Article

Neuron

Arousal and Locomotion Make Distinct Contributions to Cortical Activity Patterns and Visual Encoding

Highlights

- Behavioral state transitions reveal epochs of arousal without locomotion
- Isolated arousal is linked with suppressed firing rates and altered LFP activity
- Locomotion is associated with elevated visual cortex firing rates
- Arousal mediates enhanced visual processing

Authors

Martin Vinck, Renata Batista-Brito, Ulf Knoblich, Jessica A. Cardin

Correspondence

jess.cardin@yale.edu

In Brief

Spontaneous and sensory-evoked brain activity varies with behavior, but the contributions of arousal state and motor activity to these changes remain unclear. Vinck et al. identify separate roles of arousal and locomotion in regulating sensory processing in visual cortex.

Vinck et al., 2015, Neuron *86*, 740–754
May 6, 2015
http://dx.doi.org/10.1016/j.neuron.2015.03.028

Cell Press

Neuron
Article

Arousal and Locomotion Make Distinct Contributions to Cortical Activity Patterns and Visual Encoding

Martin Vinck,[1,3] Renata Batista-Brito,[1,3] Ulf Knoblich,[1,4] and Jessica A. Cardin[1,2,*]
[1]Department of Neurobiology, Yale University School of Medicine, 333 Cedar Street, New Haven, CT 06520, USA
[2]Kavli Institute of Neuroscience, Yale University, 333 Cedar Street, New Haven, CT 06520, USA
[3]Co-first author
[4]Present address: Allen Brain Institute, 551 N. 34th Street, Seattle, WA 98103, USA
*Correspondence: jess.cardin@yale.edu
http://dx.doi.org/10.1016/j.neuron.2015.03.028

SUMMARY

Spontaneous and sensory-evoked cortical activity is highly state-dependent, yet relatively little is known about transitions between distinct waking states. Patterns of activity in mouse V1 differ dramatically between quiescence and locomotion, but this difference could be explained by either motor feedback or a change in arousal levels. We recorded single cells and local field potentials from area V1 in mice head-fixed on a running wheel and monitored pupil diameter to assay arousal. Using naturally occurring and induced state transitions, we dissociated arousal and locomotion effects in V1. Arousal suppressed spontaneous firing and strongly altered the temporal patterning of population activity. Moreover, heightened arousal increased the signal-to-noise ratio of visual responses and reduced noise correlations. In contrast, increased firing in anticipation of and during movement was attributable to locomotion effects. Our findings suggest complementary roles of arousal and locomotion in promoting functional flexibility in cortical circuits.

INTRODUCTION

Patterns of cortical activity differ dramatically across behavioral states, such as sleeping, anesthesia, and waking (Berger, 1929; Haider et al., 2013; Steriade et al., 1993; Steriade et al., 2001). Likewise, neural responses to sensory inputs depend strongly on ongoing patterns of internally generated activity (Civillico and Contreras, 2012; Hasenstaub et al., 2007; Livingstone and Hubel, 1981). The generation of multiple activity patterns associated with sleep and anesthesia states has been examined in great detail (Berger, 1929; Contreras et al., 1996; Destexhe et al., 1999; McCormick and Bal, 1997; Steriade et al., 1993, 2001). However, relatively little is known about transitions between distinct waking states, such as quiescence, arousal, and focused attention.

Recent studies in rodents have contrasted inactive versus active behavioral states, in particular quiescent versus whisking (Crochet and Petersen, 2006; Gentet et al., 2010; Zagha et al., 2013) or running (Bennett et al., 2013; Fu et al., 2014; Keller et al., 2012; Niell and Stryker, 2010; Polack et al., 2013; Reimer et al., 2014; Saleem et al., 2013; Schneider et al., 2014; Zhou et al., 2014), and found profound differences in cortical activity patterns that resemble the effects of focused spatial attention in primates (Cohen and Maunsell, 2009; Fries et al., 2001; Harris and Thiele, 2011; McAdams and Maunsell, 1999; Mitchell et al., 2009). In mouse primary visual cortex (V1), locomotion is accompanied by altered firing rates, a reduction in low-frequency fluctuations in the membrane potential and local field potential (LFP), and an increase in LFP gamma-band oscillations (Keller et al., 2012; Niell and Stryker, 2010; Polack et al., 2013; Reimer et al., 2014; Saleem et al., 2013). Enhanced firing rates during locomotion are particularly prominent in inhibitory interneurons (Bennett et al., 2013; Fu et al., 2014; Niell and Stryker, 2010; Polack et al., 2013; Reimer et al., 2014). Locomotion is also associated with an increase in the gain of visual responses (Bennett et al., 2013; Niell and Stryker, 2010; Polack et al., 2013; Reimer et al., 2014).

Because the most commonly studied active states involve a substantial motor component, it remains unclear whether the associated changes in cortical activity patterns are specific to motor output or more generally attributable to changes in global arousal. Recordings during manipulations of the visual environment suggest that much of the change in firing rates during locomotion is consistent with multimodal processing of visual and motor signals (Keller et al., 2012; Saleem et al., 2013). The integration of locomotor and visual signals in V1 may thus represent elements of predictive coding or play a role in spatial navigation. However, locomotion-associated changes in cortical activity have been replicated by noradrenergic and cholinergic manipulations in the absence of motor output (Fu et al., 2014; Lee et al., 2014; Polack et al., 2013). Changes in V1 activity during locomotion may therefore result from recruitment of neuromodulatory systems that regulate global arousal levels.

Wakefulness comprises states of low and high arousal, but the relationship between changes in arousal and cortical activity remains poorly understood. The functional impact of motor feedback signals to sensory cortex is likewise only beginning to be explored (Guo et al., 2014; Lee et al., 2013; Schneider et al., 2014; Zagha et al., 2013). Here we used behavioral state monitoring and manipulation to dissociate the roles of locomotion and arousal in regulating neural activity in mouse V1. We

