Chapter 1
Introduction to Efferent Systems

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1.1 Introduction and Overview

Organisms must learn what representations in the world are important – that is, which sights, smells, and sounds indicate safety, food, or danger. Knowledge of what is and is not important is acquired by information arising from the sensory organs, and this knowledge is then acted upon by the motor system, expressed by approach or avoidance behavior. A loud "Hey you!" will evoke a strikingly different motor and autonomic response compared to that of a sultry "Hello, handsome." Likewise, a patron can ignore the sounds inside a busy restaurant but not when his name is being called. Stimuli that have no immediate significance become relegated to "background noise" and can be disregarded. During our lifetimes, we learn about stimuli and stimulus context. The sound and sight of gunshots in the street are generally different from those experienced in a movie theater. Stimulus content and context are presumably processed in the cerebral hemispheres, where significance is established.

Historically, sensory information had been thought to access the cerebral hemispheres by ascending the neuraxis via successive links to reach the forebrain where a hypothetical "central processor" resided. Implicit in this conceptualization was the notion that subsequent to cortical processing, descending motor signals were generated to produce a response. The discovery that the central nervous system (CNS) initiated neuronal projections that terminated upon auditory receptors (Rasmussen 1946, 1953) and muscle spindles (Hagbarth and Kerr 1954) contributed to a revolution of thought, which introduced the idea that the brain could control or at least modulate signals arising *from* a sense organ (Granit 1955;

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Galambos 1956). These new data challenged classical thinking that sensory pathways conveyed information about the external world without modification. Instead, there were indications that sensory information might be modified at multiple levels of the nervous system, and these data ignited the concept of central control of sensory input (Galambos 1956). In short, the process of "priority setting" could be initiated at potentially every synaptic station along the ascending sensory pathways by feedback circuits.

As an outgrowth of this new approach to sensory processing, Rasmussen (1953) introduced a more expansive use of the term "efferent" to describe the centrifugal pathway to the inner ear. Until this time, the term "efferent systems" applied to motoneurons that carried nerve impulses away from the CNS to act on glands, organs, or muscles. These efferent motoneurons represented the final common pathway to target structures in the periphery that initiated autonomic (e.g., change in pupillary tension, heart rate, or glandular secretion) and/or voluntary (e.g., skeletal muscle contractions) responses. Rasmussen extended the definition of the term "efferent" to include his sensory pathway that conducted impulses away from the CNS to a sensory organ in a manner analogous to motoneuron projections to skeletal muscle. Thus, the term "sensory efferent" was born.

This more inclusive approach to sensory processing begged the question: Why would a sensory system have descending circuits? One answer was that it needed to influence the information that was ascending (Granit 1955; Galambos 1956). In this case, modulation might consist of feedback enhancement or suppression of ascending information. For example, binaural hearing refers to the auditory processing involved in the comparison of sounds received by one ear to the sounds received by the other ear. The interaction between these sounds provides important spatial cues for determining the direction and the distance of sound sources. Interaural time and intensity differences plus head-related transfer functions are the dominant cues for identifying the location of a sound source within three-dimensional auditory space (Popper and Fay 2005). Essential to this process is the assumption that the binaural system is functionally and structurally symmetrical such that sensitivity, rate of response, numbers of neurons, and magnitude of response from each ear are equal for equal stimulation. Biological systems, however, only approximate symmetry. One role of descending systems could be to equilibrate the response of each ear with respect to the midline. Another might be to balance the sensitivity of each ear (Cullen and Minor 2002; Darrow et al. 2006). Experience would calibrate the responses of the organism when a sound occurred on the midline. Descending systems might augment a smaller signal or depress a stronger signal to balance the output of a structure pair for midline stimuli. This balancing act would establish a reference from which more lateralized sounds could be compared.

Environmental sounds may be described by their composition of different frequencies. Because sounds of different frequencies can vary systematically across other physical parameters when perturbed (e.g., low frequencies are less disrupted by large objects compared to high frequencies), animals can learn about their auditory environment by using such spectral information. There are spectral cues that are created by the interactions among sound, the head, and the pinnae that are used to resolve front–back locations, to determine sound elevation, and to localize sound using one ear alone. Head and pinnae position, movement of the sound source, and feedback from other sensory detectors (visual, vestibular, and proprioception) also play into perception of space (Oertel and Young 2004). Organisms learn to distinguish between near and distant sounds via cues that include sound clarity, overall sound level, the amount of reverberation relative to the original signal, and timbre. In light of individual differences and asymmetries in head shapes, external ear morphology, and cochleae, the relationship between cue values and sound location is presumed to be learned through experience. Moreover, as the organism's head and body grow with maturation, cue values associated with particular locations in space will change. Sound motion and/or organism motion must also be entered into the equation. The brain must constantly recalibrate its three-dimensional coordinate system to preserve auditory space, and descending feedback circuits could facilitate the constant adjustments.

We listen, detect, localize, identify, and then attend to those sounds we have deemed important. In addition, we can deemphasize elements of our auditory environment if they are routine or uninteresting. Each of these activities is performed across a number of auditory streams, both in parallel and in tandem. At any instant in time, sounds from multiple sources impinge upon our ears, and humans have the ability to separate sound streams from each other. Unique characteristics bind sounds to a common source, such as the intonation of a French horn during a symphonic performance, or a hawk's screech among a cacophony of bird songs. It is the extraction of these characteristics, coupled with learned significance of some sounds over others, that provides certain survival advantages for attending one signal while ignoring others. Mechanisms for these activities, however, remain poorly understood. Complex neural circuits extract learned information from memory in real time to focus and/or switch attention in hearing. For example, we follow a conversation in a noisy restaurant or "eavesdrop" on a different conversation or flip back and forth between the two.

The process of hearing is initiated within a remarkably complex sensory organ, the inner ear (also known as the cochlea). Sensory hair cells reside in the bony cochlea and function to convert environmental sound into neural signals used by the brain, to separate sounds into elemental bands of their constituent frequencies, and to compress the amplitudes of sounds so that it is possible to process the huge range of sound intensities that are encountered during a normal day. It is the feature of "gain control" where soft sounds are amplified and loud sounds are dampened that is so crucial to how we hear. In this case, the term "gain" resembles the volume on stereo amplifiers and iPods. It is the process of selective gain that facilitates the ability to discriminate one sound in the presence of competing sounds.

In the auditory system, central pathways are initiated from the cochlear nucleus and ascend the neuraxis through a series of parallel lines and serial synaptic stations (Fig. 1.1). The processing of sound by the brain starts from the analysis of very basic attributes (Kiang et al. 1965; Evans 1975), and it becomes progressively more complex as one ascends the progressive hierarchy of auditory stations (Tsuchitani 1977;

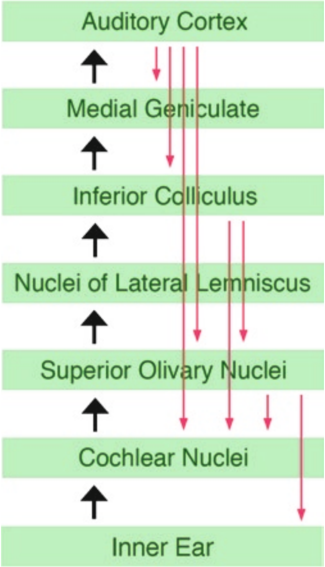

Fig. 1.1 Simplified box diagram of central auditory system. The main components of the system are labeled and begin with the cochlear nuclei. Subdivisions of nuclei are not included. *UP arrows* indicate sequence of progression of ascending auditory information. *Down arrows* indicate the start and termination of descending projections

Aitkin et al. 1984). This linear and sequential processing of auditory information as it ascends toward the cerebral hemispheres has been referred to as a feedforward mechanism (Mackay 1956). The construction of an auditory percept is based on such processing and depends upon prior knowledge and situational context. Feedforward mechanisms alone, however, do not seem adequate for achieving stimulus recognition that is simultaneously invariant and flexible for our rapidly changing environment.

Hearing is a dynamic process. Cognitive functions including attention, memory, and expectation modulate the nature of the sensory information reaching consciousness. The function of any cortical area must be influenced by ongoing perceptual requirements. In this context, there is no starting point for information flow. Streams of information from cortical centers interact with each other and in turn modulate the information ascending from the sensory periphery. Presumably, these descending and lateral feedback circuits enable the rapid discrimination of signals from noise, the sharpening of tuning curves, and the switching of attention. What remains remarkable is that this process is constantly engaged.

Knowledge about how the brain modulates auditory processing has grown significantly over the years. Although most research still tends to focus on the ascending central pathways, it is apparent that a parallel system of descending pathways exists and that it has an important role in hearing (Fig. 1.1). In fact, the descending corticothalamic projections greatly exceed the ascending thalamocortical projections (Jones 2002). Descending systems are found that involve higher control of visceral reflexes (Menétrey and Basbaum 1987; Card et al. 2006), gating of sensory information (Wiederhold and Kiang 1970; Dewson 1967; Sherman and Guillery 2002;

Waleszczyk et al. 2005; Wang and Wall 2005), regulation of postural reflexes (Matesz et al. 2002; Barmack 2003), and modulation of motor behavior (Canedo 1997). It is therefore timely to review what we know about auditory and vestibular efferents, how current research has contributed to our understanding of brain function, and to indicate avenues for future research.

1.2 Overview of the Volume

In the more than 60 years since Rasmussen reported his discovery of efferents, the significance of his work continues to grow. The ten chapters that follow in this volume cover a wide range of topics addressing the biology of auditory and vestibular efferents. Basic research summaries of the anatomy, electrophysiology, and pharmacology segue into cellular and molecular features of the inner ear. Chapters on the development and evolution of efferent systems illuminate key phylogenetic stages and ontogenetic mechanisms that have given rise to present-day efferent systems. The final chapters provide an overview of central efferent anatomy and neuronal responses and plasticity to efferent activation.

The fundamental relationship between structure and function represents a starting point for understanding any biological system. We use anatomical methods to study how systems are constructed, and to infer how interconnected structural components work together. Chapter 2 by Chris Brown exploits this strategy to discuss the anatomy of olivocochlear neurons. Two major groups of olivocochlear neurons have been identified (Warr and Guinan 1979). The lateral olivocochlear neurons reside in the lateral part of the superior olivary complex and send unmyelinated axons that terminate primarily on the peripheral processes of auditory nerve fibers under the inner hair cells. In contrast, medial olivocochlear neurons inhabit the medial part of the superior olivary complex and send myelinated axons that terminate on the cell bodies of outer hair cells (OHCs). The obvious structural differences in these two systems support the notion that they will subserve different functions (Brown 1987). There is also growing evidence suggesting that there are distinct subgroups that comprise the lateral and medial olivocochlear system. It seems that with increased sophistication and resolution of methods, more components will emerge to help us understand how this system of relatively few neurons is capable of serving the function of gain control in hearing.

The physiological response properties of the efferent neurons are described in Chap. 3 by John Guinan. Efferent spike-trains affect auditory nerve responses by modulating basilar membrane motion and hair cell status. In light of the anatomical differences outlined in Chap. 2, it is not surprising that the lateral and medial olivocochlear systems utilize different mechanisms to alter the operation of the cochlea. The lateral effects have been parsed into separate dopaminergic and cholinergic components. Indirect activation of these efferents can increase or decrease auditory nerve responses, and the separate groups of lateral efferent neurons presumably mediate these different effects. It has been proposed that one function of the lateral efferent system is to balance the outputs from the separate ears to enable sound localization based on interaural level differences (Guinan 1996; Darrow et al. 2006). The lateral efferents are unmyelinated and have slow conduction velocities, and so exert effects that have a long (minutes) time course.

In contrast to the lateral efferent system, the medial efferent system operates on a fast (on the order of 100 ms) or a medium (tens of seconds) time course. The fast effect dampens the cochlear amplifier by reducing receptor currents and by hyperpolarizing the OHCs (Guinan 1996). In turn, basilar membrane motion is depressed and the spike rate in the affected auditory nerve fibers is reduced (Cooper and Guinan 2006); both effects lower the sensitivity of the ear to sound. It remains to be determined whether these effects are completely separate or a result of cascading, sequential mechanisms.

The medium-speed effect is hypothesized to help protect the ear against overstimulation (Maison and Liberman 2000). An independent measure of medial efferent action is its effect on otoacoustic emissions. Otoacoustic emissions are sounds that originate in the cochlea, travel back through the middle ear and into the ear canal, where they can be detected. These emissions get most of their energy from the OHCs and medial efferent activation reduces the amplitude of the emissions. In addition to the fast inhibition, there is a slow inhibitory effect that lasts for tens of seconds that is attributable a decrease in OHC stiffness (Dallos 1997). It is this change in OHC stiffness that influences the overall sensitivity of the inner ear, and a less sensitive ear is less prone to damage by loud sounds.

The separate synaptic mechanisms utilized by the lateral and medial olivocochlear efferents within the inner ear represent an important component in describing cellular events that mediate efferent action. Understanding the cellular and molecular basis of neurotransmission will not only expand our knowledge of brain function but also reveal potential intervention strategies (e.g., pharmacological or transgenic treatment) to redress abnormalities in hearing. Neurotransmitter release occurs when an action potential invades the ending of an efferent terminal. Chemical mechanisms involving efferent synapses are discussed in detail by Bill Sewell in Chap. 4, where cochlear efferent neurochemistry is highlighted. The main chemical released by efferents is acetylcholine but other neuroactive substances are involved as well, including opioid peptides, calcitonin-gene related protein, dopamine, GABA, and serotonin (Schrott-Fischer et al. 2007). The medial efferent fibers terminate as large endings primarily against the OHCs and release acetylcholine when activated. Acetylcholine binds to nicotinic cholinergic receptors located on the postsynaptic OHCs and causes the OHCs to become permeable to calcium. The calcium that enters is thought to activate the release of more calcium. This calcium activates a class of calcium-activated potassium channels where potassium leaves the OHC and hyperpolarizes the cell (Fuchs and Murrow 1992). The lateral efferents are cholinergic too, and are associated with additional neuroactive substances, but little is known about the function of these other chemicals.

The role of special nicotinic receptors and various ion channels are discussed by Eleonora Katz, Ana Belén Elgoyhen, and Paul Fuchs in Chap. 5 to explain how acetylcholine mediates fast inhibition. At issue is how acetylcholine triggers inhibition of hair cells. The chapter explains cholinergic inhibition by revealing an unusual ionic mechanism that appears mediated by two separate families of ion channels. First, activation of a particular type of nicotinic receptor, the α9 nicotinic receptor, permits cationic calcium ions to enter the cell. The calcium in turn activates calcium-dependent potassium channels, and the egress of potassium swamps the entry of calcium so that the cell hyperpolarizes. This basic mechanism has been highly conserved across vertebrates, and the hyperpolarization is associated with diminished excitation of afferent fibers (Flock and Russell 1976).

The vestibular component of the inner ear, like the auditory receptor cells, is special among the sensory organs because it receives direct efferent innervation. The vestibular system is phylogenetically ancient, yet our basic understanding of the role of vestibular efferents is greatly lacking. Only recently have data been accumulating about the basic anatomy and physiology of this system. Joseph Holt, Anna Lysakowski, and Jay Goldberg update our current knowledge on this topic in Chap. 6, where the physiological consequences of efferent activation remain complicated. There are fast and slow mechanisms where excitatory effects are seen in the background discharges of vestibular afferent fibers. These effects are different for regular and irregular afferents, and such results are further complicated depending on whether the afferents arise from the central or striolar zones of the sensory epithelium (Goldberg and Fernández 1980; McCue and Guinan 1994; Marlinski et al. 2004). This field has many more questions than answers at present, but progress is being made.

One idea is that vestibular efferents respond to motor signals so that incoming information about the organisms own movements are suppressed in order to modulate afferent sensitivity during head movements (Highstein 1992; Brichta and Goldberg 2000). Another idea is that the vestibular efferents serve to balance the afferent output of the end organs from both sides of the head (Cullen and Minor 2002). A bilaterally balanced system is important because of the relative symmetry of the two end organs around a central axis. The output of one end organ is equal and opposite in sign to that of the other end organ as referenced to the central axis.

Dwayne Simmons, Jeremy Duncan, Dominique Crapon de Caprona, and Bernd Fritzsch review the development of the vestibulocochlear efferent system in Chap. 7 and highlight some pertinent and surprising findings that have helped to shape our current understanding about mechanisms of neuronal development in general and efferent function in particular. There is a working hypothesis that "ontogeny recapitulates phylogeny" where the stages in embryonic development and differentiation approximate the evolutionary history of the species. These stages are hypothesized to resemble the adult phase of ancient ancestors. Researchers have been able to examine neurons during the period when structures were immature (and therefore less complicated) and infer which groups of neurons were conserved through evolution. This strategy generated our basic knowledge about the development of specific fiber tracts and the cellular organization of the spinal cord, brainstem and cerebral hemispheres (Ramón y Cajal 1909). In addition, because the lengths and numbers of cell processes are reduced in the immature brain, details about cell-to-cell connections are more easily revealed. Combining developmental and comparative anatomical studies revealed that vestibulocochlear efferents differ embryologically from motor efferents in terms of their exclusive projection to placodally derived targets, the laterality of these projections, and the variety of neurotransmitters used (Fritzsch et al. 1999; Simmons 2002). Such data led to ideas about which cell masses were associated with which types of functions and behaviors.

The application of principles of comparative anatomy and evolutionary biology has been used to characterize and understand functional changes of complex structures. The structures involved in vertebrate hearing, for example, reflect shifts and specializations that occur over long periods of time in response to environmental pressures and physical requirements. The ecological demands establish a framework in which to consider functional morphology of the system and behavior of the organism. Individual phenotypes are hypothesized to represent a synergy of genotypes and environment, necessary for the organism to perform its biological roles. The presence of a general blueprint for the vertebrate nervous system suggests that a basic plan was established in an early common ancestor, and that with the evolution of "higher" animals, ancient structures were elaborated and/or new structures emerged that expanded behavioral and survival capabilities. Since there are no fossil records of hair cells or efferent neural systems, one strategy for studying the evolution of efferent systems is to compare basic features of hair cell sensory organs in "living fossils." The study of such relicts, proposed to be extant examples of a distant ancestor, may reveal the adaptive significance of features and structures that accompany the behavioral requirements in modern organisms. This premise, however, is complicated by the fact that such species have a long and independent history during which time they adapted to their own local environments and evolved their own specialized lifestyles. It remains to be seen if they truly represent an unchanged ancestral form.

Chapter 8 by Christine Köppl addresses the structural and functional diversity of efferent systems in terms of phylogenetic trends. The preservation, and indeed the variations of features over time that contribute to an improved "fit" of a species within its environment, are discussed as an approximation of natural selection for hearing. It is argued that inner ear efferents together with the lateral line form a coherent and whole octavolateralis system. This system is unified by the presence of hair cells, afferents, and efferents. The efferents across vertebrates are cholinergic and stain for either choline acetyltransferase or acetylcholinesterase (Roberts and Meredith 1992). Intriguingly, a group of efferent cells in the diencephalon of some otophysan fish immunostain for tyrosine hydroxylase (Bricaud et al. 2001). Could these cells be the ancestors of the dopaminergic efferent cells of the lateral olivocochlear system in mammals (Ruel et al. 2001, 2006)? Regardless of the answer to the question, efferent innervation of hair cells in the octavolateralis system has been observed in every vertebrate examined, suggesting an ancient and highly specialized feature of hearing.

During the course of vertebrate evolution, while auditory endorgans became more specialized, there were parallel changes in vertebrate brains. The correlation of structure and function has been important for evolutionary concepts because behavioral potential has been inferred from the presence and relative size of various brain structures (Sarnat and Netsky 1974; Webster et al. 1992). The growth of the cerebral cortex (encephalization) is one key to the evolutionary success of a species. The cerebral cortex and its interconnected structures enlarge substantially in size as one ascends the phylogenetic tree (see Fig. 1 of Meltzer and Ryugo 2006). With this "encephalization" has come an expansion in behavioral capacity that has culminated in the richness of human culture – ethics, art, science, philosophy, and so on. The corticofugal pathway – descending projections from cerebral cortex to lower brain centers – was elaborated along with growth of the forebrain and is one component to the efferent system (Malmierca and Ryugo 2010). Its prominence in mammals presumably contributes to the refinement and enhancement of auditory processing (Winer and Lee 2007).

Chapter 9 by Brett Schofield describes in detail the long descending "chains" of projections as well as feedback "loops" that comprise the descending auditory circuitry. These descending systems extend throughout the brain and their distribution emphasizes that the modulation of ascending information occurs beyond that observed at the auditory end organ. The complexity of the circuitry underlies the variety of auditory functions that could be influenced.

Chapter 10 by Donald Robertson and Wilhelmina Mulders explores electrophysiological data that address the central effects of efferent activation. If the main effect of olivocochlear efferents is to reduce the gain of cochlear sensitivity, what is the function of the descending circuits that terminate in central structures? With the enormous and complex ascending auditory pathways, olivocochlear anti-masking does not by itself seem sufficient to account for the diverse neuronal properties involved with signal processing (Mulders et al. 2009). The chapter provides a thorough discussion of technical considerations for studying this question and a constructive critique of some of the seminal research on the topic, and includes a review of the effects on single cell responses in the cochlear nucleus and inferior colliculus by olivocochlear activation. The authors report that approximately half the neurons show olivocochlear effects similar to those described in primary afferents, whereas the others exhibit a variety of novel effects. There is definitely more research to be done on this issue.

Nobuo Suga, Weiqing Ji, Xiaofeng Ma, Jie Tang, Zhongju Xiao, and Jun Yan highlight our topic in Chap. 11 by reviewing some of the features that unify the function of descending projections. By virtue of the sensory maps, the interactions between ascending and descending pathways may be "matched" or "unmatched" in terms of shared physiological properties and receptive field responsiveness. When activation of a cortical region that is matched to a subcortical site, for example, in terms of best frequency sensitivity, visual field location or body surface, the resulting response tends to be amplified or augmented. The cortical function that mediates adjustment and enhanced sensory processing has been termed "egocentric" selection (Gao and Suga 1998). In contrast, when the sites are unmatched, the resulting response can be a shift in properties of the recipient neurons toward that of the activated source neurons, or the recipient neurons can be unaffected or even suppressed by the phenomenon of lateral inhibition. The necessary and sufficient parameters for these concepts are expertly developed.

The precise organization of sensory systems in terms of topographic maps of their respective receptor epithelia creates a powerful template with which to study development and plasticity in the central pathways. Perturbations in this organization can therefore be readily detected when the organization is modified by selective activation, sensory deprivation, injury, or experience (Parks et al. 2004). In the bat, electrical stimulation of the highly tonotopic auditory cortex results in an upward or downward shift of the preferred frequencies of collicular neurons toward that of the stimulated cortical neurons. Moreover, centrifugal shifts in tuning curves can be manipulated by experimental conditions toward or away from the neuron's preferred frequency (Suga et al. 2002). In short, response plasticity is evident in terms of changes in single neuron sensitivity as well as in expanded or compressed reorganizations of sensory maps. In both young and adult animals, response changes have been attributed to alterations in the divergent and convergent projections of the ascending projections (van der Loos and Woolsey 1973; Katz and Shatz 1996; Antonini et al. 1999; Parks et al. 2004; Sato and Stryker 2008) as well as through descending corticofugal pathways (Yan and Suga 1998; Yan et al. 2005).

1.3 Comparison with Other Sensory Systems

It is worth noting that the organization of the auditory, somatosensory, and visual pathways enjoys structural similarities but they are not identical. Each pathway exhibits a cochleotopic, somatotopic, and retinotopic structure that comprises ascending projections as well as descending loops and projections. In the somatosensory system, the processing of touch sensations begins with peripheral inputs from the body surface and continues along the ascending somatosensory pathway that includes the dorsal column nuclei (nucleus gracilis and cuneatus), the thalamic ventroposterior nucleus, and multiple neocortical regions.

Cortical control of sensory information is highlighted by descending corticofugal projections that converge on the various ascending pathways (Jabbur and Towe 1961; Landry and Dykes 1985; Weisberg and Rustioni 1976, 1977, 1979; Martinez-Lorenzana et al. 2001). Descending corticothalamic projections exhibit a dual physiological effect on neurons of the ventroposterior nucleus. Glutamatergic projections mediate tonic inhibitory actions via GABAergic neurons of the thalamic reticular nucleus as well as excitatory topographic effects on matched thalamic cells and inhibition of adjacent unmatched thalamic cells (Krupa et al. 1999). While the basic properties of the thalamic neurons are determined by the ascending feedforward projections, matched cortical activation enhances activity for discrete loci of the body and unmatched activation exerts a suppressive surround (Rapisarda et al. 1992; Ghazanfar et al. 2001; Wang et al. 2007). Neurons of pars interpolaris of the trigeminal nucleus that respond to peripheral mechanical stimulation of the face exhibit response enhancement when the facial cortical field is electrically stimulated. In contrast, when a region of cortex was stimulated where receptive fields did not include the face, responses were suppressed (Woolston et al. 1983). Functional and coherent correlated interactions within somatosensory pathways provide two complementary mechanisms for response enhancement: there is a type of "on-center" feedback excitation that augments the response to the main stimulus; and there is surround-inhibition where "off center" cortical influences reduce the response to (background) stimuli, which serves to enhance further the biologically significant stimulus.

There are significant corticofugal projections from visual cortex to the thalamus and midbrain (Guillery 1969; Van Horn et al. 2000). Elimination of visual cortex activity by cooling causes a decrease in activity of lateral geniculate cells that includes reduced spontaneous activity and peak response amplitudes (Waleszczyk et al. 2005) and loss of thalamo–cortico–thalamic synchronization (Sillito et al. 1994). The visual system has a highly topographic organization where retinal fields and binocular interactions are tightly mapped. Coherent and similar stimulation in terms of orientation, direction of movement, and contrast produced enhanced neuronal responses in the dorsal lateral geniculate nucleus, whereas dissimilar stimulation had a suppressive effect (Varela and Singer 1987). Ablation of visual cortex abolished these feature-dependent interactions. Such observations promoted the idea that corticothalamic projections are involved in the mediation of binocular interactions (Murphy and Sillito 1987; Marrocco et al. 1996). More importantly, they are consistent with the theme of sensory efferent action where descending feedback strengthens thalamic transmission when cortical activation patterns and retinal signals are congruent.

1.4 Summary

One challenge for sensory system researchers is to unravel how central efferent systems engineer the extraction of signals from noise under the wide and varied conditions of a natural environment. With respect to the auditory system, the relatively small number of efferent neurons coupled with the often small impact on gain control in the ear seems contradictory to the behavioral consequences of efferent activity. Subtle manipulations enacted by the olivocochlear system on responses from the inner ear appear to be amplified and implemented by complex brain processes. The vestibular system continues to hold many secrets regarding mechanisms of function as well. It has received somewhat less attention over the years, and its central pathways have yet to be fully described. Equally daunting is the rapid and enduring plasticity of the central vestibular system where neuronal responses exhibit remarkable compensatory adaptations to systemic perturbations. There are many avenues of research for the intrepid explorer.

In spite of our gaps in knowledge, it is evident that sensory systems distribute information over bidirectional divergent and convergent pathways. Moreover, their organization enables both parallel and serial processing at every synaptic junction. This arrangement promotes feedback modulation of signals as they pass from one structure to the next, and coding schemes can change as rapidly as required by environmental demands. If we accept the concept of "top down" influences for ongoing and continuous monitoring of our conscious experiences, we are faced with the question of what structure represents the “top”? Given that most brain structures give rise to both ascending and descending projections, perhaps there is no “top” but a continuous series of loops at every level that monitors what ascends and descends. This arrangement suggests that “on-the-fly” modifications of neural activity can be initiated at every level of the relevant pathway, emphasizing that the underlying mechanisms of efferent action are just beginning to be understood.

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