Adaptation of orienting behavior: from the barn owl to a robotic system

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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

In order to cope with the variability of the world, autonomous systems should be able to constantly tune their motor output to the current operating conditions. Nature, in the course of evolution, has faced this very problem. Biological systems are highly flexible in the face of variable phenotypic and environmental conditions. The understanding of the basic principles of such adaptability can lead to new insights in the design of more robust and efficient systems.

In the last two decades, the adaptation of orienting behavior has been carefully investigated in the barn owl. The barn owl is a nocturnal predator with highly accurate visual and auditory localization. Since the correspondence between orienting movements and sensory inputs strongly depends on the sensorimotor characteristics of the individual, orienting behavior needs to be continuously adjusted by the brain. Manipulations of the sensory inputs have shown that the barn owl is able to adapt to drastic perceptual changes [1].

The optic tectum (OT) is a brain structure well known to be involved in the production of orienting behavior. Neighboring OT neurons are activated by stimuli in multiple sensory modalities originating from similar spatial locations, so as to create aligned neural maps of extra-personal space in the different modalities. These sensory maps of space are also aligned with a motor map in which the activation of neurons elicit movements of the head toward different locations. Such a registration among sensory and motor maps implements an economical scheme in which different modalities access a common motor output. In the barn owl it has been shown that behavioral adaptation has a physiological correlate in the reestabilishment of alignment among sensory and motor maps of space in the OT.

By simulating in a computer model part of the sensory and motor pathways to and from the OT, we have recently proposed 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* [2]. 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 the synaptic changes underlying neural plasticity. This hypothesis relies on a large body of biological evidence. Here we consider the application of this model to the control of a robotic head, in the presence of both auditory and visual stimulation. We show that the model produces accurate and robust orienting behavior, and quickly recovers good performance after alterations of sensory or motor conditions.

II. MODELING THE BARN OWL NERVOUS SYSTEM

Following the known anatomy and physiology of the barn owl, we have modeled the visual and auditory pathways dedicated to localization of the azimuth (see Fig. 1). Cells were modeled as leaky integrators with a superimposed noise term. Since only the localization of the azimuth was considered, all the modeled maps of space were unidimensional arrays.

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 a simulated retinal map by means of a set of topographically organized connections (adjacent receptors of the retina are

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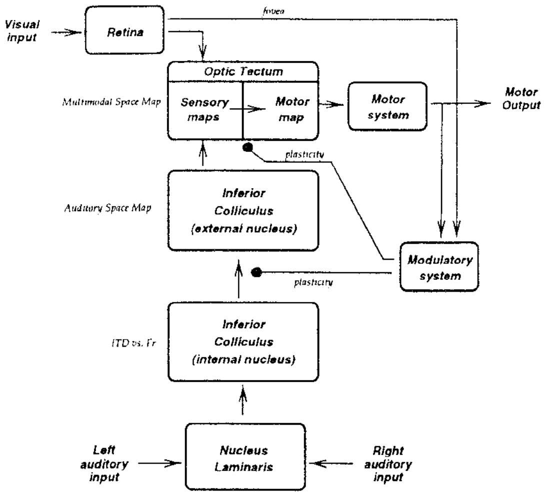

Fig. 1. Neural stages involved in the process of azimuth localization in the barn owl which were included in the model: the auditory and the visual pathways converge at the level of the tectum where they create sensory maps of the surrounding space, and project to the motor system. The modulatory system replicates the presumed role of subcortical modulatory centers with diffuse projections. It is activated for foveation and motor events and regulate the changes in the strengths of the connections. Under the action of the modulatory system, the neural circuits which lead to correct movements are selected by increasing the weights of their connections, whereas the connections within the pathways which did not lead to foveation events are decreased.

connected to adjacent areas of the OT). They also received topographically organized connections from the auditory pathway and projected to the motor units.

It has been shown that the barn owl uses differences in the time of arrival of the sounds at the two ears (interaural time differences (ITDs)) for estimating the azimuth of a sound source. Starting from the cochlea, a dedicated neural pathway processes ITDs. In the model, the activation of units in the first binaural nucleus in the ITD pathway, the nucleus laminaris (NL), was designed so as to fit as closely as possible the physiological data. Unit activation was a function of the amplitudes and phases of the Fourier transforms of the two input auditory signals. It was characterized by a narrow frequency range and showed a periodicity with respect to ITD. Following the anatomical organization of the NL, as revealed by electrophysiological recordings, NL units were arranged such that their sensitivities to frequency and ITD were aligned along perpendicular directions. As a result, the modeled NL can be seen as a bidimensional array, where each unit is identified by a characteristic value of frequency and ITD. NL units projected topographically to the units in the central nucleus of the inferior colliculus (ICc). In the ICc short-range excitation and longer range inhibition contributed to sharpen the selectivity of the units. ICc units projected to the external nucleus of the inferior colliculus (ICx). As in the ICc, the modeled 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 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 motoneurons 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 peak of activation in OT.

Random initial connectivity was assumed both at the level of the ICx and between sensory and motor maps in the OT. This assumption reflected the experimental evidence that these two sites undergo drastic plastic changes during development and adaptation. According to the proposed learning scheme, synaptic modifications at these sites were mediated by the activation of a modulatory system, which 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 modulatory system consisted of a single unit, which received afferents from both the fovea and the motoneurons. In this way, the modulatory unit was active when a stimulus was in the center of the visual field or when movement was executed, and was highly active when these two events occurred almost simultaneously. At each time step of the simulations, the strength of the connection ω_{ik} between unit i and unit k was modified as a function Φ_L of the activity of the pre- and post-synaptic elements and of the modulatory term V, such that $\Delta\omega_{ik} = \Phi_L(\epsilon_1 U_i U_k + \epsilon_2 V)$. The first term is the usual Hebbian local factor which is different for different connections; the second term is a global factor shared by all the plastic synapses. Φ_L was designed such that the connection weights among highly correlated units could be decreased or increased depending on the level of activity of the modulatory system. Potentiation typically occurred for units whose activations were correlated when the activation of the modulatory system was high. This happened after a successful saccade, which brought the stimulus onto the fovea. By contrast, when the modulatory system was not strongly activated, such as when the system moved but did not localize the target, highly correlated units were mostly depressed.

III. RESULTS

The model was tested both by means of computer simulations [2] and experiments with a robotic system. In the real-world experiments, the programs which implemented the neural model were executed on a Unix workstation connected to a VME system. The pan axis of a robotic head was used for orienting toward different locations. Visual

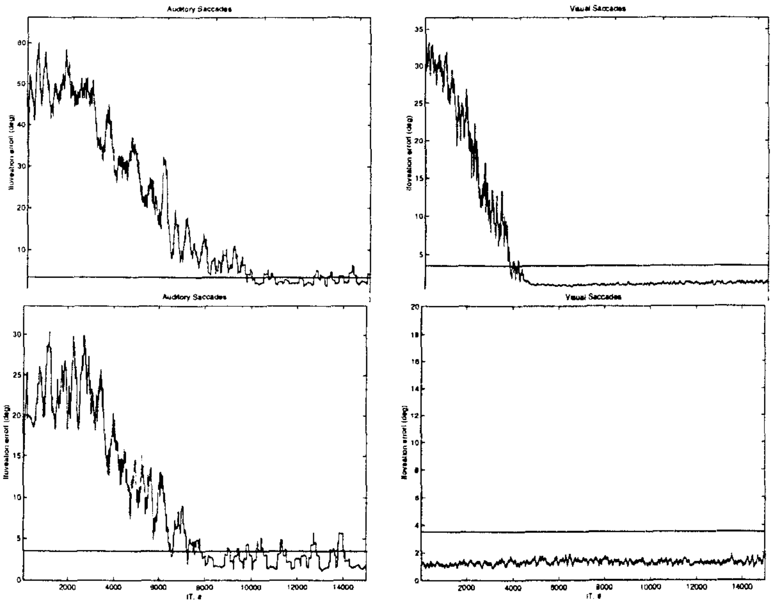

Fig. 2. Improvement of system performance with sensorimotor experience. The foveation error is the distance of the projection of the target on the retina from the fovea, measured after execution of a movement. (*Top*) Learning with normal sensorimotor experience: both the accuracy of saccades toward auditory (*left*) and visual (*right*) targets are shown. (*Bottom*) Adaptation to a translation of the visual field by 20^o to the left. The system adapted by aiming to the side of the target by an amount equal to the visual displacement. Note that, similarly to the barn owl, the system is immediately able to localize visual targets, but needs to readapt the audiomotor coordination. The data refer to a system composed of 100 x 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.

signals were acquired by a camera at the center of the pan axis. Two microphones, one at each side of the camera, acquired the auditory signals. Sensory data were processed in real-time by dedicated boards on the VME bus, which extracted the visual location of the source and estimated the Fourier transforms of the signals. Visual and auditory stimuli were provided by activating one of 15 loudspeakers and lights located on a frame in front of the system.

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. Good performance was usually achieved after the presentation of few thousand stimuli (the equivalent of few hours of learning) independent of the actual positions of the camera and microphones. The final level of accuracy and the speed of learning were a function of the number of units and parameters of the model (an example is shown on the top of Fig. 2). The capability of the system to recover from changes in its characteristics, was tested by manipulating sensory inputs and motor outputs in several ways. In particular, experiments of translation of the visual field have demonstrated the ability of the proposed learning scheme to adapt to drastic alteration of the sensory conditions. In these experiments, which replicated the chronic insertion of prismatic goggles on the eyes of the barn owl, the input image was systematically shifted by 20^0 after good behavioral performance had already been reached. As occurs in the barn owl, the system adjusted the orienting behavior so as to look at the side of the target by an amount which compensated for the visual shift. An example of recovery of good performance is shown on the bottom part of Fig. 2.

Overall, these experiments have shown that the model can account for continuous adjustment of orienting behavior in the presence of severe changes in the sensory and motor conditions. In addition, computer simulations have illustrated the robustness of the model with respect to noise in the sensory inputs, and its stability over a wide range of parameters.

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