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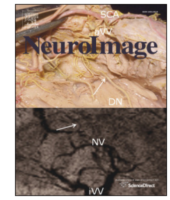

Review

Five methodological challenges in cognitive electrophysiology

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ABSTRACT

Here we discuss five methodological challenges facing the current cognitive electrophysiology literature that address the roles of brain oscillations in cognition. The challenges focus on (1) unambiguous and consistent terminology, (2) neurophysiologically meaningful interpretations of results, (3) evaluation and comparison of different spatial filters often used in M/EEG research, (4) the role of multiscale interactions in brain and cognitive function, and (5) development of biophysically plausible cognitive models. We also suggest research directions that will help address these challenges. We hope that this paper will help foster discussions and debates about important themes in the study of how the brain's rhythmic patterns of spatiotemporal electrophysiological activity support cognition.

Contents

Introduction

Cognitive electrophysiology is a field that bridges neuroscience and psychology, and focuses on understanding how cognitive functions (including perception, memory, language, emotions, behavior control, and social cognition) are supported or implemented by the electrical activity produced by populations of neurons. The main methodological tools used by cognitive electrophysiologists are EEG and MEG, and intracranial recordings such as electrocorticogram and single- and multi-unit recordings. Although these methods span a range of species and spatial scales, they all share the common feature that they measure electromagnetic activity. Thus, the major assumption underlying the broad spectrum of cognitive electrophysiology studies is that one key neural mechanism of processing and transferring information is (or, at least, can be understood through) electrical activity.

The purpose of this paper is to highlight and discuss five major methodological challenges facing cognitive electrophysiology. Some of these challenges are related to each other; discussing them individually is done mainly for convenience. Indeed, in several cases, addressing one challenge may help address other challenges. We focus mainly on methods and data analyses involving time–frequency-based approaches, because these are the most rapidly developing methodological approaches in cognitive electrophysiology, and, as will be described below, have a large potential for understanding neurophysiological processes underlying cognitive operations.

Some readers may disagree with the importance of some of these challenges, or could name additional challenges than the five presented here. Nonetheless, we hope that this paper will help catalyze further discussions in current trends and important future directions in cognitive electrophysiology.

Challenge 1: Widespread agreement on analysis terminology

Consider the following statistical analysis terms: correlation, ANOVA, factor analysis, and receiver operating characteristic (ROC). When someone says that they performed an ANOVA, there is no ambiguity about which sets of equations were applied to the data. Furthermore,

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even though the term ROC provides little insight on the mathematical procedure underlying that analysis, most people with a background in engineering, math, psychology, or physics will know what an ROC analysis implies and how the results can be interpreted.

Precision and widespread agreement in analysis terminology is lacking in cognitive electrophysiology. This is problematic because inconsistent, ambiguous, or confusing terminology impedes cross-study comparisons and theory development (Gardiner and Java, 1993; Tulving, 2000). To illustrate this point, consider the following electrophysiological data analysis terms: synchronization, event-related spectral perturbation, time–frequency response, and connectivity. These and other terms are ambiguous and are often lab- or software-specific. When someone says that they found an increase in alpha synchronization, you do not know whether they mean an increase in power at one electrode or an increase in phase-based connectivity between two electrodes. This confusion arises because some researchers use the term “synchronization” to indicate the squared amplitude of the frequency band-specific filtered signal at one electrode (Pfurtscheller, 1992), whereas other researchers use this same term to indicate consistency in phase angle differences between two electrodes. However, these two analyses have very different interpretations, putative neurophysiological origins, theoretical implications, and methodological concerns. Terms like spectral perturbation (Makeig, 1993) and time–frequency response are also ambiguous, because they could refer to spectral changes expressed in power, phase, connectivity, band-specific network properties, or any number of other features of time–frequency-based analyses.

Within a field of science, there should be a one-to-one mapping between terms and their meanings (also called the *incontrovertibility of terms* rule; Gardiner and Java, 1993). However, cognitive electrophysiology suffers from a many-to-many terminology mapping problem: the same term can have different meanings (e.g., the term “synchronization,” as described in the previous paragraph); and different terms can indicate the same mathematical procedure (e.g., inter-trial phase coherence vs. phase-locking index/value can refer to the same analysis, which assesses the consistency of phase angles at one electrode-time–frequency point over trials). The many-to-many mapping of analysis terms to mathematical procedures slows scientific progress by creating confusion about how to interpret findings reported in results sections, and how to compare results across studies that use different terms.

Another confusing and ill-defined—but often used—term is “activation.” A brain region is said to be activated (or deactivated) if its activity increases (or decreases) with respect to a baseline or control condition. Although this term is widely used in univariate fMRI analyses and relatively simple analyses of action potential data such as average spike rate, this term becomes less tractable for multi-dimensional electrophysiological activity such as field potentials (Singh, 2012). For example, if a brain region exhibits an increase in inter-trial phase clustering in the theta band, a decrease in alpha-band power, no change in gamma-band power, and an increase in theta–gamma coupling, is this brain region activated or deactivated? In some cases, increases in power that seem to lack a clear frequency structure are referred to as “activation” (Burke et al., 2013; Miller et al., 2009), but this approach may obscure the fine temporal structure of activity, such as multiple overlapping frequencies (Crone et al., 2011) or temporal or correlation-based information coding (Engel et al., 1992; Tsukada et al., 1996).

Perhaps the lack of terminological convergence was less of a concern a few decades ago, when few research groups were performing time–frequency-based analyses, and most analyses were based on the squared amplitude of the frequency band-specific signal (i.e., power). However, the lack of consistency in analysis terminology becomes problematic as more scientists begin applying sophisticated data analyses. With varied and sometimes ambiguous terminology, rapid and efficient cross-study comparisons become increasingly difficult.

The challenge, therefore, is to adopt a widely accepted and unambiguous terminology for describing multivariate changes in electrophysiological data. We recommend using analysis terms that closely and succinctly reflect the mathematical procedure applied to the data (Cohen, 2014), rather than using terms that reflect interpretations of putative neurophysiological events underlying time–frequency features. For example, when extracting the energy of a frequency band-specific signal (the squared amplitude), the term “power” should be preferred over terms such as “synchronization” because “power” is an unambiguous description of the analysis, whereas synchronization is a speculative interpretation of a result (in this case, that the neural networks measured by the electrode became synchronized; Pfurtscheller and Lopes da Silva, 1999). At least in the context of electrophysiology data, it might be best simply to avoid using functional univariate terms like “de/activation.” Instead, terms could describe the statistical properties of the data, such as “relatively increased power in the beta-band,” or “correlation between alpha phase and gamma power.” In Table 1, we suggest analysis terms for some commonly used analyses.

Challenge 2: Neurophysiological interpretation of time–frequency results

The mathematical development of time–frequency-based data analyses, and their applications to studying cognition, has advanced beyond the understanding of the neurophysiological events that might underlie the results of those analyses. For example, the difference between phase-locked and non-phase-locked (also known as evoked and induced, respectively) activities remains unclear, with theory and models suggesting complex interactions between neurobiological events that may be measured as phase-locked vs. non-phase-locked events (Burgess, 2012; David et al., 2006; McLelland and Paulsen, 2009; Tallon-Baudry and Bertrand, 1999), but little empirical data to provide firm conclusions. Another example is functional connectivity estimated between two electrodes, which can be based on correlations in frequency band-specific power time series (Bruns et al., 2000), or on a clustering of phase value differences (Lachaux et al., 1999). It is unclear whether connectivity based on power and on phase reflects similar mechanisms (e.g., long-range activation of inhibitory interneurons; Bush and Sejnowski, 1996), and it is unknown whether the same mechanisms underlie connectivity in different frequency bands or in different brain regions.

Table 1
Suggested terminology for time-–frequency-based M/EEG data analyses. See Cohen (2014), for more in-depth discussions and justifications of each term.

Preferred term	Description	Examples of less preferred terms
Power	Squared amplitude of frequency-band specific time series	Synchronization/desynchronization, ERS/ERD, ERSP, TFR
Inter-trial-phase-clustering	Length of average vector from a distribution of unit phase angles at one time–frequency point over trials.	Phase-locking, phase-coherence, phase-reset
Inter-site-phase-clustering	Length of average vector from a distribution of unit phase angle differences between two electrodes at one time–frequency point over trials.	Phase-locking, phase coherence, coherence, synchronization, coupling, phase correlation

Notes. Terms are less preferred if they are ambiguous, imprecise, or are interpretations of putative neural events rather than descriptions of analysis methods. ERS = event-related synchronization; ERD = event-related desynchornization; ERSP = event-related spectral perturbation; TFR = time–frequency response.

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