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Functional organization and plasticity in the adult rat barrel cortex: moving out-of-the-box

Ron D Frostig

Recent advances in functional imaging and neuronal recording techniques demonstrate that the spatial spread and amplitude of whisker functional representation in the somatosensory cortex of the adult rodent is extensive, but subject to modulations. One of the strongest modulators is naturalistic whisker use. In the cortices of rodents that have been transferred from their home cage to live for an extensive period in a naturalistic habitat, there is suppression of evoked neuronal responses accompanied by contraction and sharpening of receptive fields, and contraction and weakening of whisker functional representations. These unexpected characteristics also describe modulations of whisker functional representations in the cortex of a freely exploring rodent during short whisker-based explorations. These and related findings suggest that cortical modulations and plasticity could follow a 'less is more' strategy and, therefore, highlight how different cortical strategies could be utilized for different behavioral demands.

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Introduction

The cortical target of this review is the posteromedial barrel subfield (PMBSF) — a subfield of the rodent's primary somatosensory cortex (SI) that represents with exquisite order 5 rows of large whiskers. The focus of this review is the whisker functional representation (WFR), a population measure defined as the cortical area activated by single whisker stimulation (also known as the cortical point-spread function). The concept of a WFR is fundamental to questions about cortical processing at the systems level. For example, small, minimally overlapping WFRs represent a cortical strategy of independent

processing areas for each whisker, whereas large and overlapping WFRs represent a cortical strategy in which a given area simultaneously processes inputs from many whiskers. Because different cortical strategies could be recruited for different behavioral demands, determining under what circumstances a particular strategy is used is essential to the understanding of cortical function. In this review, discussion is limited to the systems level of the living cortex; see Feldman and Brecht, and Fox and Wong [1,2] for recent reviews on potential underlying mechanisms of functional organization and plasticity in the PMBSF.

Functional organization

Basic description of a whisker functional representation

Mapping a WFR in the PMBSF has traditionally been achieved using single electrode recording and, more recently, using electrode-array recordings. Using electrode recordings, one could stimulate an individual whisker and directly measure the spread and amplitude of evoked neuronal activity over progressively larger distances from the activated barrel (the layer IV area where input from the whisker first reaches the cortex). Alternatively, and more crudely, one could try to indirectly infer the WFR characteristics from receptive-field mappings. The optimal way to characterize a WFR is to use functional imaging methods, because it is possible to obtain high spatial resolution images of a large cortical area repeatedly within short time periods.

There are several issues with the characterization of the size and amplitude of a WFR to consider when comparing findings obtained from different labs; issues that are common to research on functional organization and plasticity of the brain. The first issue is that the characteristics of a WFR depend on the type and level of anesthesia or wakefulness: WFRs typically contract and weaken with deeper anesthesia [3] and, as discussed below, the characteristics of WFRs are modulated by different states of wakefulness (e.g., quiet wakefulness versus exploratory navigation). The second issue is the spatial context of whisker activation: the WFR of a single whisker can be modulated by activation of WFRs of other whiskers. Activated neurons within different WFRs can either mutually facilitate or inhibit each other, typically depending on the timing of their activation [4–9], frequency of whisker activation [10], direction of whisker stimulation [11] and behavioral state [12]. The third issue is that the previous pattern of whisker use could induce WFR plasticity, as discussed below in the plasticity section.

The fourth issue — more common in functional imaging — is the arbitrary nature of choosing activity thresholds of functional images to determine the size of a WFR (e.g., deciding to threshold a WFR image at 90% versus at 50% of peak activity could dramatically influence the reported size of an imaged WFR). Finally, the fifth issue is that size and amplitude of a WFR depend on both the type of whisker stimulation and its exact parameters. This last issue has been demonstrated using optical imaging based on voltage sensitive dyes. Qualitatively different types of whisker stimuli, such as a puff of air versus direct mechanical stimulation, induce different spatiotemporal profiles of cortical activation [13]. Even when only direct mechanical stimulation is applied to the whisker, quantitative differences in stimulation parameters evoke different WFRs for the same whisker. A clear example was demonstrated by Petersen *et al.* [14] who showed, using voltage sensitive dye (VSD)-based optical imaging, that whereas weak mechanical stimulation of a whisker evoked a WFR that is roughly barrel-sized in area, stronger stimuli, which better mimic the natural whisker stimulation of a navigating rodent, evoked activation above the appropriate barrel within 10 ms, but within 50 ms such activation spread almost evenly over the entire PMBSF; see also Derdikman *et al.* [13] for large WFRs obtained using VSD-based optical imaging. Nevertheless, despite all the above issues, some generalizations emerge from the research on WFRs.

VSD-based optical imaging is sensitive to subthreshold activation of the upper layers of the cortex [15], and its findings complement those of *in vivo* intracellular recordings demonstrating large subthreshold receptive fields in PMBSF, findings that indirectly imply large WFRs. Moore and Nelson [16] used whole cell recordings and found subthreshold receptive fields that included ≥ 25 whiskers. Similarly, Zhu and Connors [17] used whole cell recordings in PMBSF and reported that, on average, subthreshold receptive fields included >10 whiskers. In addition, Brecht and Sakmann [18,19] showed large receptive fields in both layer IV and layers 2,3 respectively, as did Higley and Contreras [8,9]. Local field potential (LFP) recordings, an indicator of subthreshold activation, also revealed very large WFRs [20,21].

Using optical imaging based on intrinsic signals, a hemodynamic-based functional imaging method, Brett-Green *et al.* [22] imaged different WFRs in the anesthetized rat. Although peak optical activation was always found above the appropriate barrel, each whisker symmetrically activated large portions of PMBSF and for WFRs located near the SI border, activation even crossed the border of SI and reached the border of primary auditory cortex (AI). These imaging findings were confirmed by post-imaging single unit recordings guided by the functional image of the WFR. Other imaging findings based on intrinsic signal imaging also reported WFRs of different sizes,

all bigger than the underlying barrels [23–29]. Similar results were also reported using the recently developed flavoproteins (mitochondrial proteins involved in aerobic glycolysis) autofluorescence functional imaging [30,31], a technique that is independent from the cortical hemodynamic system.

Large WFRs were also demonstrated by suprathreshold, single unit recordings using microelectrodes or microelectrode-arrays. Using post-imaging mapping with single unit recordings, Masino [32] demonstrated that following whisker stimulation evoked spiking neurons could be reliably detected 1.6 mm away from peak optical activity, and in some cases even farther away. Single unit recordings from microelectrode arrays also showed large WFRs [3,33,34].

Modulations of a whisker functional representation

Because all the above-mentioned studies were obtained in anesthetized rodents, it was not clear whether large WFRs are also typical of an awake, behaving rodent. A large WFR was imaged in the awake, restrained rat using intrinsic signal optical imaging [35]. Furthermore, a recent study by Ferezou *et al.* [36••] using VSD-based optical imaging compared the size and amplitude of an individual WFR within the same mouse while anesthetized or during wakefulness. This direct comparison demonstrated that the WFR in the awake, restrained mouse was even larger (44%) than its size in the anesthetized state, thus confirming that large WFRs are also typical of an awake PMBSF. However, the functional organization of an awake, restrained mouse is not necessarily representative of all behavioral states. Indeed, different behavioral states can also modulate neuronal activation and, therefore, the size and amplitude of a WFR. Fanselow and Nicolelis [12] demonstrated in behaving, adult rats that whisking (active, exploratory movements by whiskers) during exploration reduced the response magnitude of neurons in PMBSF compared with that during unrestrained, quiet wakefulness. Furthermore, in a series of experiments [20,37,38], Castro-Alamancos and co-workers have demonstrated the important role of arousal (as opposed to quiet wakefulness) associated with whisking during exploratory navigation as a cortical modulator that induces suppression of cortical activation. Cortical arousal, either artificially induced by brain-stem stimulation in an anesthetized rat or as measured in behaving rats during exploration, leads to contraction and weakening of WFRs, coupled with reduction in evoked cortical activity — as measured either by LFP or with single units. At the same time arousal also led to an increase in the evoked neuronal firing synchronization, and induced sharpening of the underlying receptive field (i.e., the suppression of the center receptive field is weaker compared with the suppression of the surround receptive field, resulting in a better response to the appropriate whisker compared with

that to its neighbors) [20,37,38]. The sum of these arousal-based changes is a modulation of the functional organization of the cortex in such a way that each whisker has a smaller representation containing smaller and sharper receptive fields — a functional organization that is typically associated with high-resolution discrimination abilities [39••]. In a clear demonstration of the depressed state of the cortex during active exploration, Ferezou *et al.* [36••], using VSD-based optical imaging of a single, spared whisker (i.e., all neighboring whiskers were removed) WFR in the behaving mouse, showed that its passive stimulation during unrestrained quiet wakefulness results in a large WFR that spans the entire PMBSF, whereas the same passive stimulation during active whisking strongly diminishes both its amplitude and size, resulting in a small and weak WFR. Only during active contact with an object by the spared whisker was large activation imaged, similar to activation seen during quiet wakefulness. These findings, however, should be cautiously interpreted because they are based on a spared whisker rather than a full whisker array, and therefore miss potential interaction between WFRs that could modulate the final size of the WFR. Various other modulations of neuronal activation patterns during active exploration with full whisker arrays were demonstrated in adult rats trained to achieve a goal using their whiskers [38,40,41]. However, these studies did not focus at the level of a WFR; see review by Kleinfeld *et al.* in this issue.

In summary, the emerging view is that the WFR of a single whisker in the adult PMBSF is a dynamic entity that can be modulated by a host of parameters and behavioral conditions. It is characterized by spatially large suprathreshold and even larger subthreshold components, which enable each WFR to inform most, if not all, WFRs in the PMBSF. However, active whisker-based exploratory navigation can modulate the functional organization of the cortex from a strategy of pooling information across many whiskers to a strategy that emphasizes smaller and more focused WFRs with less overlap and thus less pooling. Such behavioral modifications seem to relate to an unexpected perspective on the issue of WFR adult plasticity, reviewed next.

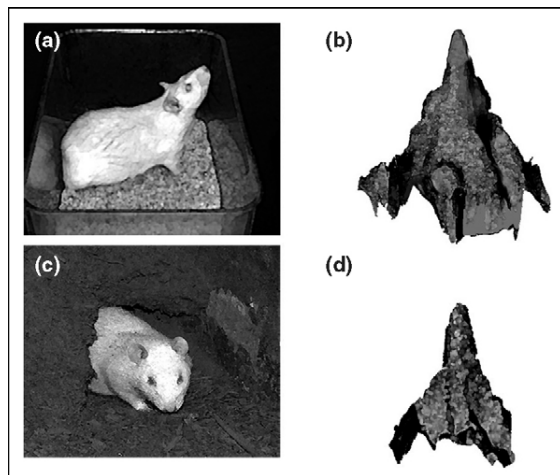
Plasticity

Until recently, experiments on experience-dependent plasticity in the adult PMBSF seem to be consistent only with the traditional ‘competition’ view of cortical plasticity, originally formulated for the developing cortex: advantageous inputs to the cortex induce stronger neuronal responses and gain more cortical territory at the expense of less advantageous neighboring inputs. Such a view is typically associated with underlying synaptic mechanisms that follow Hebbian rules — namely that cortical inputs with an ‘advantage’ induce synaptic strengthening of their pathways resulting in expansion and strengthening of their cortical representations. Thus,

for example, if a single whisker is spared by removing all other large whiskers on the snout — by follicle destruction, plucking or trimming — the spared WFR typically expands and strengthens, as demonstrated using 2-deoxyglucose (2DG) imaging, single unit recordings and intrinsic signal optical imaging (reviewed in [1,42,43]). Such plasticity has been recently generalized even to innocuous modulations, such as positive reinforcement given to a rodent following passive stimulation of a row of whiskers within the intact whisker array that resulted in an enlargement of the WFRs of the stimulated whiskers [44].

The first study to introduce the possibility of alternative types of plasticity in the adult PMBSF was a 2-DG imaging study by Welker and co-workers [45]. In this study the authors used a special magnetic stimulation system to stimulate passively an individual whisker within the intact whisker array continuously for up to 4 days in an awake, unrestrained mouse. The WFR of the stimulated whisker, rather than exhibiting the expected competition-based expansion and strengthening, was weakened and contracted. Indeed, the same group reported recently that this type of continuous passive stimulation results in a differential increase of inhibitory synapses compared with excitatory synapses in layer IV, which could help to explain their earlier findings [46]. Because of the unusual form of continuous, passive single whisker stimulation used in this study, it wasn’t clear how to interpret these findings, but later studies using a more naturalistic type of whisker stimulation demonstrated similar findings. Using chronic intrinsic signal optical imaging in the adult rat enabled Polley *et al.* [47] to follow a WFR of a spared whisker for one month. Whereas in caged rats the spared whisker FR expanded and increased in amplitude, the spared whisker FR in rats that were allowed to use their whiskers for a few minutes of navigation outside the cage contracted and weakened. Identical findings were reported using chronic intrinsic signal imaging of WFRs in non-deprived adult rats (i.e., rats having fully intact whisker arrays), by Polley *et al.* [48••]. Several WFRs were imaged within the same rat before and after transferring rats from their standard cage (SC) to live for a month in a naturalistic habitat (NH). The naturalistic habitat is an environment designed to imitate the rats’ natural surroundings as a means to encourage the expression of innate behaviors not otherwise possible in the SC, such as digging and remodeling an underground tunnel system, interactions with other rats and foraging. The WFRs in SC controls didn’t exhibit plasticity when repeatedly imaged over a month, whereas the WFRs of rats that spent a month in the NH exhibited massive plasticity: 46% contraction and 20% weakening of WFRs, as illustrated in Figure 1. In addition, the authors demonstrated that although spontaneous single-unit activity didn’t differ between NH and SC groups (thus ruling out a general increase in cortical inhibition), the response magnitude of evoked neuronal activity following whisker

Figure 1



An illustration to show the plasticity of an individual WFR of an adult rat before and after transfer from the standard cage to a naturalistic habitat. **(a)** A rat in a standard cage; **(b)** a 3-D image of a single WFR obtained from this rat. **(c)** The same rat after spending a month in a naturalistic habitat (the image shows the rat emerging from an underground tunnel in the naturalistic habitat); **(d)** a 3-D image of the same WFR obtained from this rat. For (b) and (d) the x and y axes show the spatial extent of evoked optical response and the z axis shows its amplitude. Note that after a month in the naturalistic habitat, the WFR was contracted and reduced in its amplitude [48**].

stimulation was reduced, and receptive fields were contracted yet sharper in the NH group. The single unit results indicate that the findings are not a simple outcome of increased cortical inhibition, but are rather related to a specific suppression of evoked neuronal responses in the cortex.

Taken together, these results suggest that previous patterns of whisker use are a strong modulating force for WFRs: continuously activating a whisker in a freely behaving rodent, or moving either deprived or non-deprived adult rats out of their SC to promote a more naturalistic use of their whiskers, induces a refinement of the functional organization of the PMBSF. WFRs in PMBSF become spatially focused, weaker, and more metabolically efficient following repeated active whisker use. These refinements are also detected at the underlying neuronal level: neurons exhibit smaller, sharper receptive fields and sparser evoked firings. These findings do not fit easily with the standard competition view, the underlying Hebbian mechanisms, and the common view that 'larger and stronger' is always synonymous with 'better' in the context of cortical representation.

The findings obtained from moving rats to the NH appear similar to those from the above-mentioned studies demonstrating that natural whisking during short exploratory navigation outside the SC induces cortical suppression that results in reduced evoked responses,

smaller and sharper receptive fields [12,20,37,38]. It is thus conceivable that prolonged natural use of whiskers, especially for digging, remodeling and exploring in underground tunnels within the NH, could lead to plasticity by consolidation of the suppression in the size and response magnitude of WFRs. That is, a case of persistent cortical modulation that eventually translates into a potentially permanent modification of the functional organization of the cortex. If this theory is correct, a refined cortex that exhibits small, weak WFRs might be characteristic of adult rats that are allowed to use their whiskers continuously in a more naturalistic manner.

Conclusions

WFRs in the adult PMBSF are typically large and, therefore, overlap, especially when subthreshold activation is also taken into account. However, there are various conditions and contexts that can modulate the size and amplitude of WFRs both rapidly and reversibly, for example by changing patterns of whisker use between quiet wakefulness versus exploration, or during slower plasticity that refines the functional organization of cortex over time, as in the case of transferring rodents 'out-of-their box' into a naturalistic habitat. These findings highlight the dynamic nature of WFRs, and demonstrate that there are other strategies of cortical plasticity in addition to the classical competition-based plasticity. The rapid developments in functional imaging techniques and electrode-arrays, which can now also be applied to behaving rodents, will hopefully lead to the establishment of a conceptual framework that will enable a better understanding of when and how different forms of dynamics in the adult cortex are utilized by different states of behavior.

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References and recommended reading

Papers of particular interest, published within the annual period of review, have been highlighted as:

- of special interest
 - of outstanding interest
1. Feldman DE, Brecht M: **Map plasticity in somatosensory cortex.** *Science* 2005, **310**:810-815.
 2. Fox K, Wong RO: **A comparison of experience-dependent plasticity in the visual and somatosensory systems.** *Neuron* 2005, **48**:465-477.
 3. Erchova IA, Lebedev MA, Diamond ME: **Somatosensory cortical neuronal population activity across states of anaesthesia.** *Eur J Neurosci* 2002, **15**:744-752.
 4. Kelly MK, Carvell GE, Kodger JM, Simons DJ: **Sensory loss by selected whisker removal produces immediate disinhibition in the somatosensory cortex of behaving rats.** *J Neurosci* 1999, **19**:9117-9125.
 5. Shimegi S, Ichikawa T, Akasaki T, Sato H: **Temporal characteristics of response integration evoked by multiple**

- whisker stimulations in the barrel cortex of rats. *J Neurosci* 1999, **19**:10164-10175.
6. Shimegi S, Akasaki T, Ichikawa T, Sato H: **Physiological and anatomical organization of multiwhisker response interactions in the barrel cortex of rats.** *J Neurosci* 2000, **20**:6241-6248.
 7. Webber RM, Stanley GB: **Nonlinear encoding of tactile patterns in the barrel cortex.** *J Neurophysiol* 2004, **91**:2010-2022.
 8. Higley MJ, Contreras D: **Nonlinear integration of sensory responses in the rat barrel cortex: an intracellular study in vivo.** *J Neurosci* 2003, **23**:10190-10200.
 9. Higley MJ, Contreras D: **Integration of synaptic responses to neighboring whiskers in rat barrel cortex in vivo.** *J Neurophysiol* 2005, **93**:1920-1934.
 10. Ego-Stengel V, Mello e Souza T, Jacob V, Shulz DE: **Spatiotemporal characteristics of neuronal sensory integration in the barrel cortex of the rat.** *J Neurophysiol* 2005, **93**:1450-1467.
 11. Kida H, Shimegi S, Sato H: **Similarity of direction tuning among responses to stimulation of different whiskers in neurons of rat barrel cortex.** *J Neurophysiol* 2005, **94**:2004-2018.
 12. Fanselow EE, Nicolelis MA: **Behavioral modulation of tactile responses in the rat somatosensory system.** *J Neurosci* 1999, **19**:7603-7616.
 13. Derdikman D, Hildesheim R, Ahissar E, Arieli A, Grinvald A: **Imaging spatiotemporal dynamics of surround inhibition in the barrels somatosensory cortex.** *J Neurosci* 2003, **23**:3100-3105.
 14. Petersen CC, Grinvald A, Sakmann B: **Spatiotemporal dynamics of sensory responses in layer 2/3 of rat barrel cortex measured in vivo by voltage-sensitive dye imaging combined with whole-cell voltage recordings and neuron reconstructions.** *J Neurosci* 2003, **23**:1298-1309.
 15. Grinvald A, Hildesheim R: **VSDI: a new era in functional imaging of cortical dynamics.** *Nat Rev Neurosci* 2004, **5**:874-885.
 16. Moore CI, Nelson SB: **Spatio-temporal subthreshold receptive fields in the vibrissa representation of rat primary somatosensory cortex.** *J Neurophysiol* 1998, **80**:2882-2892.
 17. Zhu JJ, Connors BW: **Intrinsic firing patterns and whisker-evoked synaptic responses of neurons in the rat barrel cortex.** *J Neurophysiol* 1999, **81**:1171-1183.
 18. Brecht M, Sakmann B: **Dynamic representation of whisker deflection by synaptic potentials in spiny stellate and pyramidal cells in the barrels and septa of layer 4 rat somatosensory cortex.** *J Physiol* 2002, **543**:49-70.
 19. Brecht M, Roth A, Sakmann B: **Dynamic receptive fields of reconstructed pyramidal cells in layers 3 and 2 of rat somatosensory barrel cortex.** *J Physiol* 2003, **553**:243-265.
 20. Castro-Alamancos MA: **Role of thalamocortical sensory suppression during arousal: focusing sensory inputs in neocortex.** *J Neurosci* 2002, **22**:9651-9655.
 21. Brett-Green B, Paulsen M, Staba RJ, Fikova E, Barth DS: **Two distinct regions of secondary somatosensory cortex in the rat: topographical organization and multisensory responses.** *J Neurophysiol* 2004, **91**:1327-1336.
 22. Brett-Green BA, Chen-Bee CH, Frostig RD: **Comparing the functional representations of central and border whiskers in rat primary somatosensory cortex.** *J Neurosci* 2001, **21**:9944-9954.
 23. Erinjeri JP, Woolsey TA: **Spatial integration of vascular changes with neural activity in mouse cortex.** *J Cereb Blood Flow Metab* 2002, **22**:353-360.
 24. Sheth S, Nemoto M, Guiou M, Walker M, Pouratian N, Toga AW: **Evaluation of coupling between optical intrinsic signals and neuronal activity in rat somatosensory cortex.** *Neuroimage* 2003, **19**:884-894.
 25. Sheth SA, Nemoto M, Guiou M, Walker M, Pouratian N, Hageman N, Toga AW: **Columnar specificity of microvascular oxygenation and volume responses: implications for functional brain mapping.** *J Neurosci* 2004, **24**:634-641.
 26. Devor A, Dunn AK, Andermann ML, Ulbert I, Boas DA, Dale AM: **Coupling of total hemoglobin concentration, oxygenation, and neural activity in rat somatosensory cortex.** *Neuron* 2003, **39**:353-359.
 27. Devor A, Ulbert I, Dunn AK, Narayanan SN, Jones SR, Andermann ML, Boas DA, Dale AM: **Coupling of the cortical hemodynamic response to cortical and thalamic neuronal activity.** *Proc Natl Acad Sci USA* 2005, **102**:3822-3827.
 28. Dubroff JG, Stevens RT, Hitt J, Maier DL, McCasland JS, Hodge CJ: **Use-dependent plasticity in barrel cortex: intrinsic signal imaging reveals functional expansion of spared whisker representation into adjacent deprived columns.** *Somatosens Mot Res* 2005, **22**:25-35.
 29. Rector DM, Carter KM, Volegov PL, George JS: **Spatio-temporal mapping of rat whisker barrels with fast scattered light signals.** *Neuroimage* 2005, **26**:619-627.
 30. Shibuki K, Hishida R, Murakami H, Kudoh M, Kawaguchi T, Watanabe M, Watanabe S, Kouuchi T, Tanaka R: **Dynamic imaging of somatosensory cortical activity in the rat visualized by flavoprotein autofluorescence.** *J Physiol* 2003, **549**:919-927.
 31. Weber B, Burger C, Wyss MT, von Schulthess GK, Scheffold F, Buck A: **Optical imaging of the spatiotemporal dynamics of cerebral blood flow and oxidative metabolism in the rat barrel cortex.** *Eur J Neurosci* 2004, **20**:2664-2670.
 32. Masino SA: **Quantitative comparison between functional imaging and single-unit spiking in rat somatosensory cortex.** *J Neurophysiol* 2003, **89**:1702-1712.
 33. Ghazanfar AA, Nicolelis MA: **Spatiotemporal properties of layer V neurons of the rat primary somatosensory cortex.** *Cereb Cortex* 1999, **9**:348-361.
 34. Petersen RS, Diamond ME: **Spatial-temporal distribution of whisker-evoked activity in rat somatosensory cortex and the coding of stimulus location.** *J Neurosci* 2000, **20**:6135-6143.
 35. Martin C, Berwick J, Johnston D, Zheng Y, Martindale J, Port M, Redgrave P, Mayhew J: **Optical imaging spectroscopy in the unanaesthetized rat.** *J Neurosci Methods* 2002, **120**:25-34.
 36. Ferezou I, Bolea S, Petersen CCH: **Visualizing the cortical representation of whisker touch: voltage-sensitive dye imaging in freely moving mice.** *Neuron* 2006, **50**:617-629.
- A technical tour-de-force. The authors image the WFR of a spared whisker in the adult mouse during quiet, unrestrained wakefulness and during free exploratory behavior. The results enable the visualization of strong, and sometimes rapid, modulation of whisker functional representations during these states.
37. Castro-Alamancos MA, Oldford E: **Cortical sensory suppression during arousal is due to the activity-dependent depression of thalamocortical synapses.** *J Physiol* 2002, **541**:319-331.
 38. Castro-Alamancos MA: **Absence of rapid sensory adaptation in neocortex during information processing states.** *Neuron* 2004, **41**:455-464.
 39. Castro-Alamancos MA: **Dynamics of sensory thalamocortical synaptic networks during information processing states.** *Prog Neurobiol* 2004, **74**:213-247.
- This thorough review summarizes the author's line of research on the effect of arousal (as opposed to quiescent states) on the thalamocortical network in the barrel system of the anesthetized and behaving rat. His and others' research demonstrate that during arousal the cortex is suppressed, a situation that seems advantageous for sensory processing.
40. Krupa DJ, Wiest MC, Shuler MG, Laubach M, Nicolelis MA: **Layer-specific somatosensory cortical activation during active tactile discrimination.** *Science* 2004, **304**:1989-1992.
 41. Ganguly K, Kleinfeld D: **Goal-directed whisking increases phase-locking between vibrissa movement and electrical activity in primary sensory cortex in rat.** *Proc Natl Acad Sci USA* 2004, **101**:12348-12353.
 42. Kossut M: **Plasticity of the barrel cortex neurons.** *Prog Neurobiol* 1992, **39**:389-422.

43. Fox K, Glazewski S, Schulze S: **Plasticity and stability of somatosensory maps in thalamus and cortex.** *Curr Opin Neurobiol* 2000, **10**:494-497.
44. Siucinska E, Kossut M: **Experience-dependent changes in cortical whisker representation in the adult mouse: a 2-deoxyglucose study.** *Neuroscience* 2004, **127**:961-971.
45. Welker E, Rao SB, Dorfl J, Melzer P, van der Loos H: **Plasticity in the barrel cortex of the adult mouse: effects of chronic stimulation upon deoxyglucose uptake in the behaving animal.** *J Neurosci* 1992, **12**:153-170.
46. Knott GW, Quairiaux C, Genoud C, Welker E: **Formation of dendritic spines with GABAergic synapses induced by whisker stimulation in adult mice.** *Neuron* 2002, **34**:265-273.
47. Polley DB, Chen-Bee CH, Frostig RD: **Two directions of plasticity in the sensory-deprived adult cortex.** *Neuron* 1999, **24**:623-637.
48. Polley DB, Kvasnak E, Frostig RD: **Naturalistic experience •• transforms sensory maps in the adult cortex of caged animals.** *Nature* 2004, **429**:67-71.
- The authors provide a demonstration of unexpected cortical plasticity following transfer of adult rats from their home cage to a naturalistic habitat, resulting in refined cortical functional organization.

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