Gamma or no gamma, that is the question

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Numerous studies suggest that gamma-band synchronization is central to visual processing, yet most of them have used artificial stimuli. A new study using electrocorticography (ECoG) in humans reported finding no gamma for many natural images and for visual noise. However, we highlight that sensitive metrics can reveal clear gamma not only for natural images, but for noise stimuli and even during the absence of visual stimuli. This shows the importance of using appropriate metrics for detecting rhythmic synchronization and investigating the function of gamma during natural viewing.

Gamma-band synchronization has been related to several cognitive functions, in particular perceptual binding, selective attention, short- and long-term memory [1]. Many of these studies were performed in the visual domain using artificial stimuli, like drifting gratings. It is therefore crucial to investigate whether insights gained under controlled but artificial conditions also hold for natural conditions. As a first step, this requires testing whether gamma-band synchronization is at all present during natural viewing. We recently addressed this question by performing ECoG recordings from macaque monkeys as they freely viewed photographs of natural scenes [2]. Natural viewing led to pronounced gamma-band activity in visual cortex (Figure 1A, B), with a clear spectral peak indicative of oscillatory activity between 50 and 80 Hz that was highly significant for each of the 65 natural images tested. This suggests that gamma-band activity plays a functional role for cognition during natural viewing.

By contrast, a recent ECoG study [3] in human subjects reported a different pattern of results. In this study, two human subjects were presented with grating and noise stimuli. The authors modeled the observed power spectra using two components. One was a 1/f^x component, which corresponds to a straight line in a double-logarithmic power-frequency plot and is thought to reflect basic biophysical processes like postsynaptic potentials or action potentials that are short and therefore spectrally broad.

The second was a Gaussian component, which was supposed to capture the gamma peak.

The authors restricted the gamma peak frequency to lie between 35 and 80 Hz and the standard deviation to be 10% of the peak frequency.

Using these measures, the authors reported observing sustained gamma-band activity with a clear spectral peak around 50 Hz in response to grating stimuli. By contrast, they claimed that noise stimuli elicited increases only for the 1/f^x, but not the gamma component. Indeed, a gamma component is hardly visible in the double-logarithmic plots of raw power provided in Figure 2B of [3]. Based on these findings, the authors concluded that 'because [gamma oscillations] are absent for many stimuli, which observers can see and recognize, the oscillations are not necessary for seeing'. Here, we review the presented evidence and arrive at alternative interpretations of these data.

First, although their double logarithmic plots of raw power during baseline and stimulation might lack a gamma-band peak (Figure 1C), we note that a conventional plot of power change from baseline to stimulation can reveal a convincing spectral peak around 130 Hz (Figure 1D; data provided as supplementary material in [3]). Indeed, a previous magnetoencephalography study reported that increasing noise in motion stimuli reduced power between 60 and 100 Hz and increased power around 130 Hz [4]. This higher gamma-band peak is beyond the constraints placed by the Hermes *et al.* authors for their Gaussian fit. Nevertheless, the peak in the power-change spectrum reveals a rhythmic component, and its frequency and width are likely related to several previous findings. Noisy stimuli lack the higher-order correlations that give rise to spatial structures such as edges and objects in natural stimuli [5]. They therefore likely activate many small and spatially disparate neuronal groups to varying degrees and in a spatially incoherent way. The frequencies of the local gamma rhythms are likely relatively high, because smaller stimuli and correspondingly smaller neuronal assembly sizes lead to increasing gamma frequencies [6], and the frequencies are likely variable, because the variable activation strengths lead to variable gamma peak frequencies [7,8].

One of the ECoG subjects was also presented with 99 images of faces or houses, each presented only once and with 30% of the pixels replaced by noise. In these data, the authors find some gamma-band activity, but because
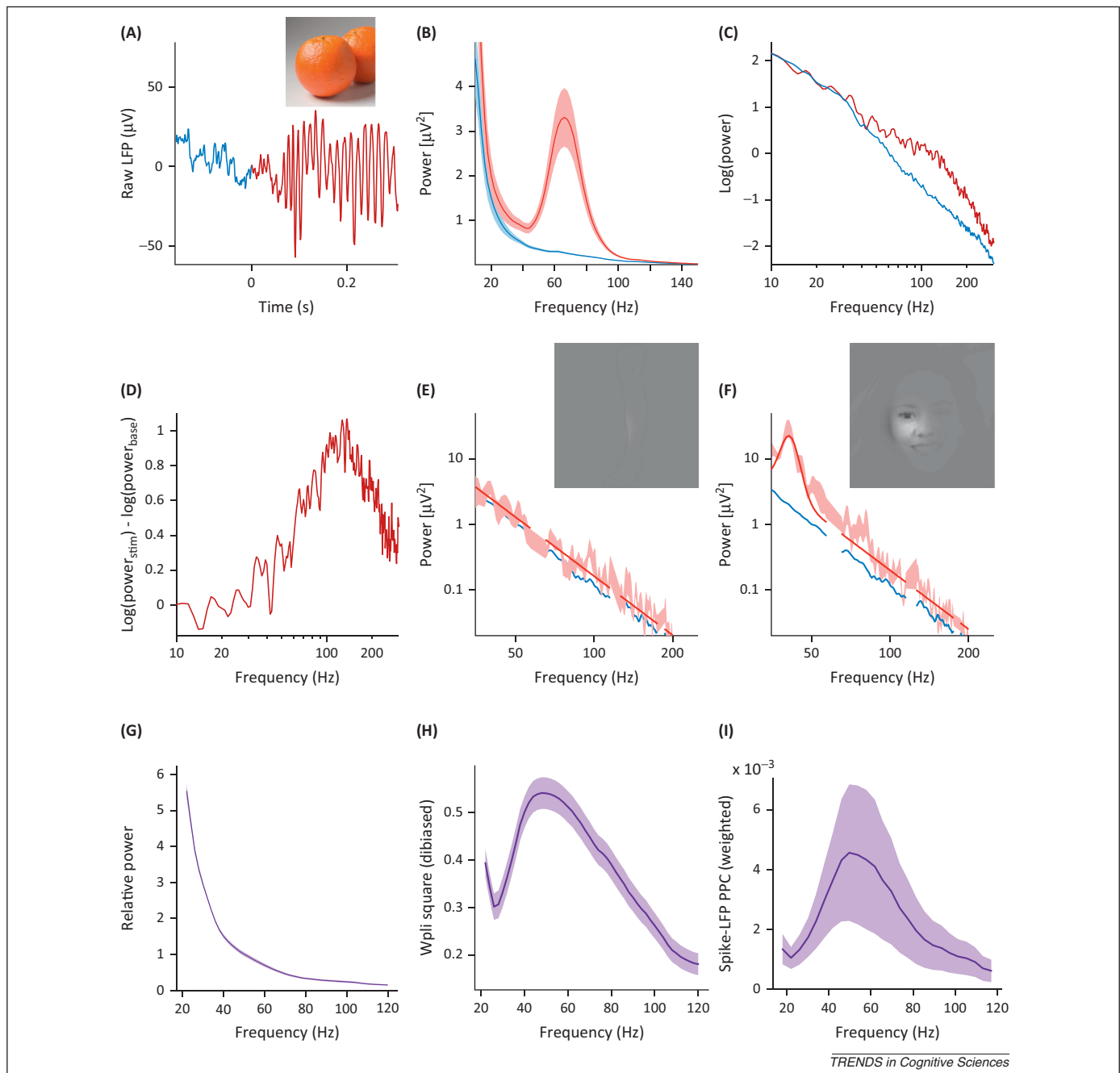

Figure 1. Differential sensitivity to detect gamma with different stimuli and metrics. (A) Example of a raw LFP trace from monkey V1 during free viewing of the photograph of two oranges (inset), reproduced from [2]. (B) Average power spectra showing a clear gamma-band peak during natural viewing (red) as compared to baseline (blue), produced from data displayed in Figure 3 of [2]. (C) Raw power spectra from a human V1 ECoG electrode during stimulation with visual noise (red) and baseline (blue) reproduced, with permission, using the data shown in Figure 2B and provided as supplementary material of [3]. (D) Same data as in (C), but plotted as the stimulus-induced power change, that is, the spectrum in (D) is the red minus the blue spectrum of (C). (E, F) Examples of receptive-field stimuli and power spectra reproduced, with permission, from Figure S3 of [3]: (E) corresponds to column 1, row 3, (F) corresponds to column 11, row 5. (G) Average raw LFP power spectrum from monkey V4 during a pre-stimulus fixation period after presentation of an attentional cue (reproduced from Figure S4C of [9]). (H) For the same data as shown in (G), the average WPLI spectrum (weighted phase lag index [10]), quantifying phase consistency between LFP from neighboring electrodes (corresponding to Figure S4A of [9]). (I) Spike-LFP PPC spectrum (pairwise phase consistency [9]), quantifying the phase consistency between spikes and LFP from neighboring electrodes (corresponding to Figure 2D of [9]).

different stimuli induce gamma at different frequencies [7,8], and noise induces additional frequency shifts as just described, this dataset is less instructive than a third one, presented in Figure S3 of [3]. This third subject was presented with 72 images of faces, houses, cars and limbs. The authors report that 'some natural images elicit narrowband gamma' but emphasize that 'many images do not elicit significant gamma oscillations in V1'. However, a close reading of [3] reveals that a majority of 40/72 images

elicited a gamma-band peak that reached significance even though there were only five to six trials of 1 second per image and the authors' approach to testing for the presence of gamma with constrained Gaussian fits to raw power spectra was rather insensitive, as exemplified above. Furthermore, several images for which the authors failed to find gamma contained hardly any spatial structure in the electrodes' receptive fields (Figure 1E; note that the subject was fixating). By contrast, for appreciable receptive field

stimulation, gamma was often detected despite few trials and insensitive metrics (Figure 1F). Thus, natural stimuli yield more pronounced gamma oscillations than artificial noise stimuli, because noise lacks higher-order correlations produced by spatial structure [5].

Importantly, even the convincing absence of a peak in a power spectrum calculated from a large dataset does not demonstrate the absence of a rhythm. Figure 1G shows the average raw LFP power spectrum from many recording sites in area V4 of two macaque monkeys during a pre-stimulus fixation baseline after presentation of an attention cue [9]. There is no sign of a gamma-band rhythm. Figure 1H shows for the same data a metric of phase consistency [10] between simultaneously recorded LFPs from neighboring electrodes. The presence of a clear gamma-band peak demonstrates the presence of gamma-band rhythms in both LFPs, because the absence of a rhythm in either LFP would have resulted in random phases and an absence of phase consistency. This gamma rhythm can be traced down to isolated single neurons (putative interneurons), as demonstrated by a clear gamma-band peak in spike-LFP phase-locking shown in Figure 1I. Thus, stimulation of the receptive field is not required for a gamma rhythm to be present in visual cortex if the subject is awake and attentive. Further, rhythms can be present while the LFP power spectrum does not show a peak. Therefore, the absence of significant Gaussian fits to power spectra from few ECoG electrodes, constituting recordings at one particular level of resolution, does not justify the conclusion that gamma 'oscillations are not necessary for seeing' [3]. Rather, this is a particularly clear example for absence of evidence that is not evidence of absence.

These overlooked aspects of the Hermes *et al.* results strongly suggest that visual cortical gamma is not an arcane phenomenon elicited only under specific artificial stimulation conditions. Rather, appropriate metrics reveal that gamma is abundant during the awake state including natural viewing. This demonstrates the importance of sensitive metrics in the investigation of rhythmic neuronal synchronization. Further, it validates studies on gamma using artificial stimulation conditions. Finally, it will allow future studies to investigate in detail whether the functions of gamma that have been identified under controlled yet artificial conditions also exist during natural viewing.

References

1 Fries, P. (2009) Neuronal gamma-band synchronization as a fundamental process in cortical computation. *Ann. Rev. Neurosci.* 32, 209–224

2 Brunet, N. *et al.* (2013) Visual cortical gamma-band activity during free viewing of natural images. *Cereb. Cortex* http://dx.doi.org/10.1093/cercor/bht280

3 Hermes, D. *et al.* (2014) Stimulus dependence of gamma oscillations in human visual cortex. *Cereb. Cortex* http://dx.doi.org/10.1093/cercor/bhu091

4 Siegel, M. *et al.* (2007) High-frequency activity in human visual cortex is modulated by visual motion strength. *Cereb. Cortex* 17, 732–741

5 Olshausen, B.A. and Field, D.J. (1996) Emergence of simple-cell receptive field properties by learning a sparse code for natural images. *Nature* 381, 607–609

6 Gieselmann, M.A. and Thiele, A. (2008) Comparison of spatial integration and surround suppression characteristics in spiking activity and the local field potential in macaque V1. *Eur. J. Neurosci.* 28, 447–459

7 Ray, S. and Maunsell, J.H. (2010) Differences in gamma frequencies across visual cortex restrict their possible use in computation. *Neuron* 67, 885–896

8 Roberts, M.J. *et al.* (2013) Robust gamma coherence between macaque V1 and V2 by dynamic frequency matching. *Neuron* 78, 523–536

9 Vinck, M. *et al.* (2013) Attentional modulation of cell-class-specific gamma-band synchronization in awake monkey area v4. *Neuron* 80, 1077–1089

10 Vinck, M. *et al.* (2011) An improved index of phase-synchronization for electrophysiological data in the presence of volume-conduction, noise and sample-size bias. *Neuroimage* 55, 1548–1565