SUPPLEMENTARY INFORMATION

Local Field Potentials analysis

Real-time neuronal signals were recorded from multiple channels (up to 16 channels, 40 kHz A/D conversion on each channel) using the Multichannel Acquisition Processor system (MAP, PlexonInc). Low frequency signals were pre-filtered between 0.7 to 170 Hz, further amplified and digitized at 1 kHz as LFP signals. LFPs were further filtered between 0.5 Hz and 100 Hz using a 4th order Butterworth filter. In order to remove line artifacts, we applied a digital notch at 60 Hz (4th order elliptic filter, 0.1 db peak-to-peak ripples, 40 db stopband attenuation). All filtering was applied by using forward and backwards filtering in order to obtain zero phase shifts. We discarded all trials that had more than 3 points outside the mean ± 4 standard deviations to avoid influence of irregular artifact noise from muscle activity or other sources.

The amplitude of LFPs was measured in each trial by standard deviation, peak-valley amplitude, or average voltage for specific periods of interest (i.e., in the 300 ms after the onset of the adapting stimuli, the 100ms inter-stimulus period, and the 300 ms after the onset of the test stimulus). We assessed whether LFPs were selective for orientation and whether adaptation affects LFP amplitude tuning by performing a trial-by-trial ANOVA test. To examine whether adaptation influences LFPs in specific frequency bands, we further calculated the time-frequency power spectrum of the LFP responses. In order to obtain optimal spectral concentration (Jarvis and Mitra, 2001; Mitra and Pesaran, 1999; Pesaran et. al., 2002; Womelsdorf et. al. 2006) we used the multitaper method by multiplying each data epoch with the taper and then Fourier transformed. We estimated the average LFP power density during the presentation of the test stimuli and during the inter-trial interval.

The power spectral density was normalized by dividing the average power spectrum during the 300ms fixation period before the presentation of the adapting stimulus (averaged across all trials in a session). This helped balance the power spectrum between low and high frequency within same amplitude range (raw LFP power is domain at low frequency), and also made it possible to compare stimulus and adaptation driving component among recordings at different electrodes and brain activity status. We defined the average power of alpha, beta, and gamma bands as the mean power at frequencies between 8~13Hz, 15~30 Hz, 35~80 Hz. We calculated the average power using
rectangle approximation of the integral of the signal's multi-taper power spectral density. The frequency accuracy of the power spectral density is 1000/128 Hz (due to the 1 kHz sampling rate and the 128-ms Hanning tapered window; the frequency space was sampled every 3.9 Hz).

To examine whether adaptation increases the coupling between the spike trains and LFPs, we calculated the spike triggered average (STA) and spike-field coherence (SFC). The coherence between two signals is a complex quantity whose magnitude is a measure of the phase synchrony for a given frequency. We computed spike-triggered averages (STAs) by averaging the LFP signal within a window centered ±150 ms on each elicited spike within 300 ms after the onset of the test stimulus. STA is normalized for spike count as it is calculated by summing all LFP segments and then dividing by the number of spikes. To quantify STA, we calculate its power spectrum (i.e., the magnitude of all frequency components of the STA as a function of frequency). SFC was computed by dividing the power spectrum of the STA to the average of all power spectra of the LFP segments that were used to obtain the STA (Womelsdorf et al., 2006). Thus, SFC is independent of the firing rate of the single units and the power spectrum of the LFPs. SFC ranges from 0 – lack of synchronization, to 1 – perfect phase synchronization. We also assessed the temporal SFC spectrum by using windows of ±150 ms that were moved over the data in 10-ms steps from 100 ms before the onset of the adapting stimulus to 100 ms after the disappearance of the test stimulus. To compute the z-scored SFC values, we used the following transformation: $z = \beta(q - \beta)$, where $q = \sqrt{-\frac{(V - 2) \cdot \log(|C|^2)}}, \beta = 1.15, C$ is the spike-field coherence, and $V$ is number of degrees of freedom (cf. Jarvis and Mitra, 2001).

References


Supplementary Figure 1. Spike density and LFP power for the spike-LFP pair shown in Figure 1B-C.

(A) The PSTHs represent the responses of the neuron from Fig. 1C to the adapting and test stimuli in the control (blue) and adaptation (red) conditions. The two horizontal bars represent the presentation of the adapting and test stimuli. Adaptation led to a 28% decrease in the mean response to the test stimulus. (B) Changes in power spectral density during adaptation vs. control for the LFP response from Fig. 1B as a function of time since the presentation of the adapting stimulus. The power for each condition was computed by considering the entire range of test orientations across all trials in the session. Adaptation led to a 15.9% decrease in the mean gamma power during the presentation of the test stimulus.
Supplementary Figure 2. Change in gamma power (adaptation vs control) as a function of test orientation.

The figure represents the normalized gamma power as a function of the absolute difference between the preferred orientation at the LFP site and test orientation for the entire population of LFPs. Gamma power is calculated during control, iso-orientation adaptation (the adapting stimulus is within 45° of the preferred orientation at the LFP site), and orthogonal adaptation (the adapting stimulus is > 45° of the preferred orientation at the LFP site).
Supplementary Figure 3. Adaptation influences oscillatory synchronization (computed as Spike-Triggered Average, STA) between spikes and LFPs.

These examples reveal oscillatory synchronization between pairs of spikes and LFPs from different, nearby, electrodes during the presentation of the test stimuli. Spikes could be more tightly phase-locked to the LFP oscillations around specific frequencies. We calculated the power spectra of the STAs in order to assess how adaptation alters the power density in different frequency bands, and found that the power spectra of the STAs reveal pronounced gamma synchronization, i.e., adaptation increases spike-LFP coherence in the gamma frequency band (LFP was filtered between 30-80 Hz).
Supplementary Figure 4. Spike density and LFP power for the spike-LFP pairs shown in Figure 3A-D.

(A-C) The PSTHs represent the responses of the neuron from Fig. 3A (panel A) and Fig. 3C (panel C) to the adapting and test stimuli in the control (blue) and adaptation (red) conditions. The two horizontal bars represent the presentation of the adapting and test stimuli. Adaptation led to a 13%
(panel A) and 49.3% (panel C) decrease in the mean responses to the test stimulus. (B-D) Changes in power spectral density during adaptation vs. control for the LFP response from Fig. 3B (panel B) and Fig. 3D (panel D) as a function of time since the presentation of the adapting stimulus. The power for each condition was computed by considering the entire range of test orientations across all trials in the session. Adaptation led to a 20% (panel B) and 47% (panel D) decrease in the mean gamma power during the presentation of the test stimulus.
Supplementary Figure 5. Change in gamma SFC (adaptation vs control) as a function of electrode distance.

This figure represents the change in gamma SFC (adaptation vs control) as a function of electrode distance. We divided our population of spike-LFP pairs based on the distance between electrodes as follows: 0 mm (same electrode), <2 mm, 2-4 mm, and >4 mm. We found that for nearby recording sites (0 mm and <2 mm) adaptation significantly increases the synchronization of V4 neurons in the gamma band ($P<0.01$, Wilcoxon signed-rank test for both groups). For larger electrode distances (2-4 mm and > 4 mm), adaptation causes statistically nonsignificant changes in gamma-frequency synchronization ($P>0.1$ for both groups, Wilcoxon signed-rank test). Error bars represent s.e.m.
Supplementary Figure 6. Our single unit recordings are uncontaminated by 60 Hz noise.

(A) The mean normalized autocorrelation function for the entire population of cells (computed for the presentation of the test stimulus) clearly shows the absence of a 60 Hz peak. (B) The mean power spectrum for our population of spike trains (computed using the Discrete Fourier transform) reveals the absence of a 60-Hz component that is significantly different from the power at other frequencies (power has been computed during the presentation of the 300-ms test stimulus; error bars represent standard deviation).
Effect of adaptation on neuronal activity

Impact of adaptation spike field coherence  In Supplementary Fig. 7 we show the rastergrams in both the adaptation ($\alpha = 0.65$) and control ($\alpha = 0.85$) condition. Depression enhanced the impact of the background oscillations on spike generation. The histograms of spikes in the postsynaptic population in panel B) represent the likelihood of spiking during different phases in one cycle of the oscillatory background input. The standard deviations in the adaptation and control cases are $0.398\pi$ and $0.45\pi$, respectively.

Supplementary Fig. 7 C) illustrates how SFC increased with synaptic depression, measured by $1 - \alpha$ (also shown is a second order polynomial regression fit). Here we chose the oscillatory input, $A \sin(2\pi ft)$, to represent the LFP. Choosing the total synaptic input to the postsynaptic population averaged over all cells to represent the LFP gives similar results (See. Supplementary Fig.8). The increase in SFC with synaptic depression is similar to the phenomenon of stochastic resonance (Wiesenfeld & Moss 1995), although here it is the effective drive and reverberatory activity in the postsynaptic network that are changin (See Supplementary Fig. 9). The inset in panel C) shows the spike-triggered averages (STAs) in both the adaptation and control cases. When data is pooled over different values of the depression constant, $\alpha$, the change in SFC is strongly negatively correlated with the change in firing rate, as shown in Supplementary Fig. 7 D). This is in agreement with experimental data (see Fig. 4A) in main text).

Impact of adaptation on the neuronal response  The relationship between the neuronal response and adaptation is shown in Figure 5 in the main text. With an increase in synaptic depression, as measured by $1 - \alpha$, the mean and variance of the response decreased. The results remained qualitatively unchanged over a range of parameters. For instance, Supplementary Fig. 10 illustrates the case when $\mu = 4.375$ mV, $g_{E}^{ext} = 0.00335$, $g_{E}^{net} = 0.066$.

Adaptation increases discriminability  We examined how adaptation impacts discriminability. We assumed that two sets of inputs resulted in different responses of cells in the presynaptic pool. We then measured how well these inputs could be discriminated from the postsynaptic response in the control and adaptation conditions.

Two inputs ($\mu_{\text{presynaptic}} = 8.4$ mV and $8.625$ mV) evoked average firing rates $18.25$ Hz and $21.08$ Hz in the presynaptic pool. Spikes were again shuffled to keep SFC in the presynaptic pool fixed at around $0.36$. The firing rate of the postsynaptic population was obtained from an average of firing rates of 50 cells in 20 realizations of network connectivities (each with probability of connection
Supplementary Figure 7: A) Rastergrams of the postsynaptic population response in the high SFC (adaptation) and low SFC (control) regime. B) Histograms of spike occurrences during one cycle of the background input (bin size $0.024\pi$) (peak of the oscillation at phase $\pi/2$). C) SFC as a function of depression strength measured by $1 - \alpha$. Parameters used are $\tau_m = 10$ ms, $V_L = -65$ mV, $\mu = 3.975$ mV and $A = 2.435$, $D = 32.5$, $g_{ext}^{E} = 0.00375$, $g_{E}^{net} = 0.068$, $\tau = 1$ ms, $\beta = 0.25$. The inset shows the spike triggered average (STA). D) Change in SFC is plotted against the change in firing rate pooled over different adaptation strengths. shows a strong negative correlation of the two. In panels (A), (B) and (C), for control, $\alpha = 0.85$, $\alpha_{net} = 0.9625$ and for adaptation, $\alpha = 0.65$, $\alpha_{net} = 0.9125$. 
Supplementary Figure 8: STA and SFC computed from the average synaptic input to the postsynaptic population. The results are very similar to those obtained using only the sinusoidal component presented in the main text, and Fig. 7.

equal to 0.25). For each realization of the network, the firing rate of each cell was obtained from an average of 7 time windows of 300 ms based on voltage evolution during a 2.1 s time interval. Since the response was stationary, this was equivalent to obtaining results from 7 different realizations for each fixed connectivity. This gave a total of 140 realizations.

The variance of the response was computed across all 50 cells, and 7 time windows for each fixed connectivity. Therefore, 350 time windows were used in the computation of the variance.

The responses of postsynaptic cells approximately followed Gaussian distributions $P(\nu_1, \sigma_1^2)$ and $P(\nu_2, \sigma_2^2)$ (See Figure 6 in main manuscript). Here $\nu_i$ and $\sigma_i$ are the mean firing rate and variance in the response to stimulus $i$.

We computed discriminability using

$$d' = \frac{|\nu_2 - \nu_1|}{\sqrt{(\sigma_1^2 + \sigma_2^2)/2}}$$

In the control condition where $\alpha = 0.85$, $\alpha_{net} = 0.9625$, we obtained $\nu_1 = 37.83$ Hz, $\sigma_1 = 8.42$ Hz in response to the first input, and $\nu_2 = 46.82$ Hz, $\sigma_2 = 9.29$ Hz in response to the second input, giving $d' = 1.01$. We assumed that adaptation resulted in synaptic depression, and set $\alpha = 0.65$, $\alpha_{net} = 0.9125$. This lead to $\nu_1 = 15.76$ Hz, $\sigma_1 = 3.97$ in response to the first input, and $\nu_2 = 24.46$ Hz, $\sigma_2 = 5.84$ Hz in response to the second input, leading to $d' = 1.74$. These results are shown in Figure 6 in the main manuscript. This result is robust: Fig. 10 (B) illustrates how discriminability changes for a different set of parameters.

Supplementary Fig. 11 A) shows $d'$ as a function of depression strength: Discriminability
Supplementary Figure 9: An example of the change in the total synaptic input to a cell in the postsynaptic population. After adaptation, the recurrent input to the cell is decreased significantly, and hence the reverberatory activity is reduced.

Supplementary Figure 10: A) Mean, variance of firing rate and SFC as functions of depression strength. B) PDFs of postsynaptic cells’ firing rate in the control and adaptation cases. Parameters are identical to those used in Fig. 7 except for $\mu = 4.375$ mV, $g_{E}^{ext} = 0.00335$, $g_{E}^{net} = 0.066$, and for the panel (B), $\alpha = \alpha_{net} = 1$ for control and $\alpha = 0.8$, $\alpha_{net} = 0.95$ for adaptation.

increases initially. However, if depression is too strong (here when $(1 - \alpha)$ is above 0.35), discriminability decreases. The value $d'$ at each point in Fig. 11 A) was computed by averaging over 140 trials (7 points from 20 trials each with fixed connectivity, with firing rate and variance computed as above). In particular, here we used 50 values for $\alpha$ uniformly chosen between 0.6 and 0.85.
Supplementary Figure 11: A. $d'$ as a function of depression strength, measured by $1 - \alpha$. B. Scatterplot of $d'$ and firing rate. C. Signal discrimination at different frequency bands. For panels (A) and (B), parameters are identical to those used in Fig. 7.

and used 20 fixed connectivities for each value (1000 total points). The plot presents $d'$ and SFC computed over 7 trials for each of those 1000 cases.

We also investigated the effect of the frequency of the background input on discriminability. Supplementary Fig. 11 C) shows how $d'$ changes as the peak frequency in the background oscillations occurs at 20, 40, 60, 80 and 100 Hz. The mean and variance of $d'$ was calculated from 20 samples of $d'$ each computed over 7 trials with a fixed connectivity, as above. The ability of postsynaptic cells to distinguish small changes of incoming stimuli was maximal when the background oscillations had a spectral peak around 60 Hz.

References