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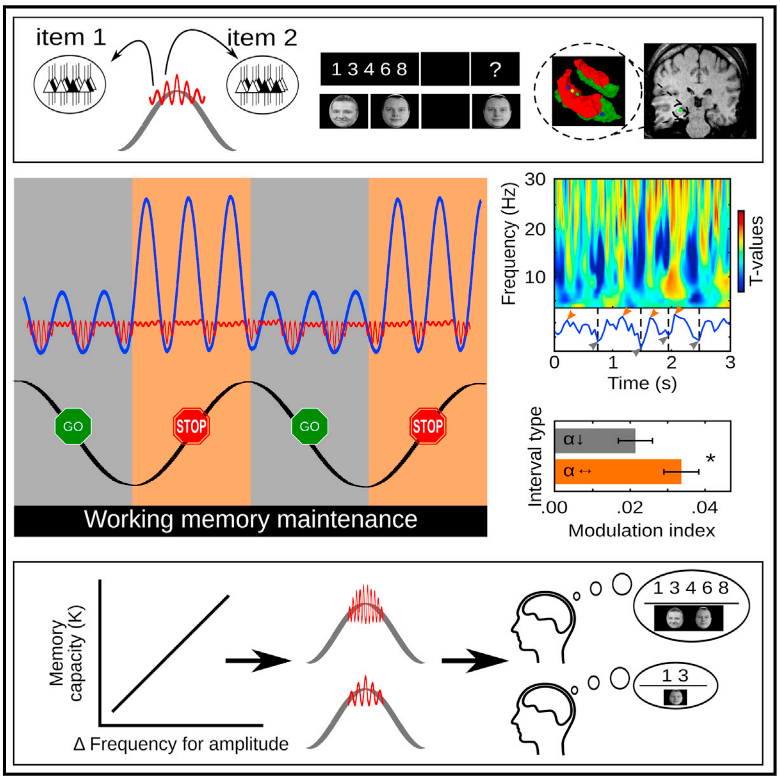
Article

Rhythmic Working Memory Activation in the Human Hippocampus

Graphical Abstract



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In Brief

Leszczyński et al. find in two independent datasets that successful working memory maintenance is a dynamic process. It depends critically on rhythmic fluctuations between two different oscillatory modes of processing in the human hippocampus. These fluctuations predict successful task performance and individual working memory capacity.

Highlights

- Working memory depends on rhythmic fluctuations in the human hippocampus
- Periods of memory activation are interleaved with periods of constant power levels
- Fluctuations between these two modes of processing are organized by delta rhythm
- A hierarchy of oscillations predicts successful performance and individual capacity

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Rhythmic Working Memory Activation in the Human Hippocampus

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SUMMARY

Working memory (WM) maintenance is assumed to rely on a single sustained process throughout the entire maintenance period. This assumption, although fundamental, has never been tested. We used intracranial electroencephalography (EEG) recordings from the human hippocampus in two independent experiments to investigate the neural dynamics underlying WM maintenance. We observed periodic fluctuations between two different oscillatory regimes: Periods of "memory activation" were reflected by load-dependent alpha power reductions and lower levels of cross-frequency coupling (CFC). They occurred interleaved with periods characterized by load-independent high levels of alpha power and CFC. During memory activation periods, a relevant CFC parameter (load-dependent changes of the peak modulated frequency) correlated with individual WM capacity. Fluctuations between these two periods predicted successful performance and were locked to the phase of endogenous delta oscillations. These results show that hippocampal maintenance is a dynamic rather than constant process and depends critically on a hierarchy of oscillations.

INTRODUCTION

Working memory (WM) refers to the temporary retention of information that is no longer perceived. Therefore, successful performance in WM tasks requires keeping neural representations active during the maintenance interval. According to the multiplexing buffer model of WM, maintenance of multiple items relies on repeated interactions between neural oscillations in a high- and a low-frequency range (Lisman and Idiart, 1995; Lisman and Jensen, 2013). In detail, this model assumes that individual WM items are represented by cells firing synchronized in the gamma cycle (>30 Hz). Maintenance of item sequences depends on the sequential reactivation of these assemblies during consecutive phase ranges of simultaneous low-frequency oscillations.

The multiplexing buffer model assumes that representations of individual items (via high-frequency oscillations) do not occur during the entire cycle of low-frequency oscillations. Instead, these high-frequency oscillations are thought to be restricted to active "duty cycles," i.e., restricted phase ranges that correspond to higher levels of neural excitability (Mehta et al., 2002; Jensen et al., 2012, 2014). Between successive duty cycles, excitability is actively reduced in order to avoid overlap and interference between the representations of item sequences. Such an active inhibition has been related to oscillations in the alpha frequency range (8–12 Hz; Jensen et al., 2012; Sauseng et al., 2009; Thut et al., 2006; Jokisch and Jensen, 2007; Bonnefond and Jensen, 2012; Klimesch, 2012; Haegens et al., 2011; Spaak et al., 2012), although a similar function has been attributed to theta as well (Mehta et al., 2002). In particular, alpha power and phase reflect an attenuation of action potentials (Haegens et al., 2011) and high-frequency activity (Spaak et al., 2012). We will use the term "inhibition" when referring to this property of alpha oscillations. Notably, this term refers to an interpretation of alpha oscillations and not to electrophysiologically measured inhibition. A decrease of alpha power, in turn, reflects a release from inhibition (c.f. disinhibition). Furthermore, according to this alpha-inhibition model, increases in alpha power are accompanied by shorter duty cycles and decreases in alpha oscillations by longer duty cycles, respectively (Jensen et al., 2014; Figure 1A).

As a consequence of the separation of duty cycles by periods of inhibition, the amplitude of high-frequency activity is modulated by the phase of low-frequency activity, a phenomenon described as phase-amplitude cross-frequency coupling (CFC; Siegel et al., 2009; Axmacher et al., 2010). The multiplexing buffer model assumes a functional relevance of the CFC ratio, i.e., the frequency ratio between the most strongly modulated high-frequency activity (mHFA-max) and the most strongly modulating low-frequency oscillation (mLFA-max). This ratio (mHFA-max/mLFA-max) should be positively correlated with WM capacity, because longer low-frequency cycles allow representing longer sequences of items.

When alpha power is high, gamma-band activity occurs during a more restricted alpha phase range (shorter duty cycles), so that CFC strength is enhanced (Spaak et al., 2012; as described above, a similar function has previously been assigned to theta oscillations; Mehta et al., 2002). In the context of WM, this