Evidence for macroscopic traveling waves from sEEG

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Abstract:

Macroscopic traveling waves (MTWs) in the cortex (>15cm) have been associated with cognitive processes such as perception, attention and working memory, as well as revealing single-trial relationships to event-related potentials (ERPs). However, their status remains unresolved, with some studies suggesting they result from localized oscillatory sources and blurring artifact from extra-cranial measurements. We apply a novel method to estimate the spatial frequency (SF, i.e., the characteristic scales) of phase-gradients in sEEG (stereotactic electro-encephalography). In humans, these intra-cranial depth contacts offer good spatial resolution and often-times good spatial coverage of the cortex with minimal blurring artifact. We find the spectral power of phase-gradients is highest at the longest wavelengths, up to the size of the measurement array (40cm). This means that MTWs dominate activity in the cortex and suggests that M/EEG are suitable tools for their study since they primarily distort high (and not low) SF components. We interpret this large-scale coherent field as evidence for phase-gradients maintaining a distinct global organization.

Keywords: macroscopic cortex; traveling waves; phase dynamics; sEEG; intra-cranial.

Introduction

MTWs have been described in humans since at least 1949 (Goldman et al., 1949). Recent interest has blossomed, along with improving techniques for measurement of cortical signals and numerical analysis. We define MTWs in human cortex as spatially monotonic changes in phase measured over more than 15cm up to the global scale of the cortical sheet. These waves may take the form of linear gradients, spirals, and may also vary in velocity, i.e., from standing to pure traveling waves (TWs).

MTWs have been shown to vary according to conscious state and task conditions, for example, in the slow-wave range during deep sleep (Massimini et al., 2004), for alpha-band perceptual and attentional processes (Alamia et al., 2023; Fakche & Dugué, 2022) and including theta activity during different stages of working memory storage and retrieval (Sauseng et al., 2002; Zhang et al., 2018). MTWs have also been shown to be single-trial concomitants of various ERPs, such as the P2/N2 and P3, with identical task-relevant timing and characteristic frequencies (Alexander et al., 2006, 2013). Here, we assess whether MTWs describe a real global state, situated as a fast time-scale concomitant to the network states described by functional connectivity (Yeo et al., 2011) traversing the global functional gradient of the cortex (Margulies et al., 2016).

Theoretical analyses have long predicted the existence of global wave dynamics (Nunez, 1974; Wright et al., 2001). Technically, the measured waves are group waves, that is, we measure the envelope of the combined activity at some temporal frequency as it moves through the cortex. The waves arise through a dynamic balance of excitation and inhibition and activated fields radiate outward from previously activated areas. Mathematical analysis indicates activity modes that are associated with damped TWs (Wright et al., 2001), and under appropriate boundary conditions, these correspond to MTWs coordinated by long-range myelinated axons (Nunez & Srinivasan, 2006).

An alternative approach to understanding the reported MTWs is in terms of localized oscillating cortical sources mixing at the sensor level (e.g., EEG, MEG). In this approach, two spatially offset and phase-lagged components are derived by source modeling, which in turn produces the measured (assumed artifactual) extra-cranial waves (Zhigalov & Jensen, 2022).

To resolve this issue, we estimate the SF distribution of phase gradients at the cortical level. Previous studies have consistently revealed spectral power to decrease monotonically with SF. However, estimates of the relative contribution of MTW to the SF spectrum have used EEG (Freeman et al., 2003) or MEG (Alexander et al., 2016), and are therefore contaminated by volume conduction artifact or blurring by distance to the sensor array, both of which act as a low pass filter. Previous estimates with intra-cranial measurements using cortical surface arrays have had limited spatial coverage (<10cm; Alexander et al., 2019; Barrie et al., 1996) and were therefore insensitive to the longest wavelengths. Here, we use cortical depth electrodes (sEEG) which have excellent spatial resolution and coverage (although oftentimes sparse) of up to 40cm of the cortical sheet.

Methods

In the present research we analyze a publicly available data-set (*RAM Public Data - Computational Memory Lab*). We estimate SF distributions of phase gradients for 35 subjects with chronically implanted sEEG contacts. Full details of data acquisition are reported elsewhere (Ezzyat et al., 2017). Phase time-series were analyzed using short time window Morlet wavelets (2 cycles) over the frequency range 2 to 42Hz. The irregularity of the sEEG contact array makes standard methods of computing SF untenable. We therefore computed the singular vectors of each participant's complex-valued, unit length phase vectors (time-by-contact), at each frequency. This means we could characterize the phase as spatially smooth maps over the array, with each map explaining a known amount of variance within the total time-by-contact phase measurements. The smooth maps of phase allowed local difference methods (i.e., change in phase per change in distance) to be applied to estimated SF. Prior to estimation, further corrections were applied to (1) decompose standing waves into their traveling wave components, and (2) determine the approximate direction of travel.

Results

We find that sEEG spectral power decreases with SF. This means the phase-gradients measured within the grey-matter are dominated by low SF waves. This is true over a broad range of temporal frequencies.

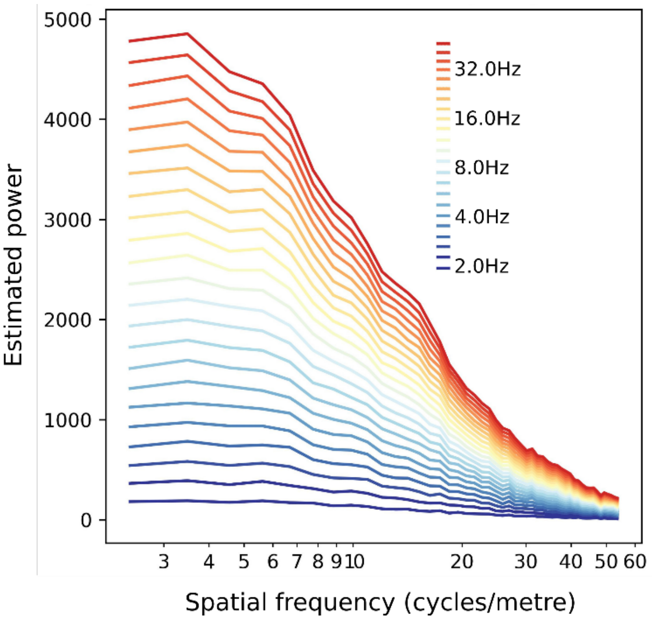

Figure 1: SF stacked spectrum (power in arbitrary units) for all participants (n=35), frequency range 2.0 to 42.2Hz. The highest power occurred for the lowest SFs (p<0.01; Chi-square), limited only by the maximum extent of the sEEG array. The SF spectrum had a similar shape across the temporal frequency range.

Conclusions

Our results concerning SF agree with previous measurements both intra- and extra-cranially (Alexander et al., 2016, 2019; Barrie et al., 1996; Freeman et al., 2003), while assessing for the first time low SF components using cortical depth electrodes. We show that macroscopic phase-gradients dominate the cortical signal and cannot be attributed solely (or mainly) to artifactual blurring via extra-cranial measurements. This result is at odds with the view that extra-cranial measurements of MTWs are due to localized oscillatory sources, because the power of localized phase activity is small compared to MTWs. Since MTWs (1) dominate the cortical signal, (2) extra-cranial measurements filter out high SF signals (Srinivasan et al., 1998), and (3) source localization methods remove the long-range spatial correlations in cortical activity (Nunez & Srinivasan, 2006), M/EEG sensor-level measurements are suitable to assess the presence of MTWs.

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