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The Generation and Subtraction of Sensory Expectations within Cerebellum-Like Structures

Abstract

The generation of expectations about sensory input and the subtraction of such expectations from actual input appear to be important features of sensory processing. This paper describes the generation of sensory expectations within cerebellum-like structures of four distinct groups of fishes: Mormyridae; Rajidae; Scorpaenidae; and Aptereronotidae. These structures consist of a sheet-like array of principal cells. Apical dendrites of the principal cells extend out into a molecular layer where they are contacted by parallel fibers. The basilar regions of the arrays receive primary afferent input from octavolateral endorgans, i.e., electroreceptors, mechanical lateral line neuromasts, or eighth nerve endorgans. The parallel fibers in the molecular layer convey various types of information, including corollary discharge signals associated with motor commands, sensory information from other modalities such as proprioception, and descending input from higher stages of the sensory modality that is processed by the structure. Associations between the signals conveyed by the parallel fibers and particular patterns of sensory input to the basal layers lead to the generation of a negative image of expected sensory input within the principal cell array. Addition of this negative image to actual sensory input results in the subtraction of expected from actual input, allowing the unexpected or novel input to stand out more clearly. Intracellular recording indicates that the negative image is probably generated by means of anti-Hebbian synaptic plasticity at the parallel fiber to principal cell synapse. The results are remarkably similar in the different fishes and may generalize to cerebellum-like structures in other sensory systems and taxa.

Key Words

Expectation
Cerebellum
Plasticity
Octavolateral
Fish
Teleosts
Elasmobranchs
Long-term depression

Introduction

Many aspects of sensory processing may be understood as the generation of expectations or predictions about sensory input and the removal of such expectations from the current sensory inflow [Bullock, 1988; Barlow, 1990]. Removing what is expected allows the unexpected or novel sensory input to stand out more clearly, and it is this novel

input that conveys new information and is critical for the animal's survival. This review describes the generation of expectations in different cerebellum-like structures of fish and places this work in the context of general issues in sensory processing.

In an information-theoretic sense, the amount of information in a signal is reduced in proportion to its predictability and a completely predictable signal conveys no

(*Apteronotus leptorhynchus*). The next section of this review describes the anatomy of different cerebellum-like structures associated with octavolateral endorgans. Subsequent sections describe the expectation-like phenomena that are observed in the four different fish systems. The two final sections present an overview of the different fish systems and speculate on the significance of the findings for other structures with similar histology including the cerebellum itself.

Cerebellum-Like Structures Associated with Octavolateral Sensory Systems

Cerebellum-like structures that receive primary afferents from octavolateral endorgans are found in the medullae of fish, amphibians and mammals (fig. 1; Montgomery et al. [1995]). These structures include the dorsal cochlear nucleus (DCN) of mammals which receives primary afferents from the cochlea, the dorsal octavolateral nucleus (DON) of many nonteleost fishes and some amphibians which receives primary afferents from electroreceptors, the electrosensory lateral line lobe (ELL) of electroreceptive teleosts which also receives primary afferents from electroreceptors, and the medial octavolateral nucleus (MON) in most fishes and some amphibians which receives primary afferents from mechanical lateral line endorgans and in some cases from eighth nerve endorgans. Only a brief summary is given here. The paper by Montgomery et al. [1995] should be consulted for a more complete description of the histology and connectivity of these different structures and for additional references.

The cerebellum-like structures are composed of a sheet-like array of principal cells in which the primary afferent input maps onto the basilar regions of the array (fig. 2). The mapping of electroreceptor input to DON and ELL is somatotopically organized: the mapping of auditory input onto DCN is tonotopic. In the ELL of teleost fishes, the receptive field centers of some principal cells are excited by the same stimuli that excite afferents (E-cells), whereas the receptive field centers of other principal cells are inhibited by such stimuli (I-cells; Bastian [1981], Bell and Grant [1992], McCreery [1977]). In gymnotid fishes, the E-cells have been shown to be contacted directly by the afferents and I-cells to be affected indirectly via inhibitory interneurons [Saunders and Bastian, 1984]. The E- and I-cells have been identified so far only in the ELL of teleosts and may not exist in other cerebellum-like octavolateral structures.

Axons of projection neurons in these structures convey the output to higher, mesencephalic stages of processing.

Most if not all principal cells are projection neurons in the DON of elasmobranchs and the ELL of gymnotid fishes. In the ELL of mormyrids, however, most of the principal cells are inhibitory neurons that terminate locally on those principal cells that are projection neurons [Meek, 1993]. The ELL of mormyrids is similar in this respect to the histological pattern of the cerebellum of teleosts where Purkinje cells terminate locally within the cortex on projection neurons known as eurydendroid cells [Nieuwenhuys et al., 1974; Meek and Nieuwenhuys, 1991; Mugnaini and Maler, 1993].

The apical dendrites of the principal cells are densely covered with spines and extend into the overlying molecular layer where the spines are contacted by parallel fibers. In fishes and amphibians, the parallel fibers arise from the granule cells of an external granule cell mass that is generally known as the eminentia granularis (EG), although in elasmobranch fishes the terms dorsal granular ridge (DGR) and lateral granular area (LG) have been given to the granule cell populations supplying parallel fibers to the DON and MON, respectively. In the DCN, the parallel fibers arise from granule cells that are located both below and at the edges of the principal cell array. Stellate-like inhibitory interneurons are also present in the molecular layer of all of these structures as shown in figure 2. Additional inhibitory interneurons are present in the deeper layers which influence the center-surround structure of receptive fields and the temporal pattern of sensory responses in principal cells. Other interneurons mediate commissural inhibition of the contralateral side [Bastian et al., 1993; New and Bodznick, 1990].

The granule cell masses that give rise to the parallel fibers receive their inputs from a rich variety of sources: (1) descending input from higher stages of the modality being processed; (2) input from other sensory modalities, such as proprioception, and (3) corollary discharge signals associated with motor commands. These inputs have been identified by both anatomical and physiological means. The EG of mormyrids and the DGR of elasmobranchs have been shown to receive all three types of input, and the EG of gymnotids has been shown to receive both descending electrosensory and proprioceptive input. The different inputs to the granule cells are labeled as 'Predictive Inputs' in figure 2. Note that these inputs include all three sources of information that were referred to in the Introduction as potentially associated with current sensory input and thus potentially capable of predicting it.

The general hypothesis regarding these various structures is that the occurrence of a temporal association between parallel fiber inputs and sensory input to the deeper

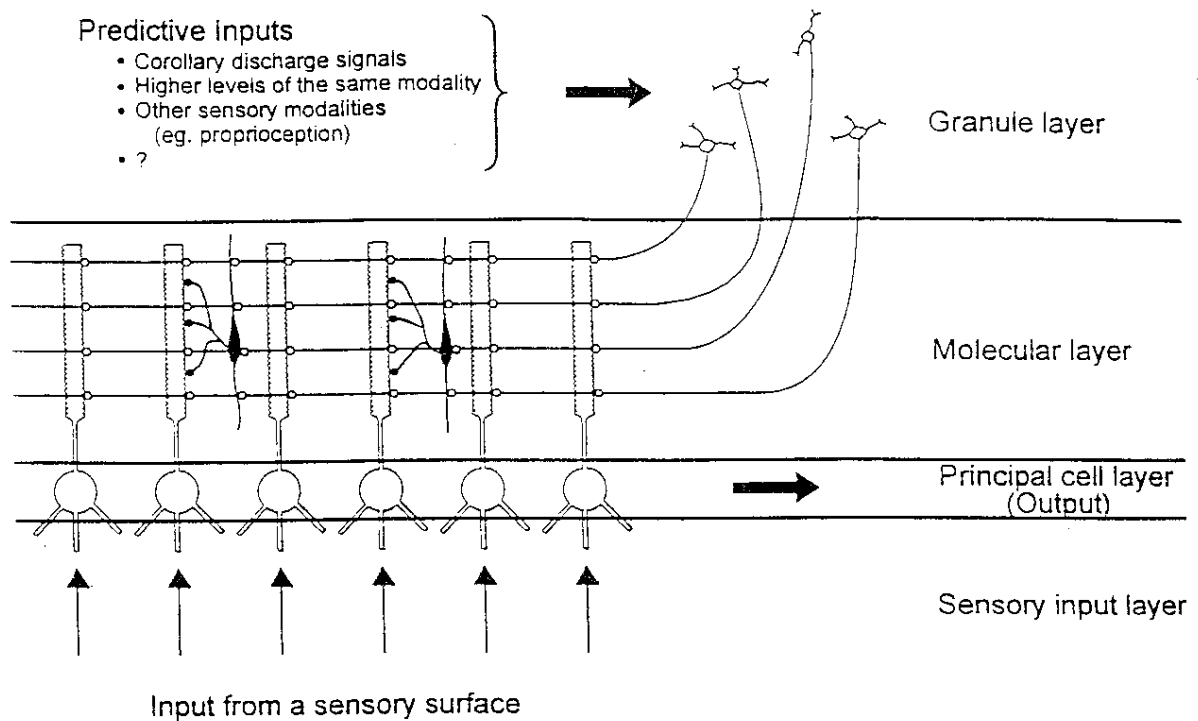


Fig. 2. Schematic drawing showing major features of cerebellum-like octavolateral structures. Inhibitory stellate cells of the molecular layer are shown in black. See text and Montgomery et al. [1995] for additional information.

fiber inputs. Addition of the negative image of expected input with the current input results in the continuous subtraction of expected from current input. Evidence for such a process in the different fish systems is presented in the following sections.

* Mormyrid Electrosensory Lobe

Evidence for the generation of a negative image of expected input was first obtained in the ELL of mormyrid electric fish [Bell, 1982]. Corollary discharge signals associated with the motor command that elicits the electric organ discharge (EOD) are prominent in the mormyrid ELL and have strong effects on the processing of reafferent sensory input that is evoked by the EOD. Experiments are done in curarized fish in which the normal EOD is blocked but in which the EOD motor command continues to be emitted ('fictive discharging') and in which the electrosensory input is controlled by the experimenter.

Some of the corollary discharge effects are fixed and do not change during many hours of recording in spite of long periods of association with sensory stimuli. These fixed effects are inhibitory for one class of electroreceptor afferents where they provide an example of the generation and subtraction of a hard-wired motor command-driven expectation about sensory input [Bell and Grant, 1989]. A hard-wired inhibitory process is effective here because the reafferent response for this class of electroreceptors is very brief and does not vary.

Other effects of the corollary discharge are plastic, however, and are strongly affected by the pattern of reafferent electrosensory input that has followed EOD motor commands in the recent past [Bell, 1982]. Pairing an excitatory sensory stimulus with the EOD command for a few minutes leads to an inhibitory corollary discharge effect at the same latency as the paired excitatory sensory stimulus. Pairing with an inhibitory sensory stimulus leads to an excitatory corollary discharge effect (fig. 3). The altered corollary discharge effects are observed by simply turning off

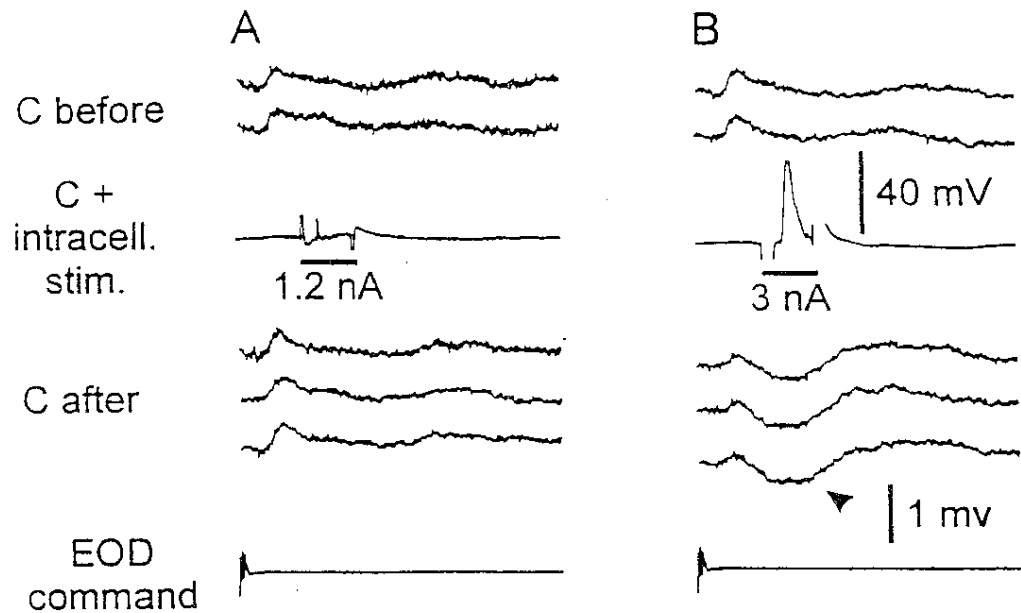


Fig. 4. Principal cell in mormyrid ELL showing plasticity in response to corollary discharge of EOD motor command due to pairing with an intracellular current pulse. All traces are triggered by the EOD motor command as indicated in the bottom trace of each column. High gain traces before (C before) and after (C after) pairing are averages of 15 sweeps taken at 15 second intervals. A single sweep at low gain shows the effect of the intracellular current pulses during pairing. **A** Effect of pairing with a low intensity current pulse that evokes only a small narrow spike (probably a somatic or axonal spike). Pairing has little effect on the response to the EOD motor command. **B** Effect of pairing with a stronger current pulse that evokes a large broad spike (probably a dendritic spike). Pairing now leads to the development of a hyperpolarizing response to the command that is centered on the time of the previously paired broad spike [from Bell et al., 1993].

et al., 1992; New and Bodznick, 1990], but the principal cells of the DON, on which the primary afferents terminate, are either unaffected or only weakly modulated during respiration. How is this possible? The absence of responsiveness in principal cells to respiratory movements was initially thought to be due entirely to a common mode rejection mechanism [Montgomery, 1984; New and Bodznick, 1990; Bodznick et al., 1992]. The receptive fields of principal cells include both an excitatory and an inhibitory region. Afferents from each of these regions are modulated by respiration. If excitation and inhibition are balanced, then the cell as a whole would be only minimally affected by respiration. This mechanism certainly contributes to the unresponsiveness of principal cells and provides another example of a hard-wired mechanism for removing a highly predictable and unwanted reafferent input.

Recent work has shown, however, that an adaptive memory-based mechanism also makes an important contribution to the reduction in reafferent responses of principal

cells [Bodznick, 1993; Montgomery and Bodznick, 1994]. The experiments were done by recording from a principal cell in DON and giving an extra electrosensory stimulus at a fixed phase of the respiratory cycle (fig. 5). The response to this extra excitatory sensory stimulus is progressively reduced over several minutes. When the stimulus is turned off after several minutes of pairing, a pause is present at the same phase of the respiratory rhythm as the previously paired excitation. Similarly, pairing with an inhibitory stimulus leads to a progressive decline in the inhibition, and turning off the stimulus reveals a burst at the time of the previously paired inhibition. Control experiments show that in most cases there is no decline to repeated stimuli in the absence of an association to the respiratory rhythm. Thus, in elasmobranchs as in mormyrids, a highly specific negative image of expected reafferent input has been generated and added to the actual input.

Granule cells of the DGR give rise to the parallel fibers and are known to receive three types of information which

a proprioceptive stimulus affected only a small proportion of principal cells, whereas the pairing with the self-generated respiratory movements resulted in a diminished response in the majority of principal cells.

Pairing a local electrosensory stimulus with a large field electrosensory stimulus that affected the whole body or with the isolated respiratory motor commands (recorded as motoneuron activity from the facial nerve of a curarized fish) were less effective than pairing with proprioceptive stimuli. Some cells appeared to be marginally affected by pairing with the whole field electrosensory stimulus but no cells were observed to change as a result of pairing with the respiratory corollary discharge signals alone.

The pairing with separate components among the set of signals present during normal respiration was clearly less effective in these fish than pairing with normal respiration itself. The methods chosen to test the individual components may not have been adequate, but it is also possible that the strongest effects in these fish are obtained only when all the available predictive signals occur together.

Medial Octavolateral Nucleus of the Scorpion Fish

Results have been obtained in the mechanical lateral line system and MON of these marine teleosts that are very similar to the results in elasmobranchs. Water flow caused by the fish's own respiration has a strong effect on primary mechanical lateral line afferents, but the principal cells that receive this input appear to be much less modulated by the respiratory rhythm. An adaptive memory-like process appears once again to be an important part of the explanation. This was shown by giving an additional stimulus to the mechanical lateral line receptors at a fixed phase of the respiratory rhythm [Montgomery and Bodznick, 1994]. The response to the additional stimulus decreased over several minutes of associated repetition, and a pause in the firing of the principal cell was observed after turning off the extra stimulus. The pause occurred at the same delay as the previously paired stimulus. Thus, in this system also, a negative image develops that opposes the predictable aspects of the mechanical lateral line input.

The Gymnotid Electrosensory Lobe

Mormyrid and gymnotid fishes are well separated phylogenetically and are believed to have evolved their electrosensory systems independently [Bullock et al., 1983]. It

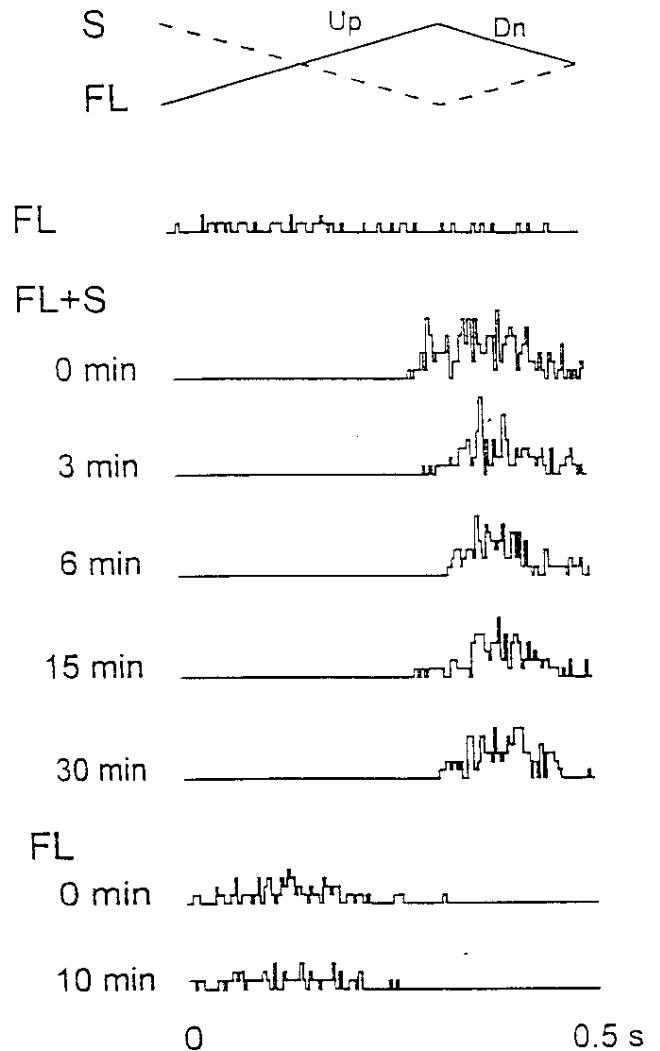
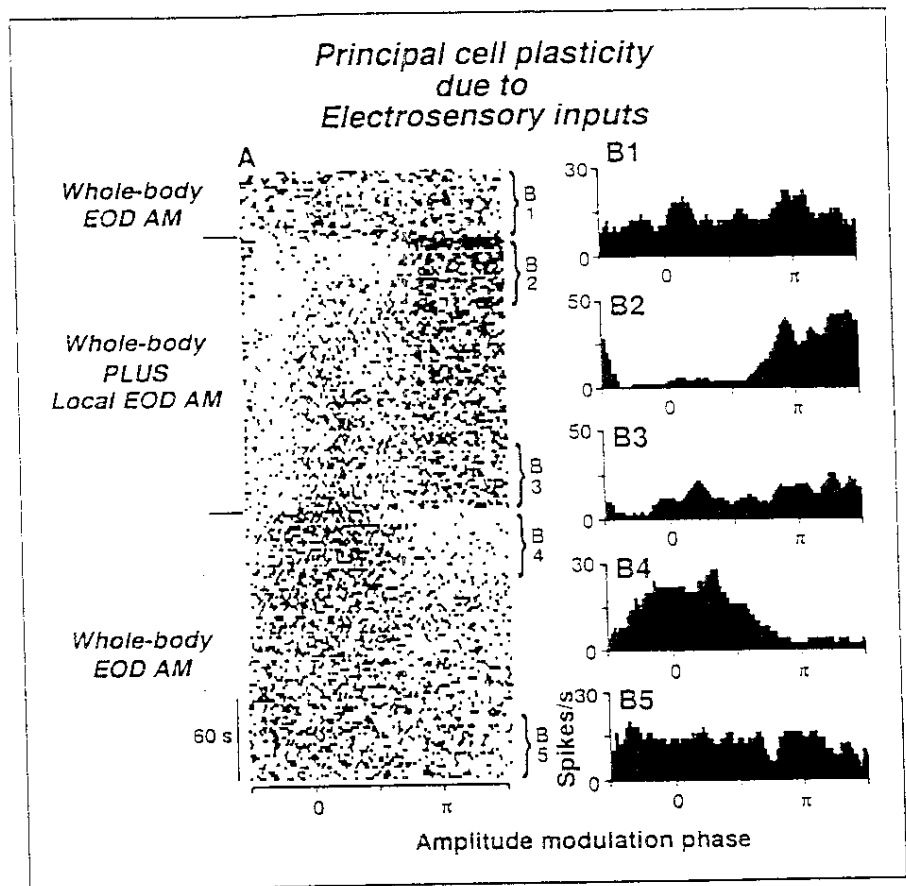


Fig. 6. Principal cell in a skate dorsal nucleus showing plasticity in the response to a proprioceptive stimulus due to pairing with an electrosensory stimulus. Histograms indicate the cell's activity during a cycle of passive lift to the ipsilateral pectoral fin (illustrated with a solid line labeled 'FL' at the top). Initially there is little response to the fin lift alone as indicated by the top histogram labeled 'FL'. A local electrosensory stimulus was then paired with the fin lift (histograms labeled 'FL+S'). The electrosensory stimulus was an amplitude modulated triangle wave which went from $+1.5 \mu\text{V}$ to $-1.5 \mu\text{V}$ with a time course that matched that used for the fin displacements. The records were taken in the order in which they are presented. Note that coupling of the local electrosensory stimulus with fin movements leads to a gradual decline in the response to the stimulus. This is due to the development of a response to the fin lift alone which is opposite to the effect of the stimulus, as seen in the two bottom histograms showing the responses to fin lift alone after the pairing [from D. Bodznick, J. Montgomery and A. Pachynski, unpubl. observ.].

Fig. 7. Principal cell in a gymnotid ELL showing plasticity in response to a whole body transverse electrosensory stimulus due to pairing with a local electrosensory stimulus. Both the whole body and local electrosensory stimuli were amplitude modulations (AM) of the fish's own EOD [see Bastian, 1995, for methods]. **A** Raster display of responses to a 0.4 Hz AM signal applied to the whole body ('Whole-body EOD AM') before and after the pairing of this whole body stimulus with a synchronous local stimulus ('Whole-body plus local EOD AM'). Note the decline in the response to whole body plus local stimulus during the pairing and the development of a response to the whole body stimulus as a result of the pairing. The vertical bar at the lower left of the rasters shows the vertical time scale. **B1–B5.** Period histograms taken from the same data as the raster display at the epochs indicated by the labeled brackets in **A** [from Bastian, 1995].



is therefore of special interest that adaptive memory-like processes are also found in the ELL of gymnotid electric fishes [Bastian, 1995].

Active or passive bending of the body or tail in an electric fish alters the spatial relation between the electric organ and electroreceptors in the skin. Both theoretical [Heiligenberg, 1975] and experimental [Bastian, 1995] work shows that such bending will alter the electric organ-induced input to electroreceptors. Bastian has examined the responses of primary afferents from electroreceptors and principal cells of ELL to passive tail bending in a discharging fish of the species *Apteronotus leptorhynchus*. The primary afferents respond the same to tail bending and to an electrosensory stimulus that mimics the effect of the tail bending on EOD induced current at the receptor. In contrast, the principal cells of ELL respond poorly to tail bending but respond quite well to the pure electrosensory stimulus.

The difference between primary afferent and principal cell responses to tail bending is again due to an adaptive memory-like process in the ELL. Pairing excitatory elec-

troensory stimuli to the receptive field of the principal cell at a fixed phase of tail movement results in a decline of the response to the stimulus during several minutes of pairing. Turning off the stimulus reveals an inhibition at the time of the previously paired excitation. Pairing with inhibitory stimuli has the opposite effects. The effects are temporally specific to the phase of bending at which the stimulus is given. Repeated tail bending alone or repeated presentation of the electrosensory stimulus alone are ineffective. Thus, in gymnotid fishes, as in the other systems, a highly specific negative image of expected input can be generated and added to the actual sensory input.

At least two types of predictive signals are available for generating the expectation about sensory input during passive tail bending: proprioceptive and electrosensory signals. Proprioceptive inputs from muscles and tendons are activated by bending, and fibers conveying proprioceptive information terminate on granule cells of Egp. Electroensory signals are also available because bending the tail will alter the pattern of electroensory input over the whole