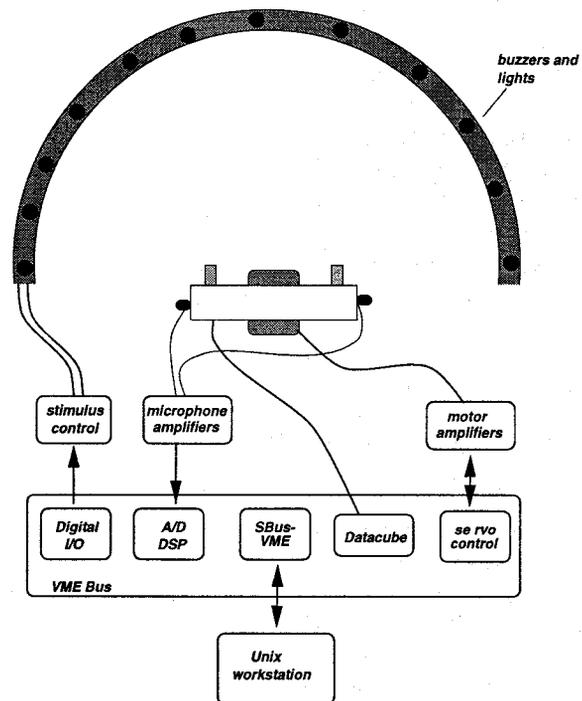


Fig. 2. System architecture controlled by the model. Cameras were moved by a TRC robotic head. Visual signals from one of the two cameras were acquired and processed by a Datacube MV200 board. Real time processing consisted in a thresholding and evaluation of the centroid of the image. Auditory signals were acquired by two microphones located at the opposite extremes of the head, and they were digitized by synchronized A/D channels. ITD values were estimated in real-time by a DSP board. An array of 15 buzzers and LEDs, controlled by a digital I/O board on the VME bus, was used for training and testing the system.

tration between auditory and visual maps in the *OT* of the barn owl during normal visual experience, after the retinal image was shifted through prismatic goggles, and after the reestablishment of normal visual input. These simulations have also illustrated the robustness of the model with respect to noise in the sensory inputs and in the activation of the units, and its stability over a wide range of parameters.

The performance of the model in the control of a real-world system was evaluated by means of the experimental setup illustrated in Fig. 2. The programs which implemented the neural model were executed on a fast Unix workstation connected via an SBus/VMEBus converter to a VME system. The pan axis of a robotic head was used for orienting toward different locations. Visual and/or auditory data were processed in real-time by dedicated boards on the VME bus, which extracted the visual location of the source and estimated the ITD, respectively. Visual and audio-visual stimuli were provided by activating one of 15 buzzers and LEDs located on a frame in front of the system. The activation of the stimuli was controlled by the workstation via a digital I/O board.

Before the exposure to sensorimotor experience some degree of orientation towards auditory stimuli occurred in the model purely because of the initial pattern of projections from *ICc* to *ICx* and in *OT*. The mean of the

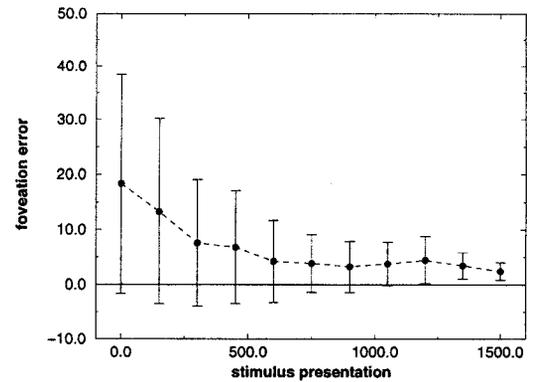
magnitude of the foveation error for all the locations was  $18.3^\circ \pm 20.1^\circ$ . The foveation error was roughly centered around zero, so that, on average, the system oriented toward the correct location in space. Without sensorimotor experience, auditory and visual receptive fields for the bimodal units of *OT* were not in strict register, and the mean absolute value of the distance between visual and auditory receptive fields was  $13.9^\circ \pm 15.1^\circ$ .

Sensory experience shaped the patterns of connections in the model by strengthening selected synapses. Due to the learning rule adopted, only those synapses that were active during successful saccades (those which brought the stimulus on the fovea) were strengthened; all others (weak pre- and/or post-synaptic activation or unsuccessful saccades) underwent depression. During saccades toward visual stimuli, learning occurred mainly at the level of the *OT*. Both *OT* and *ICx* were affected during movement in responses to audio-visual stimuli. As a result, each *ICx* unit connected strongly with all the *ICc* units that were sensitive to the particular ITD corresponding to the same location in space, independent of the frequency. The system was able to adapt whether it experienced a normal or a translated visual input.

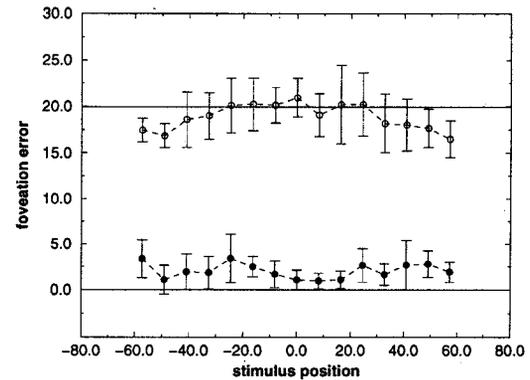
Fig. 3 (a) shows the behavioral changes occurring in the system with sensorimotor experience. After the presentation of 1500 stimuli, the mean magnitude of the foveation error for all the spatial locations is plotted at several stages of learning. In this case, the system was exposed to a visual field displaced by  $20^\circ$  to the left. At the end of the training session, the mean foveation error for saccades toward auditory stimuli was  $2.4^\circ \pm 1.6^\circ$  and the mean orientation error was  $18.9^\circ \pm 2.5^\circ$ , that is, the system aimed to the side of the stimulus by an amount equal to the visual displacement.

In order to test the capability of the model to recover from the previous exposure to a distorted visual world, we removed the visual shift in a well adapted system. Fig. 3(b) shows the change in the orientation behavior with experience (filled circles) with respect to the situation immediately after the removal of the visual shift (empty circles). At the beginning, when the model experienced a normal visual field for the first time, a systematic error was present in the saccades toward auditory stimuli. With sensorimotor experience, this error was corrected so that a mean value equal to  $2.1^\circ \pm 1.6^\circ$  was reached after 1000 saccades.

The recovery of good orientation accuracy was a consequence of the reacquired alignment of the visual and auditory receptive fields for the units in *OT*. Immediately after removal of the goggles, a gap equal to the displacement of the shift was introduced among visual and auditory receptive fields, since the visual location was translated, while the auditory location was unaffected by the shift (mean misalignment  $19.3^\circ \pm 1.2^\circ$ ). After the execution of 1000 saccades, visual and auditory receptive fields were in good alignment (mean misalignment  $1.1^\circ \pm 0.5^\circ$ ).



(a)



(b)

Fig. 3. System performance with sensorimotor experience. (a) Improvement in the accuracy of orienting behavior with learning. The foveation error is the distance of the projection of the target on the retina from the fovea, measured after the execution of the movement. The visual field was chronically translated by  $20^\circ$  to the left. The system adapted by aiming to the side of the target by an amount equal to the visual displacement. (b) Recovery of performance after the removal of the visual shift. The empty dots show the absolute value of the foveation errors for saccades toward auditory stimuli measured immediately after the removal of the visual shift. The filled dots show the errors for saccades toward auditory stimuli in the same spatial locations, after learning has occurred. The data refer to a system composed of  $100 \times 300$  units in *ICc* and 100 units in each of the other maps. During training, single visual or audio-visual stimuli were applied in random positions and they were removed after the execution of the first saccade.

## V. DISCUSSION

Robustness is a crucial issue in the design of autonomous systems. Environmental conditions change continuously due to a number of unpredictable factors, as do the characteristics of sensors and motors. In order to maintain good performance in the presence of such changes, robust autonomous systems need to continuously accommodate their behavior to the current operative conditions.

Biological systems show clear examples of such capability of adaptation. Individuals of the same animal species present significant variations in their phenotypic appear-

ance and their bodies undergo dramatic changes during their lives. Nevertheless, their brains are able to constantly tune motor output so as to ensure proper behaviors.

The understanding of the principles which underly the high degree of flexibility of nervous systems may provide new insights for the design of more robust automata. It is important to investigate biological systems at different levels, so as to understand how neural events are linked to behavior and perception. Only in this way can truly global theories emerge.

As an example of such an approach, in this paper we have investigated how it is possible to adaptively orient toward visual and auditory sources despite major phenotypic changes. Auditory localization requires the extraction of spatial cues from the incoming signals, before producing corresponding activation of the motor system. Since these auditory cues change drastically with the size and shape of the system, and with the characteristics of the microphones, it is difficult to establish the correct correspondences *a priori*. On the contrary, such sensorimotor transformation needs to be tuned on the basis of experience.

The neural structures involved in the process of calibrating auditory localization have been carefully characterized in the barn owl, a nocturnal predator which relies on audition for its own survival. We have shown that physiological data are well explained in the context of value-dependent learning [20], a paradigm which proposes that a signal related to the saliency of sensorimotor events is broadcast to multiple part of the brain where it modulates synaptic plasticity [5], [6]. In this paper we have shown that the application of this biological model to the control of a robotic system produces accurate sound localization both in the presence of normal and altered visual conditions and it is able to recover from sudden changes in the sensory inputs.

Recently, neuroscientists have turned their attentions toward the use of robotic systems as a way to quantitatively test and analyze theories which would otherwise remain at a speculative stage. These efforts can establish a direct link between natural and artificial sciences and offer new ideas to Robotics and Artificial Intelligence. It is our opinion that comprehension of the fundamental functional principles of the brain will dramatically affect the design of real-world automata.

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