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Glomerular microcircuits in the olfactory bulb

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Abstract

Microcircuits in the olfactory bulb have long received particular attention from both experimentalists and theoreticians, due in part to an abundance of dendrodendritic interactions and other specialized modifications to the canonical cortical circuit architecture. Recent experimental and theoretical results have elucidated the mechanisms and function of these circuits and their presumed contributions to olfactory stimulus processing and odor perception. We here review the architecture and functionality of a prominent olfactory bulb microcircuit: the glomerular network.

Introduction

In natural environments, the olfactory system must identify signals of potential interest in chemically noisy environments, within which odors are distributed unpredictably in time and space and odorants from innumerable sources intermix freely. The neural circuitry of the olfactory bulb (OB), to which primary olfactory receptor neurons project, has long been thought to mediate the primary processing of odor representations that enables the detection, identification, and comparison of these signals. We here review the architecture and function of OB glomeruli, the first neuronal microcircuit of the olfactory system.

Glomeruli contain the first afferent synapses of the olfactory system, where primary sensory neuron axonal arbors interact with the dendritic processes of principal neurons (mitral and middle/deep tufted cells) and multiple types of local interneurons. Historically, study of the function of these glomerular microcircuits has been somewhat neglected in favor of the conspicuous lateral interactions among mitral cells and granule cell interneurons in the deep OB. Recently, however, new experimental work on glomerular layer interneurons has enabled a considerably more sophisticated attribution of function to the neural circuits of the glomerular layer than was previously plausible. We here review the architecture of these circuits together with their function. Specifically, we detail how the first layer of processing in the olfactory bulb effects signal normalization and decorrelation via the concerted utilization of multiple excitatory and inhibitory feedforward and feedback processing strategies.

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Organization of olfactory representations

Primary olfactory sensory neurons (OSNs) line the nasal cavity, where they interact with inhaled odorant molecules. Canonically, each OSN expresses a single species of odorant receptor (OR) that largely determines their olfactory receptive field, or molecular receptive range – i.e., the range of molecular epitopes that will bind to the OR and activate the OSN. Each OSN is activated by a corresponding range of odorant molecules, and any single odorant molecule will activate multiple different OSNs to different degrees. Consequently, odors activate unique and characteristic patterns of neuronal activation – distributed representations – across the population of OSNs (Adrian, 1953; Kauer, 1991; Moulton, 1967; Stewart, Kauer, & Shepherd, 1979). Due to the convergence of all OSNs expressing a given OR onto one or two common glomeruli (discrete clusters of tangled neurites surrounded by glial cells) in the surface layer of the OB, activation of these glomeruli directly reflects the activation of specific OR species. Consequently, odor-specific distributed representations can be directly observed via imaging studies of OB glomeruli (Friedrich & Korsching, 1997; Johnson, Farahbod, Xu, Saber, & Leon, 2004; Johnson, Woo, Hingco, Pham, & Leon, 1999; Johnson, Woo, & Leon, 1998; Meister & Bonhoeffer, 2001; Rubin & Katz, 1999; Wachowiak, Cohen, & Zochowski, 2002). Studies of these distributed representations in concert with other data have revealed an important characteristic of odor representations with consequences for the architecture of olfactory bulb microcircuits: unlike other primary sensory networks, the physical proximity of glomeruli and their corresponding columns in the olfactory bulb is not correlated with similarities in their receptive fields (Cleland, Johnson, Leon, & Linster, 2007; Cleland & Sethupathy, 2006; Fantana, Soucy, & Meister, 2008; Soucy, Albeanu, Fantana, Murthy, & Meister, 2009). Specifically, the olfactory receptive field of a given glomerulus is not informative about those of its physical neighbors (Soucy *et al.*, 2009). Consequently, decorrelation and other computations that rely on neural representations of stimulus similarity cannot utilize spatially localized or center/surround neural mechanisms (such as nearest-neighbor lateral inhibition) such as are utilized by other sensory systems, but instead require mechanisms that are independent of such ordered topographies (Cleland *et al.*, 2007; Cleland & Sethupathy, 2006; Linster, Sachse, & Galizia, 2005), as detailed below.

Glomerular microcircuits: local and global computation

Glomerular microcircuitry exhibits a unique architecture adapted to process the distributed odor representations conveyed to it by the OSN population (Figure 1). Glomeruli are anatomically distinct regions of the superficial OB within which inputs from a single class of OSNs synapse with the dendrites of olfactory bulb principal neurons (mitral and middle/deep tufted cells) and interneurons (periglomerular and external tufted cells). These distinct regions, surrounded by glial cells, are considered functional units of the olfactory bulb because each receives inputs from a distinct class of OSNs. Glomeruli consist primarily of the axonal arbors of OSNs, which outnumber other neurons innervating the glomerulus by 1–2 orders of magnitude (Schoenfeld & Knott, 2004). OSN terminal arbors synapse upon the dendritic arbors of mitral (Mi) cells, the principal projection neurons of the OB, as well as on the dendrites of local interneurons including excitatory external tufted (ET) cells and on the dendritic spines of a subclass of inhibitory periglomerular (PG) cells. PG neurons in turn inhibit mitral cells; in particular, the subclass of PG cells that receives monosynaptic input from OSNs delivers feedforward inhibition directly onto mitral cell dendrites within the same glomerulus. Whereas these interactions between OSNs, mitral cells, and PG cells are local to a single glomerulus, ET cells are interconnected with other glomeruli via a network of glutamatergic superficial short axon (sSA) cells in a lateral excitatory network that also activates PG cells, thereby further inhibiting mitral cells with a globally averaged level of feedforward inhibition (Aungst *et al.*, 2003;Cleland *et al.*, 2007). Interestingly, aside from this broad ET/sSA cell network, and a small number of PG cell axons that project to other glomeruli, the different glomeruli within

the same OB are not substantially interconnected (Pinching, 1970;Pinching & Powell, 1971a,1971b).

In sum, the glomerular microcircuit consists of a wholly local, dendrodendritic, feedforward inhibitory component (OSN-PG-Mi; Figure 2A), as well as a broadly laterally distributed feedforward inhibitory component that is conveyed by axonal projections and regulated by a network of recurrent feedback excitatory connections (OSN-[ET-SA-ET]-PG-Mi; Figure 3A). The local feedforward inhibitory projection is comparable to the input layer architecture of other cortical microcircuits, although the graded, dendrodendritic implementation of this operation is highly specialized, and the global feedforward inhibition mediated by the ET/SA network provides additional complexity necessary for the effective processing of olfactory sensory input but lacks a clear counterpart in the canonical cortical microcircuit. The output of these glomerular microcircuits is further processed in deeper bulbar layers (primarily the external plexiform layer) before being forwarded to secondary olfactory cortices (Cleland & Linster, 2003); the laterally projecting feedback inhibition mediated by this second OB processing layer roughly corresponds to the similarly structured feedback inhibition of canonical cortical circuitry. Of course, despite its functional utility, this analysis of the glomerular microcircuit is not exhaustive – the full circuit topology can be broken down into arbitrarily different sets of interacting networks pursuant to particular analyses.

Glomerular microcircuit function

Glutamatergic OSN sensory input to each glomerulus directly excites mitral cell dendrites, and simultaneously inhibits the same mitral cells by activating PG cell spines that release γ-aminobutyric acid (GABA) onto the mitral cell dendrite (Figure 2A). Theoretical models of this synaptic triad indicate that this configuration of direct excitation modulated with feedforward $GABA_A$-ergic shunting inhibition regulates the receptive field of the mitral cell, decorrelating similar olfactory inputs via a process of contrast enhancement (Cleland & Sethupathy, 2006). Specifically, mitral cells exhibit net activation only when stimulated by odor ligands with the highest affinities for their associated odorant receptors; lesser degrees of OSN activation incur a net inhibitory response in which PG cell-mediated inhibition of the mitral cell overcomes its direct excitation (Figure 2B,C). Consequently, odor-evoked activity patterns across mitral cell ensembles (secondary representations) are sparser and less overlapping than are the corresponding primary representations observed among OSNs (Cleland & Sethupathy, 2006). The net effect is to decorrelate odor representations with respect to the structural and perceptual similarities of odorants. In contrast to other suggested mechanisms for olfactory decorrelation, this local mechanism does not require a built-in foreknowledge of the similarities in molecular receptive ranges expressed by different olfactory bulb glomeruli in order to distribute inhibition correctly, and is entirely independent of the physical location of glomeruli within the olfactory bulb.

Whereas local feedforward inhibition within glomeruli effects contrast enhancement among odor representations, the global feedforward inhibitory component of the glomerular microcircuit contributes to normalization of the intensity of sensory input. Normalization processes in sensory systems are essential for segregating quality from concentration effects and for constructing intensity-independent representations of stimulus quality. In principle, intensity normalization processes require global feedback inhibition, in which a uniform level of inhibition is delivered to all units in proportion to the mean activity level of all sensory inputs. In the olfactory system, this normalization has been proposed to rely upon the ET/sSA lateral excitatory network (Aungst *et al.*, 2003; Cleland *et al.*, 2007; Cleland & Sethupathy, 2006); Figure 3A). Briefly, this widespread, densely connected lateral network is activated by direct OSN excitation of ET cells within glomeruli. The lateral excitatory network of ET and sSA cells integrates these heterogeneous activation levels across the bulbar input layer and

delivers a uniform level of excitation onto a subclass of PG cells, which in turn inhibit mitral cells. Theoretical models of the ET/sSA network in the olfactory bulb demonstrate that its 'small-world' pattern of interconnectivity among glomeruli suffices to generate a global estimate of average afferent activity levels across the OB, which is delivered to mitral cells as inhibition, hence normalizing input levels so that mitral cell patterning reflects relative, rather than absolute, levels of glomerular activation across the OB (Cleland *et al*., 2007); Figure 3B).

Indeed, mitral cell responses clearly exhibit some form of normalization of input intensities. Whereas collective OSN activity levels can vary over multiple orders of magnitude, the average spike frequencies in mitral cells vary in a much more limited range, generally being only modestly inhibited or excited by increasing odor concentrations (Chalansonnet & Chaput, 1998; Harrison & Scott, 1986; Meredith, 1986). This probably improves the olfactory system's capacity to recognize the same odor at different intensities; also, avoiding high rates of spiking conserves metabolic energy.

Conclusion

Olfactory neuronal properties and bulbar circuit architecture are adapted to the physical and statistical properties of chemical stimuli and serve to mitigate the ambiguities and limitations inherent in the sensory transduction of stimuli in this modality. We here describe how glomerular microcircuits, historically underrepresented in the study of olfactory bulb processing, are able to perform decorrelation and normalization operations on odorant representations in which the spatial proximity of glomeruli and OB columns is computationally meaningless.

Odor stimulus decorrelation, or contrast enhancement, requires the delivery of inhibition onto OB columns proportional to the activation of columns exhibiting similar olfactory receptive fields (Figure 4A). Normalization, the process by which relative activation levels across a neural network are preserved independently of common mode variations in input amplitudes, requires a computation of inhibition that is effectively global in scope; that is, the strength of inhibition must be scaled to the average activity level across the bulb rather than to local activation levels if the profiles of relative activation among odor columns are to be preserved (Figure 4B). In the OB, the synaptic triad connecting OSN arbors, PG cell dendritic spines, and mitral cell dendrites in close proximity (reviewed by (Shepherd & Greer, 1998), coupled with the lateral excitatory network mediated by external tufted and short axon cells (Aungst *et al*., 2003; Hayar, Karnup, Ennis, & Shipley, 2004), can effect both decorrelation and normalization at the level of the secondary olfactory representation mediated by mitral cells (Cleland *et al.*, 2007; Cleland & Sethupathy, 2006); Figure 2,Figure 3). While their commonalities with other cortical microcircuits are clear, these circuits also are adapted to the processing of non-topographical sensory representations exhibiting unpredictable patterning and intensity profiles and therefore exhibit clear differences from the "canonical" cortical circuit as well as from those described in other primary sensory cortices. Moreover, glomerular circuits are the target of cholinergic and serotonergic neuromodulatory inputs and are important contributors to the broader regulation of olfactory perception by learning and attentional processes (Mandairon *et al.*, 2006; Mandairon & Linster, 2009).

References

Adrian ED. Sensory messages and sensation; the response of the olfactory organ to different smells. Acta Physiol Scand 1953;29(1):5–14. [PubMed: 13104158]

Aungst JL, Heyward PM, Puche AC, Karnup SV, Hayar A, Szabo G, Shipley MT. Centre-surround inhibition among olfactory bulb glomeruli. Nature 2003;426(6967):623–629. [PubMed: 14668854]

Chalansonnet M, Chaput MA. Olfactory bulb output cell temporal response patterns to increasing odor concentrations in freely breathing rats. Chem Senses 1998;23(1):1–9. [PubMed: 9530964]

ClelandTAJohnsonBALeonMLinsterCRelational representation in the olfactory system. >Proc Natl Acad Sci U S A2007104619531958 [PubMed: 17261800]

Cleland, TA.; Linster, C. Central olfactory processing. In: Doty, RL., editor. Handbook of olfaction and gustation. Vol. 2nd ed.. New York: Marcel Dekker; 2003. p. 165-180.

Cleland TA, Sethupathy P. Non-topographical contrast enhancement in the olfactory bulb. BMC Neurosci 2006;7:7. [PubMed: 16433921]

Fantana AL, Soucy ER, Meister M. Rat olfactory bulb mitral cells receive sparse glomerular inputs. Neuron 2008;59(5):802–814. [PubMed: 18786363]

Friedrich RW, Korsching SI. Combinatorial and chemotopic odorant coding in the zebrafish olfactory bulb visualized by optical imaging. Neuron 1997;18(5):737–752. [PubMed: 9182799]

Harrison TA, Scott JW. Olfactory bulb responses to odor stimulation: analysis of response pattern and intensity relationships. J Neurophysiol 1986;56(6):1571–1589. [PubMed: 3806183]

Hayar A, Karnup S, Ennis M, Shipley MT. External tufted cells: a major excitatory element that coordinates glomerular activity. J Neurosci 2004;24(30):6676–6685. [PubMed: 15282270]

Johnson BA, Farahbod H, Xu Z, Saber S, Leon M. Local and global chemotopic organization: general features of the glomerular representations of aliphatic odorants differing in carbon number. J Comp Neurol 2004;480(2):234–249. [PubMed: 15514935]

Johnson BA, Woo CC, Hingco EE, Pham KL, Leon M. Multidimensional chemotopic responses to n-aliphatic acid odorants in the rat olfactory bulb. J Comp Neurol 1999;409(4):529–548. [PubMed: 10376738]

Johnson BA, Woo CC, Leon M. Spatial coding of odorant features in the glomerular layer of the rat olfactory bulb. J Comp Neurol 1998;393(4):457–471. [PubMed: 9550151]

Kauer JS. Contributions of topography and parallel processing to odor coding in the vertebrate olfactory pathway. Trends Neurosci 1991;14(2):79–85. [PubMed: 1708541]

Linster C, Sachse S, Galizia G. Computational modeling suggests that response properties rather than spatial position determine connectivity between olfactory glomeruli. J Neurophysiol 2005;93(6): 3410–3417. [PubMed: 15673548]

Mandairon N, Ferretti CJ, Stack CM, Rubin DB, Cleland TA, Linster C. Cholinergic modulation in the olfactory bulb influences spontaneous olfactory discrimination in adult rats. Eur J Neurosci 2006;24 (11):3234–3244. [PubMed: 17156384]

Mandairon N, Linster C. Odor perception and olfactory bulb plasticity in adult mammals. J Neurophysiol 2009;101(5):2204–2209. [PubMed: 19261715]

Meister M, Bonhoeffer T. Tuning and topography in an odor map on the rat olfactory bulb. J Neurosci 2001;21(4):1351–1360. [PubMed: 11160406]

Meredith M. Patterned response to odor in mammalian olfactory bulb: the influence of intensity. J Neurophysiol 1986;56(3):572–597. [PubMed: 3537224]

Moulton, DG. Spatio-temporal patterning of response in the olfactory system. In: Hayashi, T., editor. Olfaction and Taste II. New York: Pergamon Press; 1967. p. 109-116.

Pinching AJ. Synaptic connexions in the glomerular layer of the olfactory bulb. J Physiol 1970;210(1): 14P–15P.

Pinching AJ, Powell TP. The neuron types of the glomerular layer of the olfactory bulb. J Cell Sci 1971a; 9(2):305–345. [PubMed: 4108056]

Pinching AJ, Powell TP. The neuropil of the glomeruli of the olfactory bulb. J Cell Sci 1971b;9(2):347–377. [PubMed: 4108057]

Rubin BD, Katz LC. Optical imaging of odorant representations in the mammalian olfactory bulb. Neuron 1999;23(3):499–511. [PubMed: 10433262]

Schoenfeld TA, Knott TK. Evidence for the disproportionate mapping of olfactory airspace onto the main olfactory bulb of the hamster. J Comp Neurol 2004;476(2):186–201. [PubMed: 15248198]

Shepherd, GM.; Greer, CA. Olfactory bulb. In: Shepherd, GM., editor. The synaptic organization of the brain. Vol. 4th ed.. New York: Oxford University Press; 1998. p. 159-204.

Soucy ER, Albeanu DF, Fantana AL, Murthy VN, Meister M. Precision and diversity in an odor map on the olfactory bulb. Nat Neurosci 2009;12(2):210–220. [PubMed: 19151709]

Stewart WB, Kauer JS, Shepherd GM. Functional organization of rat olfactory bulb analysed by the 2-deoxyglucose method. J Comp Neurol 1979;185(4):715–734. [PubMed: 447878]

Wachowiak M, Cohen LB, Zochowski MR. Distributed and concentration-invariant spatial representations of odorants by receptor neuron input to the turtle olfactory bulb. J Neurophysiol 2002;87(2):1035–1045. [PubMed: 11826067]

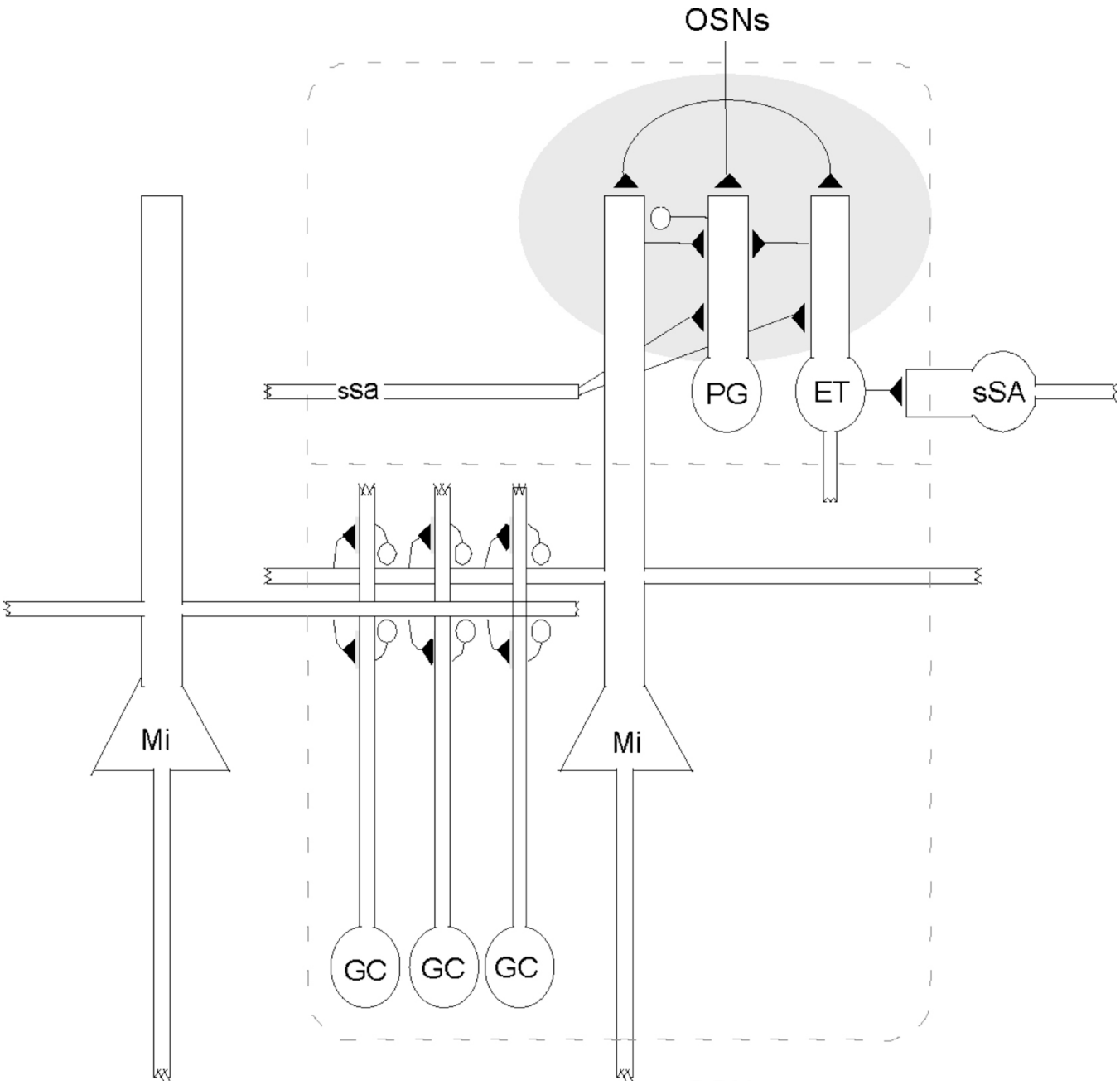

Figure 1.

Neural microcircuits of the olfactory bulb. Olfactory sensory neurons (OSNs) expressing the same olfactory receptor project to a common glomerulus in the olfactory bulb, within which their axonal arbors make synaptic contacts with the dendrites of mitral cells (Mi), periglomerular cells (PG) and external tufted cells (ET). The shaded oval depicts the extent of the glomerulus proper, which contains no cell bodies; the dashed outline depicts the extent of the olfactory bulb column associated with each glomerulus. Periglomerular and mitral cells make reciprocal dendrodendritic synaptic contacts with each other within the glomerular neuropil: periglomerular cells inhibit mitral cells while mitral cells excite periglomerular cells. External tufted cells, together with superficial short axon cells (sSA), form an interconnected lateral excitatory network that spans the glomerular layer and deliver excitatory inputs onto

periglomerular cells. Deeper within the bulb, within the external plexiform layer, mitral cell secondary dendrites extend laterally, forming reciprocal dendrodendritic synapses with inhibitory granule cells (GC). *Filled triangles*: excitatory glutamatergic synapses; *open circles*: inhibitory $GABA_A$-ergic synapses.

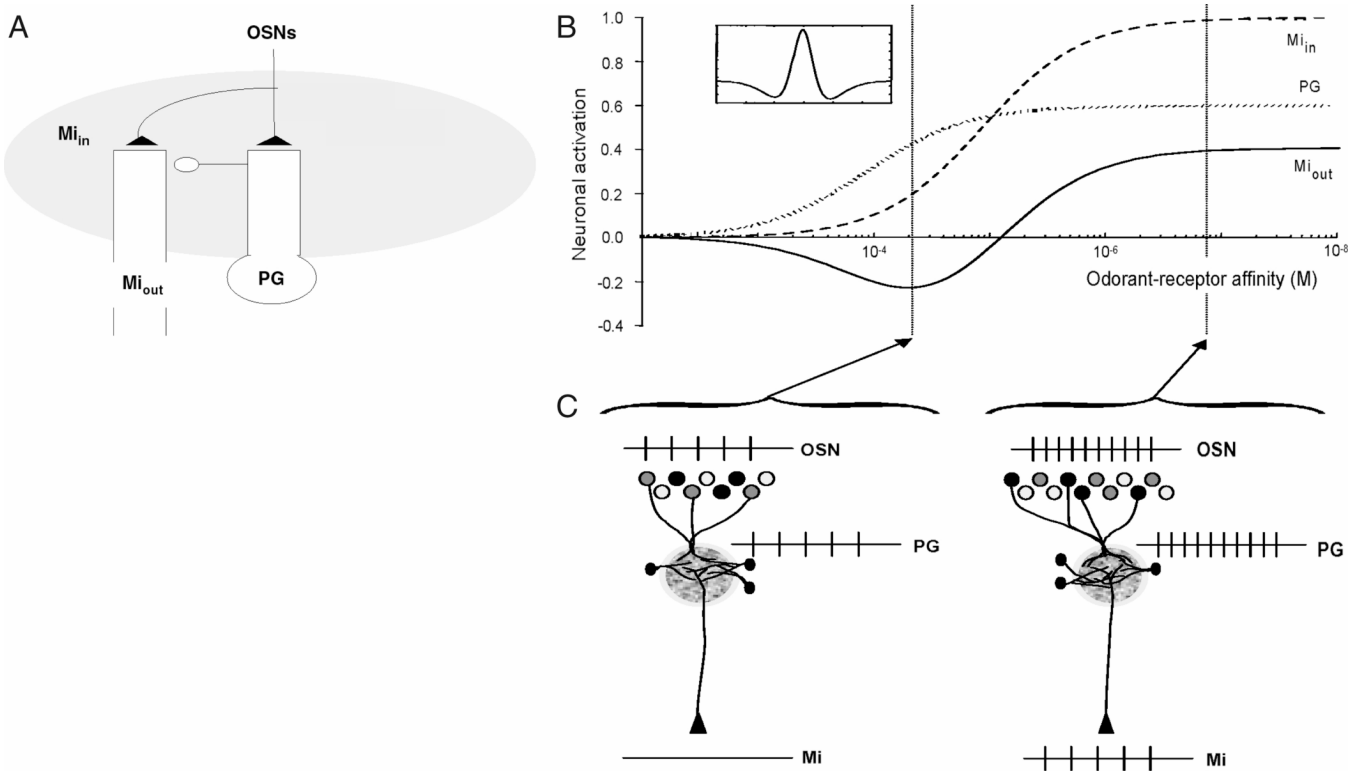

Figure 2.

Decorrelation (contrast enhancement) performed by local feedforward inhibition. **A**. Microcircuit diagram of the OSN-PG-Mi synaptic triad, labeled with reference to Figure 2B. In particular, Mi_{in} represents direct OSN input to the mitral cell, before PG inhibition is factored in, whereas Mi_{out} represents net mitral cell activity after all inputs are considered. *Filled triangles*: excitatory glutamatergic synapses; *open circles*: inhibitory $GABA_A$-ergic synapses. **B**. Illustrative model of glomerular decorrelation mechanism. OSN activation directly excites both mitral cells (Mi_{in}) and periglomerular cells (PG) in the olfactory bulb input layer; periglomerular cells concurrently inhibit mitral cell primary dendrites, resulting in a final activation function for mitral cells (Mi_{out}) that is selective for higher-affinity odor stimuli. Specifically, odorants with negligible affinity for the associated ORs evoke no response in the mitral cell, while odorants with moderate affinity activate OSNs but evoke a net inhibitory response in the corresponding mitral cell. Only the highest-affinity odorants evoke action potentials in mitral cells. The result is an 'on-center/inhibitory surround' response profile for mitral cells based on relative affinity for odorants, rather than on any connotation of space. Owing to normalization mediated by global feedforward inhibition (see text), changes in odor concentration do not disrupt this affinity-based distribution of mitral cell responses. *Abscissa*: odorant ligand-receptor dissociation constants in moles per liter; an efficacy of unity is presumed for illustrative purposes. *Ordinate*: Unitless representation of neuronal activation levels relative to baseline activity in the absence of odor stimulation. **C**. Illustration of OB microcircuit responses at two odorant-receptor affinity values. The spike trains depicted are solely to enable comparison of activities between the two figures; in reality, OSN spike densities are considerably greater than those of mitral cells, and these effects of PG cells are largely mediated via graded transmitter release. Darker ovals represent more strongly activated OSN populations. These local computations result in distributed, odor-specific activity patterns at the level of mitral cells that are considerably sparser than those conveyed by the OSNs, thereby establishing greater contrast (less overlap) between the representations of structurally similar odorants.

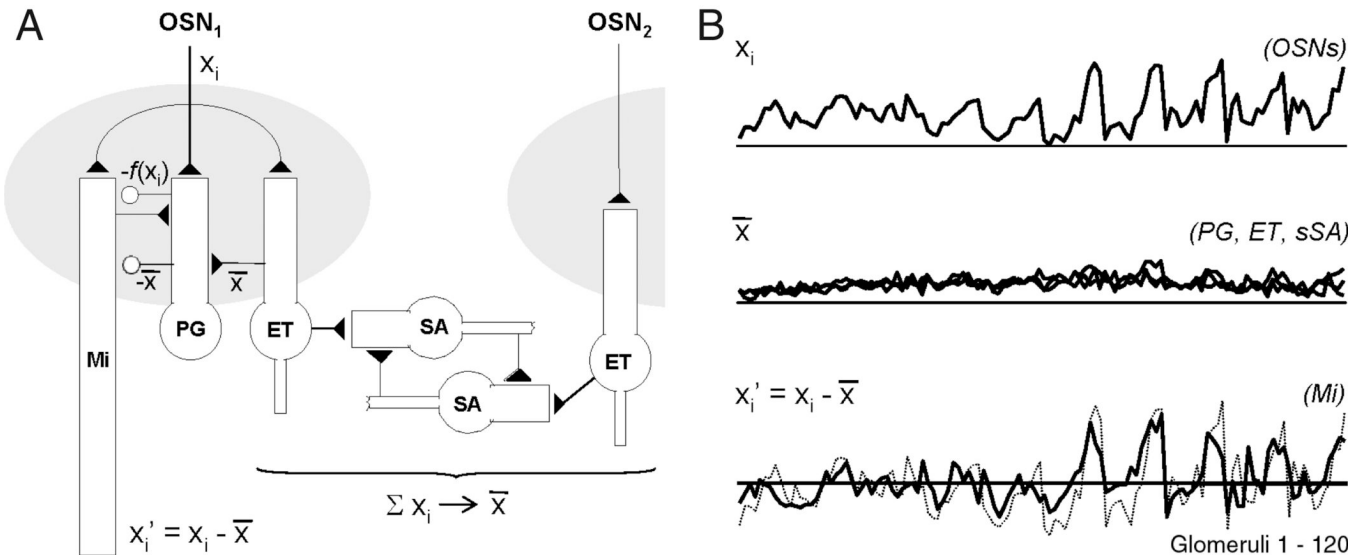

Figure 3.

Normalization of OSN inputs by glomerular layer microcircuits. **A.** Schematic of microcircuitry. OSN inputs to individual glomeruli (x_i) vary with odorant concentration as well as with the respective affinities and efficacies for each of the odorants present. External tufted cells (ET), along with superficial short axon cells (sSA), are interconnected in a dense lateral excitatory feedback network that is capable of integrating the input activity across all glomeruli and computing the sum (Σx_i) or average ($\bar{x}$) level of bulbar activation (Cleland *et al.*, 2007). This global mean activity level is transmitted from ET to PG cells, which in turn inhibit mitral cells ($-\bar{x}$). The outcome of this computation is to subtract the mean level of bulbar activation from the individual direct activation level of each mitral cell, resulting in a mitral cell representation that is normalized with respect to the mean: $x_i' = \Sigma x_i - x$. This role for PG cells in glomerular normalization may utilize a separate population of PG cells from that which mediates decorrelation ($-f(x_i)$); only an estimated 20% of PG cells receive monosynaptic input from OSNs (Hayar *et al.*, 2004). *Filled triangles*: excitatory glutamatergic synapses; *open circles*: inhibitory $GABA_A$-ergic synapses. **B.** Simulation results. A 120-glomerulus model of glomerular microcircuitry, presented with a complex odor stimulus, responded with a correspondingly high level of variance in the activation of OSNs expressing different OR species (top trace, x_i). In contrast, the variance in the activation of PG, ET, and sSA interneurons associated with the corresponding glomeruli was greatly reduced owing to the summation/averaging of activity across the ET/sSA lateral excitatory network ($\bar{x}$). The delivery of this PG-mediated inhibition to mitral cells normalized their activation levels, generating a relational representation of odor quality across the population of mitral cells (solid plotline) that closely approximated the results of a statistical z-score of sensory input levels (dotted plotline). This normalization generates relatively concentration-independent representations of odor quality at the level of mitral cell output, presumably facilitating the recognition of odors irrespective of intensity. *Abscissa*: 120 points depicting each glomerulus in the simulation. *Ordinate*: Activity levels of each cell type associated with each of the 120 simulated glomeruli. Horizontal lines in each plot depict an activity of zero; excursions below this line connote inhibition.

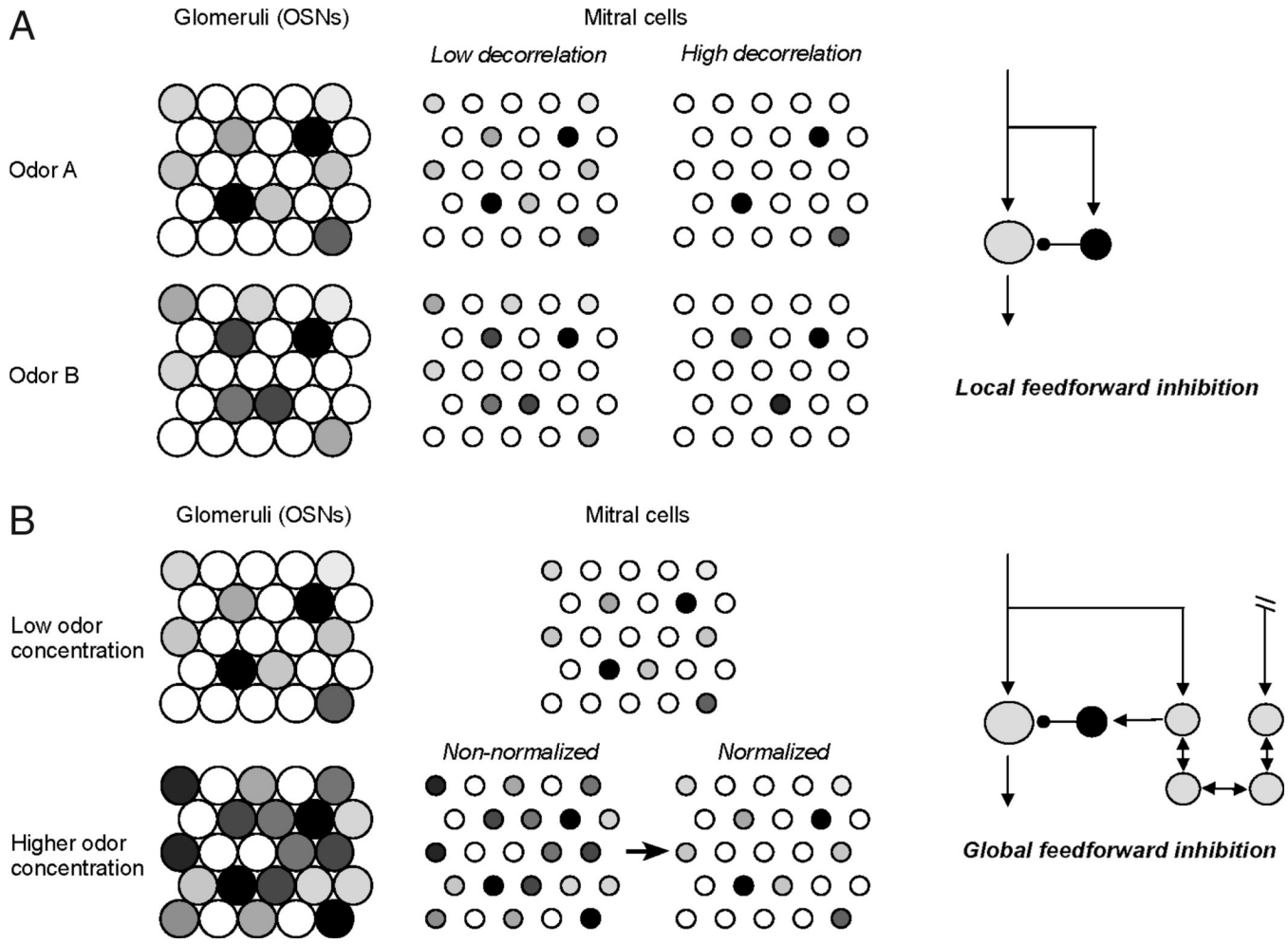

Figure 4.

Schematic illustration of glomerular microcircuit computations. **A.** Decorrelation. Odor stimuli activate unique combinations of ORs, and hence glomeruli, with characteristic patterns of activation (darker glomeruli depict greater activation). Local feedforward inhibition at the first synaptic triad implements decorrelation, enhancing the differentiability of highly similar odorants that evoke correspondingly overlapping glomerular activation patterns. When decorrelation is weak or absent, the representations of Odors A and B are very similar; however, with high decorrelation, the two representations become increasingly dissimilar from one another. **B.** Normalization. Higher odorant concentrations activate larger numbers of different OSNs as an increasing proportion of lower-affinity ligand-receptor associations become significantly active. Consequently, the glomerular activation pattern is broader and of higher amplitude than it would be for the same odor presented at a lower concentration. Global feedforward inhibition in the glomerular layer, scaled by recurrent feedback excitation, normalizes these activity patterns with respect to the mean activation level across the entire olfactory bulb. This renders the odor representation at the level of the mitral cell ensemble substantially less sensitive to concentration changes than are the underlying glomerular input patterns (compare the mitral cell patterns at the low and high odor concentrations after normalization).