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Research Report

Working memory performance inversely predicts spontaneous delta and theta-band scaling relations

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ABSTRACT

Electrophysiological studies have strongly implicated theta-band activity in human working memory processes. Concurrently, work on spontaneous, non-task-related oscillations has revealed the presence of long-range temporal correlations (LRTCs) within sub-bands of the ongoing EEG, and has begun to demonstrate their functional significance. However, few studies have yet assessed the relation of LRTCs (also called scaling relations) to individual differences in cognitive abilities. The present study addressed the intersection of these two literatures by investigating the relation of narrow-band EEG scaling relations to individual differences in working memory ability, with a particular focus on the theta band. Fifty-four healthy adults completed standardized assessments of working memory and separate recordings of their spontaneous, non-task-related EEG. Scaling relations were quantified in each of the five classical EEG frequency bands via the estimation of the Hurst exponent obtained from detrended fluctuation analysis. A multilevel modeling framework was used to characterize the relation of working memory performance to scaling relations as a function of general scalp location in Cartesian space. Overall, results indicated an inverse relationship between both delta and theta scaling relations and working memory ability, which was most prominent at posterior sensors, and was independent of either spatial or individual variability in band-specific power. These findings add to the growing literature demonstrating the relevance of neural LRTCs for understanding brain functioning, and support a construct- and state-dependent view of their functional implications.

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1. Introduction

Among research on the functional correlates of neural oscillatory phenomena, the link between theta band activity (typically 4–8 Hz) and working memory (WM) is one of the best-studied and well-supported. Collectively, recent reviews and empirical reports in this literature indicate the consensus view that theta-band activity is increased during working memory tasks, parametrically modulated by task demands, and is positively predictive of working memory performance

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(Fell and Axmacher, 2011; Hsieh and Ranganath, 2014; Itthipuripat et al., 2013; Polania et al., 2012; Sauseng et al., 2009; Zakrzewska and Brzezicka, 2014). Neuroanatomically, associations with working memory have most consistently been observed for fronto-midline theta-band activity (Hsieh and Ranganath, 2014), and for theta oscillations between frontal and parietal regions (Fell and Axmacher, 2011). On the basis of this consensus, Hsieh and Ranganath (2014) recently argued that research in this area is now poised to progress beyond simply establishing theta–WM associations, to testing different functional accounts of theta-band activity in working memory. Toward this end, the current study aimed to test the relationship between working memory ability and a particular type of theta-band activity, theta-band scaling relations. Scaling relations, as discussed in more detail below, may reflect an optimal information processing efficiency acting across multiple functional and temporal scales. This approach thus allowed us to contribute to existing functional accounts of EEG scaling relations as a neural correlate of cognition in healthy individuals.

In parallel to work on oscillatory correlates of particular cognitive functions, more general research has investigated novel properties of neural oscillations themselves (e.g., Cohen, 2014; Mazaheri and Jensen, 2010; Nikulin et al., 2007), and in the process has generated new candidate neural correlates of cognition. One such development was the discovery of long-range temporal correlations (LRTCs) in the ongoing amplitude fluctuations of the human scalp EEG (Linkenkaer-Hansen et al., 2001). In brief, the presence of long-range correlations in a time series indicates a positive temporal dependence (i.e., autocorrelation) within the signal, such that the pattern of ongoing amplitude fluctuations is not random, but possesses an inherent temporal structure, where early fluctuations predict a higher likelihood of future fluctuations in the same direction. Because the relation between the size and frequency of the fluctuations in an autocorrelated process is maintained over several orders of magnitude, the signal as a whole lacks a single characteristic scale (i.e., the mean fluctuation is a poor statistical representation of the system). These distributional characteristics are in turn understood to characterize such signals as being self-similar (specifically "self-affine") and "scale-free", where the latter is also called the "scaling relation" of the signal (Brown and Liebovitch, 2010).

One well-documented method for detecting scaling relationships is detrended fluctuation analysis (DFA). This analytic technique involves removing linear trend from a signal at various window sizes and calculating the mean fluctuation per window size. The mean fluctuation and window size are then plotted on logarithmic axes and the scaling exponent (α) is the slope of the best fitting line and an estimate of the Hurst parameter (e.g., Hardstone et al., 2012). Scaling exponents (α) in the range of $.5<\alpha<1.0$ are generally considered indicative of correlated fractal processes in the range of $1/f$ pink noise (Cannon et al., 1997). DFA thus can be used to indicate the presence of LRTCs because scaling exponents in this range indicate positive correlations at long time scales beyond a level due to chance. While the evidence seems in favor of the pervasiveness of these scaling relationships across many types of signals including neural signals, determining the functional significance of this temporal structure is a promising avenue for future research.

Fortunately, in addition to clarifying the temporal structure of spontaneous neural dynamics, there is increasing evidence for the functional significance of scaling relations observed in sub-bands of the spontaneous EEG. For example, alpha band (approximately 8–13 Hz; Klimesch, 1999) scaling relations are independent of signal power, show moderate heritability (Linkenkaer-Hansen et al., 2007), predict behavioral scaling relations (Palva et al., 2013; Smit et al., 2013), and relate to neuropsychiatric disorders and symptoms (see Hardstone et al. (2012), for a review). However, one aspect of EEG scaling relations that has received less attention to date concerns their importance for individual differences in cognitive abilities. A particularly intriguing possibility is the notion that the temporal dependence quantified by long-range correlations represents a form of dynamical memory within the system (Linkenkaer-Hansen et al., 2004). This in turn raises the question of under what conditions is it advantageous for systems to possess "memory", or conversely, when is greater memory less adaptive?

In support of the latter view, studies of broadband electrophysiological and fMRI recordings have demonstrated decreased scaling relations during task performance relative to resting states (He, 2011; He, 2014; He et al., 2010), which has been interpreted as indicating reduced maintenance of prior information in the task state, potentially enabling greater flexibility in responding to online processing demands. Band-specific EEG research has also observed decreased scaling relations in the eyes-open compared to the eye-closed resting state, potentially supporting reduced redundant processing in conditions of greater environmental stimulation (Stam and de Bruin, 2004). On the other hand, clinical studies have often found lower-scaling relations in clinical populations compared to healthy controls (see Hardstone et al. (2012)), and the view that long-range correlations might be adaptive is also consistent with the idea that particular ranges of scaling relations could reflect a state of "criticality" within the brain, that could confer optimized information processing capabilities (Botcharova et al., 2014; Kinouchi and Copelli, 2006; Shew and Plenz, 2013).

Returning then to the theta–WM literature, it is reasonable to consider what, if any, implications theta scaling relations might have for individual differences in working memory skills. While the large majority of work on theta–WM relations has focused on task-related effects, a small number of studies have related features of spontaneous, non-task-related theta activity to WM and cognitive status or functional states. For example, Stam (2000) observed that a lower correlation dimension (a related, but separate measure of signal self-similarity) of resting theta (4–7 Hz) in female participants was associated with better subsequent working memory performance in that group. This relation was observed despite an overall higher correlation dimension among female participants, and no overall condition effects on theta, or theta–WM correlations during task performance itself (Stam, 2000). Studies examining cognitive and neural effects of acute cannabis administration have demonstrated decreased resting theta power and poorer working memory performance following marijuana intoxication relative to

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