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Rigor and replication in time-frequency analyses of cognitive electrophysiology data

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ABSTRACT

Cognitive electrophysiology is a subfield of neuroscience that focused on linking M/EEG data to aspects of cognition and the neurophysiological processes that produce them. This field is growing in terms of the novelty and sophistication of findings, data, and data analysis methods. Simultaneously, many areas of modern sciences are experiencing a "replication crisis," prompting discussions of best practices to produce robust and replicable research. The purpose of this paper is to contribute to this discussion with a particular focus on cognitive electrophysiology. More issues are raised than are answered. Several recommendations are made, including (1) incorporate replications into new experiments, (2) write clear Methods and Results sections, and (3) publish null results.

1. Why replication is important

The concept of "Truth" needs a different definition in biology compared to physics. The mathematical laws of the universe do not vary according to the seasons or the number of hours since a good meal. Maxwell's equations for electromagnetic wave propagation are not influenced by cultural background or by genetic disorders.

Biology is messy, because Nature promotes diversity. Biological diversity and variability is generally a good thing. It is unlikely that intelligent life would have evolved in a perfectly stationary and ordered environment. On the other hand, diversity and variability are sources of frustration in science, and require scientists to awkwardly straddle ecological validity (poorly controlled and poorly measured diversity) and experimental control (overly constrained environments that might not reflect natural behavior). The brain is perhaps the best example of these difficulties, because it is not only diverse and variable across individuals and species, but it is also highly complex and dynamic within an individual.

Because of this, "Truth" in biology—and certainly in psychology—is difficult to ascertain, and may depend on a variety of factors. To make matters worse, we might not recognize the Truth even if we happen to stumble upon it. Therefore, the best we can strive for is "Consistency." Results should be regarded in a positive light when they are observed repeatedly in several different situations, from different research groups, and when using different data collection or analysis techniques. In other words, in lieu of an unobtainable absolute Truth, we need replications.

It is very easy to pay lip-service to the importance of replications in science, but more difficult to achieve it in practice. And as data and data analyses become increasingly complicated, replications become increasingly difficult. Even determining whether a finding has been replicated can be difficult to quantify.

The purpose of this paper is to discuss some issues related to replications in the field of *cognitive electrophysiology*, which generally refers to using the brain's electromagnetic fields in order to understand aspects of cognition and how cognitive processes are implemented by neural circuits in the brain. This paper is not the definitive word on how to perform or evaluate replications in cognitive electrophysiology; instead, it is part of a nascent and important discourse about how we can develop and add to a corpus of knowledge that can be written into textbooks and will still be observed in comparable experiments in the future.

Some of the points raised here are general and could be applied to all branches of psychological and neural sciences, while other points are more specific and apply mainly to time-frequency decomposition of neural time series data.

2. Pressures for and against replication

Needless to say, we all want to do replicable research. No one actually wants to publish findings that cannot be replicated. This is the primary motivation for collecting data from N > 1 subjects. Good reputations in science are also built on findings or methods that are replicated and used by other research groups. And reputations can be tarnished

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by repeated failed attempts to replicate findings. In other words, there is both individual and career pressure to perform replicable research.

On the other hand, there are also several factors that perhaps unintentionally apply pressure against replications. Top-tier journals (and several mid-tier journals) will reject manuscripts on the basis of insufficient novelty. Major science funding agencies generally do not give grants that only fund replications. And few university departments will be interested in hiring faculty who spend most of their time replicating existing findings. In other words, at multiple levels of the business of science, there is pressure to focus on novel and exciting research rather than on replications.

But the scientist is not just a victim here: Many (or perhaps most) scientists want to do novel and exciting research, because—let's be honest—replicating previous findings gets boring. Scientists have been known to switch fields because they get bored with replicating their own findings.

In some branches of science including cognitive electrophysiology, the issue is exacerbated by the amount of time and expertise required to perform sophisticated analyses of the data. Unlike questionnaire-based or simple computer-based tasks, an EEG study focusing on time-frequency-based analyses might take 1–2 years to complete, and it might require several years of training before being able to analyze the dataset appropriately. A PhD student or postdoc who has limited time and who is under pressure to be competitive for a faculty position or a grant cannot be blamed for wanting to focus their energy on novel experiments rather than on confirmatory replications.

These competing pressures are understandable. There is no science without progress, and progress means looking forward and pushing the envelope of knowledge by making new discoveries. The brain has been such an uncharted territory for the past millennia that it is understandable that the focus has been on new discoveries instead of confirmation and replication. Certainly the brain remains an elusive mystery, but arguably, we've now come far along enough that it is time to shift priorities towards a balance between novelty and replication.

3. Time-frequency analyses in cognitive electrophysiology

Before discussing issues related to replications, I will first briefly introduce the motivations for and mechanisms of time-frequency analyses. In most cases, researchers use time-frequency-based analyses because they want to make inferences about neural oscillations. The study of oscillations in the brain is a field with growing interest and importance (readers interested in general reviews about neural oscillations may start with Buzsáki and Draguhn, 2004; Wang, 2010).

Neural oscillations are rhythmic fluctuations in the activity of populations of brain cells. Neural oscillations are present across nearly all of the vast spatiotemporal scales of brain function, from synapses and neurons to circuits, columns, and networks, to patches of brain tissue that are measurable with noninvasive imaging such as EEG or functional MRI. Neural oscillations are perhaps the best candidate feature for understanding how multiple spatial-temporal scales are inter-connected (Le Van Quyen, 2011; Palva and Palva, 2012; Cohen and Gulbinaite, 2013). Furthermore, despite the huge differences in the sizes of the brain over different species, the speeds of neural oscillations have remained remarkably constant (Buzsáki et al., 2013). This suggests that oscillations have a fundamental role in brain function that is conserved across species. Time-frequency-based analyses are the best approach to allow inferences regarding neural oscillations.

The roles of neural oscillations in brain function and neural computation have been discussed and debated for over a century. There are several dominant theories, and many models, simulations, and empirical findings, that support the role of neural oscillations in brain function and cognition. Discussing this literature is beyond the scope of the present paper, but taking a “bird's eye view” of the literature reveals two important ideas about neural oscillations that permeate much of the theorizing and empirical findings.

First, oscillations facilitate the dynamic routing of information across anatomically distinct neural networks (Fries, 2005; Jensen and Mazaheri, 2010). In part, this occurs because strong oscillations can constrain action potential timing (Vinck et al., 2011; Lisman and Jensen, 2013; Reimann et al., 2013), and convergent and synchronized input from many afferent neurons provides a nonlinear boost in post-synaptic input (Kepecs et al., 2002; Eyherabide et al., 2009). Oscillations as a mechanism for controlling the flow of information in the brain is faster and less permanent than synaptic plasticity or other structural changes associated with long-term learning. This allows oscillations to regulate neural information flow over the course of tens to hundreds of ms, i.e., the time-frame of many cognitive processes.

Second, neural oscillations are thought to provide an internal clocking mechanism for coordinating neural computations (Buzsáki and Moser, 2013). Neural information processing is highly temporally precise (Cohen, 2011), and oscillations provide a temporally precise framework in which a sequence of information processing can be preserved, and in which the upcoming state of a neural network or circuit configuration can be predicted.

Interest in understanding the roles of neural oscillations in the brain has triggered its own rapidly growing subfield of data analysis methods to detect and characterize neural oscillations (Cohen, 2014). There are many methods to quantify oscillations in time series data; most of the dominant analysis methods involve using “template matching” procedures in which sine waves or parts of sine waves are compared against the EEG signal, and an algorithm determines the extent to which the time series contains patterns that are similar to the sine wave templates. The Fourier transform and wavelet convolution are two examples of template-matching methods.

The repertoire of time-frequency analysis methods is too expansive to detail here. A quick graphical overview of one of the dominant time-frequency analysis methods is presented in Fig. 1.

4. Replication issues in time-frequency analyses

Time-frequency-based analyses of cognitive electrophysiology data add several dimensions of complexity to replication attempts. Not only are the data transformed into a multi-dimensional space (typically, a time × frequency × electrode × condition space), but time-frequency analyses provide a new framework for additional and physiologically inspired analyses, including functional connectivity, cross-frequency coupling, and spatial multivariate analyses (often called MVPA in the fMRI literature). This increased complexity with many dependent variables makes replications a bigger challenge compared to, e.g., ERP-based studies, in which there is only a small number of dependent variables (typically just one).

This is not a fatal limitation, and we should embrace rather than shy away from the complexity of the brain. But this complexity also means that replications of time-frequency results require additional considerations.

The following sections contain brief discussions of important issues that limit or promote replications. They are listed roughly in chronological order of doing experiments, from experiment design to data collection and processing to analyses and reporting results.

5. Experiment design for time-frequency analyses

Proper experiment design can improve scientific quality, reduce or prevent headaches during data analysis and publishing, and promote replications. For general discussions about experiment design in EEG, see Luck (2014) or Cohen (2014). Three specific points will be highlighted here.

1) First and most important: Design your experiments with replications in mind. This statement has two interpretations. First, when designing your experiment, keep in mind the possibility that other