Review: How do spontaneous and sensory-evoked activities interact?

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Abstract. Twenty years ago, the seminal work of Grinvald et al. revolutionized the view cast on spontaneous cortical activity by showing how, instead of being a mere measure of noise, it profoundly impacts cortical responses to a sensory input and therefore could play a role in sensory processing. This paved the way for a number of studies on the interactions between spontaneous and sensory-evoked activities. Spontaneous activity has subsequently been found to be highly structured and to participate in high cognitive functions, such as influencing conscious perception in humans. However, its functional role remains poorly understood, and only a few speculations exist, from the maintenance of the cortical network to the internal representation of an a priori knowledge of the environment. Furthermore, elucidation of this functional role could stem from studying the opposite relationship between spontaneous and sensory-evoked activities, namely, how a sensory input influences subsequent internal activities. Indeed, this question has remained largely unexplored, but a recent study by the Grinvald laboratory shows that a brief sensory input largely dampens spontaneous rhythms, suggesting a more sophisticated view where some spontaneous rhythms might relate to sensory processing and some others not.© The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: 10.1117/1.NPh.4.3.031221]

Keywords: spontaneous activity; sensory processing; cerebral cortex; brain states.

Paper 17010SSVR received Jan. 17, 2017; accepted for publication May 16, 2017; published online Jun. 13, 2017.

1 Spontaneous Activity Influences Evoked Responses

Investigating the features detected by individual neurons or by neuronal assemblies has been one of the most successful approaches to understanding brain organization and function. This approach requires measuring the neuronal responses to a set of different sensory inputs; as a consequence, the variability of these responses between different presentations of the same stimulus has long been considered a disturbance that needed to be overcome by trigger-averaging over a number of presentations. This unfortunately led to the disregard of this variability in evoked responses—as well as the large activity fluctuations observed in the absence of stimulation—and rather consider them as noise.

Twenty years ago, however, Arieli et al.1 focused their interest on these response variabilities and spontaneous ongoing activity, using single-neuron electrical recordings coupled with voltage-sensitive dyes (VSDs) to measure coherent activities in the visual cortex of anesthetized cats. They observed, in particular, that ongoing fluctuations and response variabilities had amplitudes as large as the evoked responses, were highly correlated between neurons as far as 6-mm apart, and showed structure in both space and time. This led them to emphasize the importance of studying these activities as they speculated that the "ongoing electrical activity and its specific interactions with the activity evoked by the stimulus may be one neuronal expression of context." This speculation was greatly confirmed by their next report2 where they showed that the variability in response patterns evoked by individual stimulus presentations could be well accounted for by the ongoing patterns that immediately preceded the stimulation [Fig. 1(a)]. This evidence for integration of a deterministic response to the sensory input with the ongoing network dynamics reinforced their argument that ongoing activity "may provide the neural substrate for the dependence of sensory information processing on context and on behavioral and conscious states."

They succeeded in triggering a new consideration for ongoing dynamics, and a large number of studies that followed investigated how spontaneous activity patterns influence the responses to specific stimulations.2–23 It is noteworthy that the positive correlation that they reported between ongoing activity and sensory-evoked responses was soon contradicted and that a wider range of interactions was subsequently reported. Indeed, Petersen et al.1 observed, in the barrel cortex of anesthetized rats, that sensory-evoked responses were much stronger when ongoing activity was low compared to when it was high. More precisely, the ongoing activity in this preparation showed characteristic up and down states,24 where the whole network activity in a local neighborhood alternates between periods of tonic activity (up), possibly propagating as waves, and silence (down). During such synchronized cortical states, which can also be observed during quiet wakefulness,6,14 responses evoked by tactile or tone stimuli are typically of large amplitude and are inversely correlated to the prestimulus membrane potential.1,13,23 The sensory-evoked cortical responses are further suppressed when the cortex switches from slow wave activity to a more desynchronized state, typical of active wakefulness.6,14 Such suppression of evoked cortical activity occurring during behaviorally active states has been reported both in the primary somatosensory (see also Refs. 25 and 26) and primary auditory cortex.27–29 However, several recent studies indicate that the interaction
between behavioral activity, cortical state, and sensory-evoked responses is opposite in the primary visual cortex.\textsuperscript{4,22,30} The interplay between ongoing cortical dynamics and sensory inputs, therefore, does not seem to follow common rules across sensory modalities. Furthermore, by recording the membrane potential of mice engaged in a tactile detection task, a recent study from Petersen lab\textsuperscript{36} revealed that, although the ongoing cortical state impacts the evoked sensory response, it has no effect on the performance of the animal.

In the human neuroscience community, the study of ongoing dynamics has met a great interest\textsuperscript{3,37} (see Ref. 38 for a review). This stems from the interest for high cognitive functions in humans, such as imagination or consciousness, of which ongoing activity could be a hallmark [see also later our mention to the “default mode network (DMN)”). The influence of ongoing cortical dynamics on the processing of sensory inputs was also established. As an example, Hesselmann et al.\textsuperscript{3} found using fMRI that the perception of a flashed ambiguous face–vase stimulus depended on prestimulation activity level. Adapted from Ref. 3 with permission.

Structure of Spontaneous Activity Reflects Functional Organization and is Influenced by Experience

The Grinvald laboratory made other keystone contributions to the study of spontaneous activity by taking advantage of the exquisite topographical organization of the cat visual cortex, on the one hand, and of VSDs on the other hand, to capture this organization. Functional structures usually revealed by sensory stimulation were also found in the spontaneous dynamics: at the level of a single-neuron functional connectivity,\textsuperscript{43} where population activity maps trigger-averaged on a single-neuron spikes appeared to be near-identical in the resting or stimulation conditions; and at the level of the population representations,\textsuperscript{44} where spontaneous activity patterns were observed, which highly resembled evoked orientation maps [Fig. 2(a)].

That the spontaneous activity reflects the functional organization of the cortical network on which it is riding is not a surprise and has been confirmed at the scale of the whole dorsal surface of cortical hemispheres in mice by VSD imaging.\textsuperscript{45}

However, the spectacular aspect of spontaneously emerging orientation maps raised a new question: can the spontaneous cortical states play an active role in sensory processing, as the authors suggested that they might “reflect expectations about the sensory input?”

An additional relationship between sensory-evoked and spontaneous activities lies in the plasticity of the latter, in the sense that sensory-evoked activity can reshape the structure of subsequent spontaneous patterns through learning. This was shown in particular by Dan group\textsuperscript{45,48} who, after training rats with visual stimuli to evoke wave patterns in their primary visual cortex, observed recalls of these specific patterns in the spontaneous activity during the resting period that followed [Fig. 2(b)]. Such recalls or replays are in fact a phenomenon that is well-known and abundantly studied, in particular, in hippocampal structures.\textsuperscript{49,50}

The similarities in structure between spontaneous and sensory-evoked activities might, therefore, be learned through experience rather than innately. In this light, Berkes et al.\textsuperscript{51} emphasized changes that occur during development, whereby an initial mismatch between the statistics of spontaneous and sensory-evoked (using natural visual stimuli) activities in young ferrets disappears in adult animals [Fig. 2(c)]. There again it is suggested that spontaneous activity reflects prior expectations of “an internal model (of the natural environment) that is adapted gradually during development.”

Moreover, spontaneous activity is known to play an active role during development, in particular, in the early stages of development where propagating waves of activity are known to shape and consolidate the developing networks (see reviews in Refs. 29 and 55, as well as the review from Luhmann\textsuperscript{56} in this issue of \textit{Neurophotonics}). This is a whole field of investigation...
in itself, and it is not obvious how these spontaneous activities during early development relate to those observed in adults.

Plasticity in the spontaneous activity structure has also been shown in humans. Lewis et al.37 found that a stimulated part of the visual cortex modified its resting-state connectivity after training as compared to the untrained part. A few studies have investigated changes in the resting-state network induced by preceding task periods involving memorization or emotional content (see Ref. 38 for review).

Whereas we started this retrospective review with the influence of spontaneous activity on sensory-evoked responses,2 we have now discussed influences in the opposite direction through learning. However, another important question has been raised: does the spontaneous activity really embed a representation of “expectations” in such a way that it plays an active role during sensory processing? To address this question, a new level of interaction is envisioned: how are spontaneous dynamics affected by a sensory inflow?

3 Sensory Input Switches the Brain Internal Dynamics

3.1 Brain Dynamics during a Sensory Input

“Stimulus onset quenches neural variability: a widespread cortical phenomenon,”38 under this title, a number of well-known neuroscientists gathered 14 different electrophysiology datasets recorded in cats and monkeys, which all showed that intertrial variability decreased in sensory-evoked responses as compared to the preceding period of spontaneous activity [Fig. 3(a)]. Fluctuations present in the spontaneous activity [Fig. 3(a), top] systematically decreased in amplitude during stimulation, even in instances where this stimulation was not eliciting an “average response” [Fig. 3(a), middle] (Note that, even though it is artificial to split the signals after stimulus onset between an “average response” and “remaining fluctuations,” we chose to call these fluctuations “internal” or “internally generated” activity, as obviously it cannot be called a “spontaneous activity”). This phenomenon actually was already known from intracellular studies35 that showed how a sensory input resulted in very reproducible driving of a neuron membrane potential as compared to the spontaneous fluctuations and identified shunting inhibition as a mechanism for the rescaling of the cell excitability.

Even though it appears intuitive that a sensory drive might “clamp” the firing dynamics to fixed patterns and therefore reduce the variability due to random fluctuations generated by the network itself, neural simulations revealed interesting properties of this general effect. For example, the work of Abbott group22,61 showed not only that variability reduction was an intrinsic property of interconnected networks shifting from chaotic to driven dynamics when exposed to an input but also that complex nonlinear interactions occurred between intrinsic and sensory-driven dynamics. These included the preference for some input frequency without any resonance effect, the drive at harmonic frequencies initially not present in the input, and the curving of the spatial patterns of the input toward those of the intrinsic dynamics. Some of these effects were later confirmed experimentally.34 On the other hand, other computational neuroscientists have advocated that the reduction of variability corresponds to a very peculiar structural property of the brain network, such that its activity spans a highly multidimensional space “at the edge” of multiple bifurcations, leading to multiple
In the absence of a sensory input, the spontaneous activity can visit a large repertoire of states; however, even a weak external input can lead it to fall into one of the attractors, which decreases variability. In addition to this modeling effort, a functional role in sensory processing was proposed: the spontaneous activity, as playing an active role in sensory processing, the network explores all possibilities learned from accumulated experience. This view, however, appears quite restrictive in regard to some stereotypic and widespread spontaneous rhythms, which are unlikely to achieve a “sampling of internal representations,” such as the up and down fluctuations.

3.2 Brain Dynamics after a Sensory Input

To further investigate the interactions between spontaneous and evoked activities, Deneux and Grinvald explored how the internal dynamics would be modified “after” a brief sensory input. In the barrel cortex of anesthetized rats, with a preparation that displays the stereotypical up and down states, the authors observed that even after a brief single whisker stimulation, this rhythm was significantly perturbed for several seconds, with up events failing to occur, in particular, in the stimulated barrel-related column [Fig. 4(a)]. As a result, the interaction between internal (recurrent, top-down) and feedforward activities did not appear any more as the smooth integration of two complementary activities, but on the contrary as a competition between orthogonal activities. The authors indeed suggested that “at the onset of a sensory input, some internal messages are silenced to prevent overloading of the processing of relevant incoming sensory information.” In addition, this switch in the internal dynamics was also characterized by a transient burst of activity at around 15 Hz (identified as a thalamo-cortical oscillation) and a transient activity increase of a small fraction of the neurons [both visible in Fig. 4(a); the ~15-Hz activity is marked with gray arrows]. These two patterns occur identically as well after the onset of a longer, sustained stimulation (not visible...
in the figure, see Ref. 68 for details) and thus appear as a stereotyped sequence of events that take place in the presence of a new sensory stream. Finally, the internal activity decrease showed some spatial organization as it was maximal in the stimulated barrel location [visible in Fig. 4(a)], indicating that local mechanisms might be at work.

In this report, emphasis is put on a rupture between pre- and poststimulus onset activities, with the notion that specific switching occurs, affecting subsequent dynamics at the temporal scale of seconds. To this respect, the authors of this review also present in this issue of Neurophotonics a research article of particular interest as it reproduces in an awake monkey V4 area the variability “quenching” reported by Churchland et al.58 (yet adding the precision that the activity that is suppressed is a specific global and low-frequency fluctuation). It further shows that this suppression already occurs with maximal strength from the lowest contrast, suggesting that a specific switch occurs rather than a continuous integration.

The notion that an input may cause a switch in the dynamics of a network activity is already present in computational models of the brain65 and has been reported in in-vitro studies72–74 where microstimulations remarkably induced transitions between up and down, or between synchronized and desynchronized states, as well as in vivo, using nonphysiological stimuli.75 Also, it has been known for a long time in the human neuroscience community that sensory inputs alter synchronized rhythms, with the most famous effect being the decrease in alpha rhythms76–78 and that resting-state activity in the DMN decreases upon stimulation.39,42,79

It is in fact expected that a new sensory input might cause major changes in the global brain state, switching it, for example, from quiet to active or from asleep to conscious. Studying the details and mechanisms of these switches in addition to the mechanisms of specific rhythms taken in isolation will probably provide new insights on these complex properties of the brain network. As an example, checking how existing models of generation of the up and down fluctuations69,80,81 [Fig. 4(b)] would predict not only the evoked responses18,82 but also subsequent internal activity changes is warranted.

3.3 Global Network Changes

The changes in cortical dynamics induced by the presence of a sensory input occur also at the scale of the full brain, indicative of a change of the subject global state. This is the topic of functional connectivity studies in humans, for which the imaging techniques (EEG, MEG, fMRI, PET), characterized by coarse spatial resolution but access to the whole brain at once, are
particularly adapted. A set of structurally and functionally connected brain regions specifically deactivated during tasks that demand attention to external stimuli and innovative events has been collectively named the “DMN.” Although the understanding of its role in brain function still remains largely elusive, the implication of the DMN in internal modes of cognition (autobiographical memory, self-referential thought, and mind-wandering) as well as its alterations in neuropsychiatric disorders is the subject of intense research efforts. The ongoing DMN activity has been reported to be negatively correlated with stimulus-induced responses and perception in humans; however, positive correlation has been also observed, suggesting that the experimental context and the behavioral paradigm strongly impact the link between DMN activity and sensory processing.

4 Not One but Many Spontaneous Activities

Altogether, it appears that, despite considerable efforts aimed at studying the spontaneous activity, its functional role remains elusive and might range from low-level maintenance and consolidation of the network to high-level signature of consciousness. In particular, even though it is undisputable that ongoing states interfere with sensory processing and are reshaped by learning, direct experimental testing of whether they take an active role in sensory processing remains difficult. Obviously, it is a pitfall anyway to consider spontaneous activity as a homogeneous phenomenon, as it entails all neural processes, unconscious and conscious, that are not directly (or at least not easily) accessible to probing by identified stimulations or tasks. Even the apparent same rhythms in different contexts can in fact display important structural differences, as was shown with slow frequency activity that appeared to be more local during slow wave sleep compared to during quiet wakefulness.

However, the impressive development of in vivo optical methods, pioneered in particular by Grinvald, which allow probing cortical spatiotemporal dynamics at the single-trial level in both anesthetized and awake preparations, will undoubtedly keep on bringing precious keys to further unravel the functional interplay between internal dynamics and sensory inputs in cortical networks.

Disclosure

No conflicts of interest, financial or otherwise, are declared by the authors.

Acknowledgments

The authors are funded by the Centre National de la Recherche Scientifique, France.

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