# Theta phase at encoding leads to successful memory formation

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## Abstract

**Several studies in perception and attention have shown cyclic alternations in behavioural performance (Busch, Dubois, & VanRullen, 2009; de Graaf et al., 2013; Klimesch, Sauseng, & Hanslmayr, 2007; Mathewson, Gratton, Fabiani, Beck, & Ro, 2009; Palva & Palva, 2007; VanRullen, 2016). The main idea behind this phenomenon is that spontaneous low frequency oscillations in neural activity gate incoming sensory information, producing peaks and troughs that correlate with cycles of favorable and unfavorable states for perceptual and attentional processing. Hence, variability in behavioural performance could depend on the particular oscillation phase at which the stimulus is presented. In this study, we extend this idea to the memory domain. We used an audio-visual cue as a resetting signal to pace the moment of presentation of associated pairs of images in a memory encoding block. We found that memory success (hit rate) in a subsequent recognition block fluctuated at ~5 Hz, as a function of the moment at which the memory item had been encoded with respect to the cue.**

**Keywords:** Visual memory; theta oscillations; psychophysics

## Methods

We collected behavioural data from 38 healthy human participants performing a visual paired memory task. Each run included an encoding and a recognition block. During the encoding block, participants were asked to memorize five unrelated image pairs presented side by side, on placeholders. A cue, which is a central fixation cross and placeholders flashed synchronously together with a sound-beep, before each pair presentation. Critically, the time-lag between the cue and the image pairs to be encoded was jittered randomly between 0 and 1000 ms. Each encoding block was followed by a four-trials recognition block, where participants judged whether or not a given image pair had been presented together in the previous encoding block. Each participant provided a total of 1.408 responses.

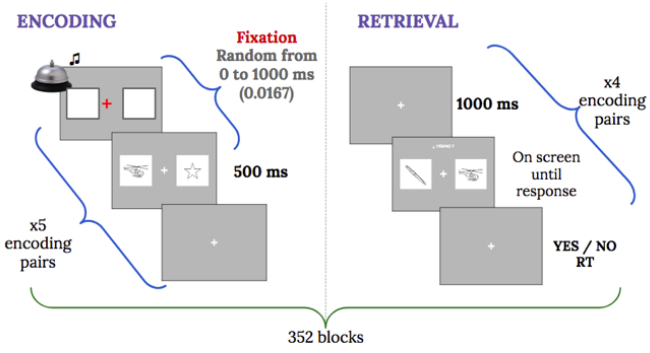


**Figure 1. Visual associative memory task.** In the encoding block, at each trial a pair of unrelated images is presented for 500 ms after a variable SOA (from 0 to 1000 ms) from a resetting signal.

## Results

We measured hit rate at the recognition block as a function of the cue-to-item interval in the encoding block. We binned cue-to-item intervals in sliding windows of 50 ms (shifted every 16.7 ms) up to 500 ms, thus generating smoothed temporal series relating behaviour to encoding time. Then, we used the Fast Fourier Transform (FFT) to extract the spectral pattern of the behavioural time series. We found that behavioural performance was periodically and selectively modulated at a frequency of ~5 Hz. The significance of this fluctuation was confirmed against simulations using surrogate data sets extracted from the same pool.

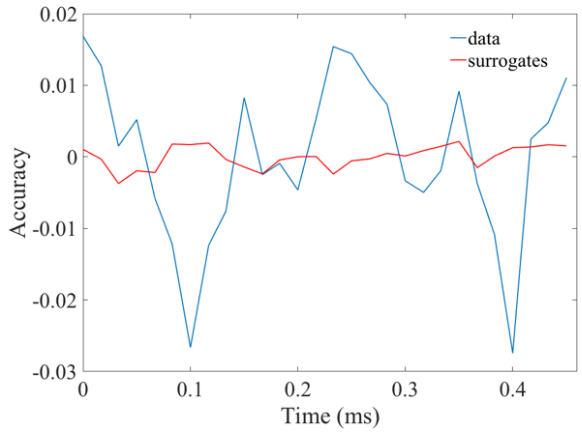


**Figure 2. Behavioural Performance.** Mean hit rate across participants as a function of time (blue line, N=30). Note the red line plots the mean hit rate obtained after 10.000 iterations of the randomized data.

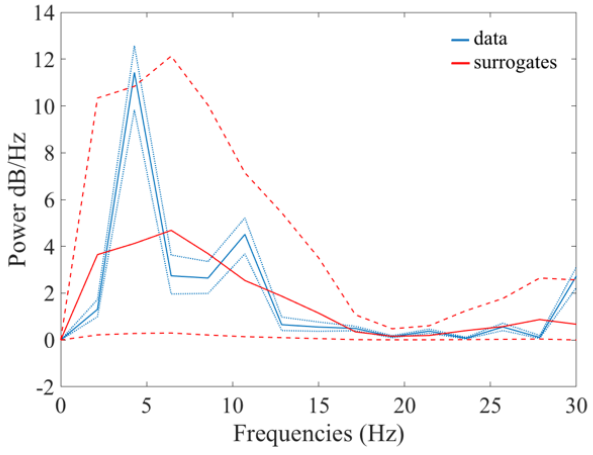


**Figure 3. Power Spectrum.** Amplitude measurement obtained using the FFT for the mean hit rate. As can be seen (blue line), there is a peak around ~5 Hz (theta band) and a ~10 Hz peak (alpha band). The peaks are found at frequency bands related to cognitive function.

## Conclusions and Discussion

The results of the present study show theta periodicity and specificity on visual associative memory performance. In particular, the data reveal that the phase at which relevant stimuli are presented for encoding is consequential for predicting later successful recognition. Our findings are in line with previous results showing that ongoing theta and alpha oscillations underlie periodicity in visual perception and attention performance (Busch et al., 2009; Busch & VanRullen, 2010; de Graaf et al., 2013; Dugue, Marque, & VanRullen, 2015; Klimesch et al., 2007; Landau, Schreyer, van Pelt, & Fries, 2015; Mathewson et al., 2009; Palva & Palva, 2007; VanRullen, 2016). Here, we suggest a link between these fluctuations in perceptual-attentional processes and successful formation of episodic memory traces.

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## References

Busch, N. A., Dubois, J., & VanRullen, R. (2009). The phase of ongoing EEG oscillations predicts visual perception. *J Neurosci, 29*(24), 7869-7876. doi:10.1523/JNEUROSCI.0113-09.2009

Busch, N. A., & VanRullen, R. (2010). Spontaneous EEG oscillations reveal periodic sampling of visual attention. *Proc Natl Acad Sci U S A, 107*(37), 16048-16053. doi:10.1073/pnas.1004801107

de Graaf, T. A., Gross, J., Paterson, G., Rusch, T., Sack, A. T., & Thut, G. (2013). Alpha-band rhythms in visual task performance: phase-locking by rhythmic sensory stimulation. *PLoS One, 8*(3), e60035. doi:10.1371/journal.pone.0060035

Dugue, L., Marque, P., & VanRullen, R. (2015). Theta oscillations modulate attentional search performance periodically. *J Cogn Neurosci, 27*(5), 945-958. doi:10.1162/jocn_a_00755

Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: the inhibition-timing hypothesis. *Brain Res Rev, 53*(1), 63-88. doi:10.1016/j.brainresrev.2006.06.003

Landau, A. N., Schreyer, H. M., van Pelt, S., & Fries, P. (2015). Distributed Attention Is Implemented through Theta-Rhythmic Gamma Modulation. *Curr Biol, 25*(17), 2332-2337. doi:10.1016/j.cub.2015.07.048

Mathewson, K. E., Gratton, G., Fabiani, M., Beck, D. M., & Ro, T. (2009). To see or not to see: prestimulus alpha phase predicts visual awareness. *J Neurosci, 29*(9), 2725-2732. doi:10.1523/JNEUROSCI.3963-08.2009

Palva, S., & Palva, J. M. (2007). New vistas for alpha-frequency band oscillations. *Trends Neurosci, 30*(4), 150-158. doi:10.1016/j.tins.2007.02.001

VanRullen, R. (2016). Perceptual Cycles. *Trends Cogn Sci, 20*(10), 723-735. doi:10.1016/j.tics.2016.07.006