Spotlight

Prefrontal alpha- and beta-band oscillations are involved in rule selection

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A recent study in monkeys reports that oscillatory neuronal synchronization between ensembles of prefrontal neurons is involved in rule selection. The study demonstrates that beta-band synchronization (19–40 Hz) reflects the selection of a rule, whereas alpha-band synchronization (6–16 Hz) reflects the active inhibition of a not-to-be-applied rule.

In daily life, people are often confronted with situations where different rules need to be applied depending on the context. For instance, the head of a hammer is used to drive a nail, whereas, in order to extract a nail, the claw must be used instead. In multilingual settings, different rules are used to interpret speech depending on the language spoken. Behavior in social settings is also dominated by context-dependent rules. For instance, one acts differently when having lunch with one's spouse than when having lunch with one's boss. Although it is well-established that the prefrontal cortex (PFC) is involved in rule selection [1], little is known about the underlying neurophysiological mechanisms.

Buschman *et al.* [2] conducted a study in which they recorded from multiple electrodes implanted in the dorsolateral PFC of monkeys. The monkeys were cued to perform either a color or an orientation discrimination task. This constituted 'the rule' (Figure 1a). The cue was followed a few hundred milliseconds later by the target stimulus, which was composed of a colored bar with a given orientation (Figure 1a). After the target stimulus was presented, the monkeys were trained to make a saccade to the left or right depending on the rule. For instance, if the color rule was to be applied, the monkey had to make a right saccade in response to a red bar and a left saccade for a blue bar. When the orientation rule was applied, the monkey would make a left saccade for a vertical bar and a right saccade for a horizontal bar. This paradigm allowed the investigation of neuronal activity associated with rule selection before and during the presentation of the target stimulus.

The authors found that the local field potentials (LFPs) of a subset of the electrodes synchronized in the higher beta band (19–40 Hz) around stimulus onset when the color rule was applied (Figure 1b, blue traces). When the orientation rule was applied, LFPs from a different set of electrodes synchronized in the same frequency band. Crucially, when the more difficult color rule was applied, the researchers observed pre-stimulus synchronization in the alpha band (6–16 Hz) for electrodes showing a preference for the orientation rule (Figure 1b, red traces). The oscillatory activity had consequences for behavior: especially stronger alpha-band synchronization allowed the monkeys to perform the task faster. In line with the behavioral effects, the higher the anticipatory alpha power for the orientation ensemble, the higher the spike rate of the color-rule ensemble during stimulus presentation. Additionally it was demonstrated that neuronal spiking was phase-locked to beta oscillations. The phasic influence of alpha oscillations remains to be further characterized. According to the pulsed inhibition hypothesis [10], the spiking activity of the orientation-selective neurons should be constrained by the phase of alpha oscillations in the pre-stimulus interval when preparing for the color rule.

The findings of this study imply that neuronal synchronization in the beta band is involved in higher-order executive functioning, such as rule selection. In particular, a given rule is represented by an ensemble of neurons in PFC that oscillate in synchrony in the beta band. This is akin to the theory of feature binding by neuronal synchronization as proposed for the visual system [3]. The strong phase-locking between spikes and LFPs demonstrates that the timing of neuronal action potentials is determined by the phase of ongoing oscillations. As such, oscillations are intimately involved in controlling the dynamics underlying neuronal computations. Oscillations might not only be important for creating neuronal ensembles within regions, but also for communication between distant regions [4]. Previous work has demonstrated that top-down modulation is mediated by long-range synchronization in the beta band [5]. It is therefore possible that the selected rule is further communicated to sensory regions by long-range beta-band synchronization.

Neuronal synchronization in the alpha band is consistent with the suggestion that alpha-band synchronization reflects functional inhibition [6]. It has previously been demonstrated that neuronal firing decreases as alpha-band power increases [7]. Furthermore, an increase in alpha-band synchronization in sensory regions has been shown to be predictive of performance when distractors can be anticipated [8]. Whereas these results have typically been reported in sensory regions, Buschman *et al.* now show that the functional role of alpha-band synchronization generalizes to include the execution of operations in PFC. The fact that performance correlates with alpha-band synchronization is in stark contrast to the conventional view that alpha-band activity simply reflects idling or rest.

The stage is now set for investigating if similar phenomena can be found in humans. Certainly, both alpha- and beta-band activity are readily detectable by EEG and

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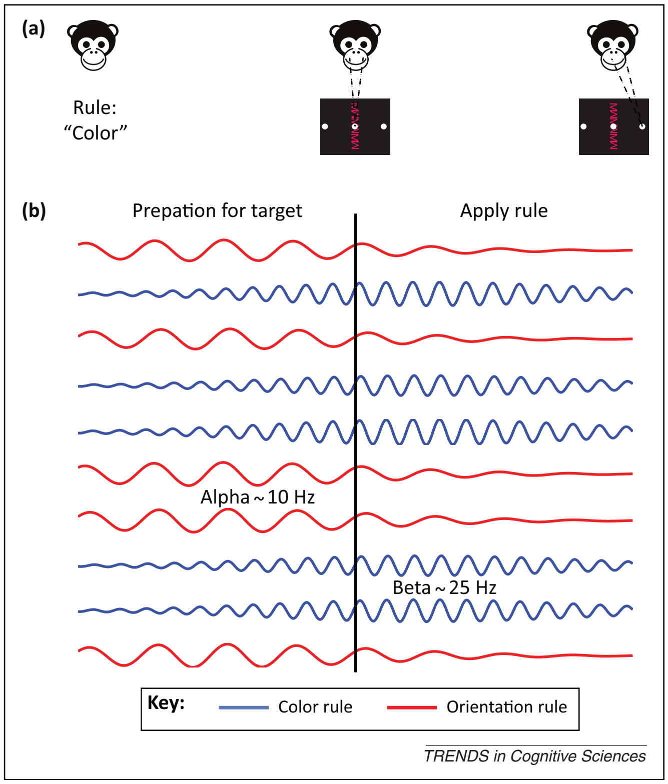

Figure 1. Neuronal synchronization associated with rule application. **(a)** Monkeys were trained to apply a color or an orientation rule as determined by the initial cue. The cue was followed by the target: a bar that was either red or blue. The orientation of the bar was either horizontal or vertical. The task of the monkeys was to identify either the color or the orientation of the bar and to respond accordingly by performing a left or a right saccade. In the example presented here, the monkey was instructed to apply the color rule. In response to the red bar, the monkey made a left saccade. **(b)** Neuronal activity was recorded from a large array of electrodes implanted in PFC. In a subset of the electrodes, LFPs synchronized in the beta band (blue traces) when the color rule was applied, whereas in another subset, LFPs synchronized in the same band when the orientation rule was applied (red traces). Importantly, the orientation-selective electrodes synchronized in the alpha band prior to the application of the color rule (red traces, left).

MEG recordings. The whole-head coverage of these techniques makes it possible to study the top-down control exercised by the PFC on sensory areas by means of coherence in the beta and alpha band [8,9]. For instance, the selection of the color rule might be reflected by the respective PFC ensemble becoming coherent with activity in ventral regions (e.g., the color selective V4) in the beta band. Similarly, the de-selection of the orientation rule would be reflected by alpha-band synchronization between PFC and dorsal posterior parietal regions.

The study by Buschman *et al.* opens new avenues for the investigation of the functional role of brain oscillations in higher cognitive functioning. Whereas anticipatory alpha-band synchronization determines the state of a network, beta-band synchronization seems to reflect stimulus-relevant processing instead. Interestingly, concepts initially applied to the interpretation of human alpha oscillations seem to apply to monkey PFC also. It would be of great interest to investigate if the beta-band findings in PFC on rule selection generalize to humans. From a theoretical perspective, there is a need to develop further the mechanistic understanding of the role of phasic entrainment provided by ongoing oscillations. Although alpha-band synchronization reflects functional inhibition, it is not clear why this type of inhibition is oscillatory. Alpha-band oscillations may be involved in prioritizing neuronal processing and organizing a temporal code [10]. Certainly, the findings of Buschman *et al.* add to a growing body of evidence that emphasizes the functional significance of neuronal oscillations by demonstrating the existence of a link between neuronal synchronization and higher cognitive operations.

Acknowledgments

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