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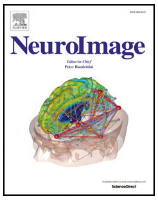

Acceptance of evidence-supported hypotheses generates a stronger signal from an underlying functionally-connected network

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ABSTRACT

Choosing one's preferred hypothesis requires multiple brain regions to work in concert as a functionally connected network. We predicted that a stronger network signal would underlie cognitive coherence between a hypothesis and the available evidence. In order to identify such functionally connected networks in magnetoencephalography (MEG) data, we first localized the generators of changes in oscillatory power within three frequency bands, namely alpha (7–13 Hz), beta (18–24 Hz), and theta (3–7 Hz), with a spatial resolution of 5 mm and temporal resolution of 50 ms. We then used principal component analysis (PCA) to identify functionally connected networks reflecting co-varying post-stimulus changes in power. As predicted, PCA revealed a functionally connected network with a stronger signal when the evidence supported accepting the hypothesis being judged. This difference was driven by beta-band power decreases in the left dorsolateral prefrontal cortex (DLPFC), ventromedial prefrontal cortex (VMPFC), posterior cingulate cortex (PCC), and midline occipital cortex.

Introduction

One cognitive function fundamental to human thought is choosing whether to accept a hypothesis. This underlies interpreting what you perceive, deciding how to act, and forming beliefs. When you judge a hypothesis, you will form a mental representation of how it relates to the available evidence. That mental representation or *gestalt* (Köhler, 1929; Metzger, 2006) should be more coherent and stable if the evidence 'fits' — in other words, if it supports the hypothesis being judged. This is demonstrated in how people are biased against evidence disconfirming their current beliefs (Buchy et al., 2007; Woodward et al., 2007), biased toward interpreting new evidence as being consistent with currently preferred interpretations (Whitman and Woodward, 2012), and generally biased toward gathering and perceiving evidence confirming their current opinions (Nickerson, 1998; Sanbonmatsu et al., 1998; Wason, 1960). The common theme across these findings is a cognitive bias favoring mental representations of evidence–hypothesis matches. We propose that this bias stems from a fundamental organizational principle of how the brain operates: namely, by forming connections between groups of neurons. Connections formed dynamically between the large sets of neurons underlying the mental representation of one concept (i.e. a hypothesis) and the sets of neurons underlying the mental representations of other concepts (i.e. items of evidence) would be easily supported by the brain's mechanisms for functional connectivity. Hence, we predicted that a match between a hypothesis being judged and the available evidence – in other words, greater cognitive coherence – should correspond to a stronger signal from at least one underlying functionally connected brain network.

In order to ask whether functionally connected network signals grew stronger in response to evidence–hypothesis matches, we analyzed the activity of brain networks while participants performed a hypothesis judgment task. Brain activity was recorded via magnetoencephalography (MEG). MEG measures a real-time signal, similar to that of the more widely used electroencephalography (EEG), but orthogonal to it and less subject to spatial distortions (Herdman and Cheyne, 2009). In the hypothesis judgment task, the available evidence either supported accepting the hypothesis being judged (referred to hereon as the *focal* hypothesis), or supported rejecting it in favor of an alternative hypothesis. The focal and alternative hypotheses each corresponded to a lake containing a mixture of black and white fish (see Fig. 1). On each trial, a single black or white fish appeared in a downstream lake. Participants had to judge the probability that it had migrated there from the focal lake rather than the alternative lake. They responded by using the buttons on a response box (right-handed)

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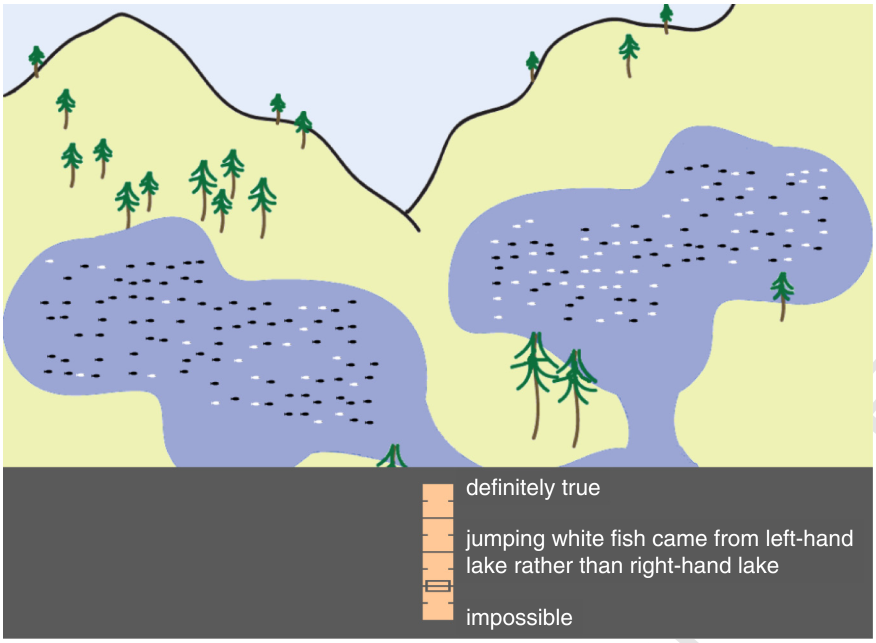

Fig. 1. The hypothesis judgment task performed by participants. At the beginning of each trial, the participants were presented with two upstream lakes, each containing a mixture of black and white fish, and a third, empty downstream lake. A single fish, randomly selected to be either black or white, jumped within the downstream lake (jump duration was 140 ms). A Likert scale on a black background then appeared, with the text "definitely true" at the top end and "impossible" at the bottom end. In the example depicted here, the question next to the Likert scale asks the participant to rate their agreement with the statement that the "jumping *white* fish came from the *left*-hand lake rather than the *right*-hand lake". In that example, the left-hand lake is the *focal* hypothesis, while the right-hand lake is the *alternative* hypothesis. The participant thus correctly rejects the focal hypothesis. The color of the jumping fish (black or white) and the location of the lake corresponding to the focal hypothesis (left-hand vs. right-hand lake) were randomized across trials. Throughout each inter-trial interval, the Likert scale and black background disappeared, and each of the lakes was empty.

to move a cursor up or down a rating scale. This was an adaptation of a paradigm described in our previously published work (Whitman, Metzak, Lavigne, and Woodward, 2013). Our goal was to identify at least one functionally connected network of brain regions displaying a stronger signal when the evidence matched the focal hypothesis, and the combined mental representation was thus more coherent.

In order to characterize functional networks underlying this task with high spatial and temporal detail, we used a beamformer algorithm to create whole-brain images of changes in oscillatory power. Use of beamformer algorithms to localize the cortical generators of oscillatory signals in MEG data can produce brain maps with a level of spatial detail similar to those seen at the cluster level in functional magnetic resonance imaging (fMRI). We were able to produce one image for each successive 50 ms post-stimulus interval by using a sliding window to average across temporally overlapping estimates of oscillatory power. This was done separately for three frequency ranges of interest, known as the alpha (7–13 Hz), beta (18 to 24 Hz), and theta (3–7 Hz) frequency bands (Engel and Fries, 2010; Kelly et al., 2006; Wu et al., 2007), and separately for each experimental condition of interest: whether evidence supported or refuted the focal hypothesis. Each beamformed image represented activity combined across trials within a given condition. We then assessed how changes in the power of cortical oscillations covaried over time between brain regions and frequency bands. To this purpose, we used principal component analysis (PCA) to identify, in an efficient and data-driven manner, the dominant brain networks defined by shared time courses of post-stimulus changes in oscillatory power. PCA analyzes a matrix of covariances or correlations between variable values (in this case spectral power in a specific frequency band at each voxel) into orthogonal components, with each component accounting for part of the pattern of covariances (Jolliffe, 1986).

We expected the brain networks involved in performing the hypothesis judgment task to include regions of the dorsal attention, vision, and frontoparietal control networks (Yeo et al., 2011) with strong contributions from parietal and lateral occipital cortices, as was found in our previous fMRI study of hypothesis judgment (Whitman et al., 2013a, 2013b). We also predicted that the left dorsolateral prefrontal cortex (DLPFC), reported to be involved in perceptual decision-making (Heekeren et al., 2004; Heekeren et al., 2006; Kim and Shadlen, 1999), might figure prominently. While the left DLPFC did not figure prominently in our previous fMRI study, its role may be more evident in the MEG data, which involve real-time measures with a much higher temporal resolution than fMRI.

The examination of oscillations in several distinct frequency bands may also reveal effects not detectable by fMRI. The power of cortical oscillations in several characteristic frequency bands is known to vary as a function of several cognitive factors. There is an extensive literature on how the power of alpha-band oscillations over parietal and occipital regions varies with spatial attention (Kelly et al., 2006; Rihs et al., 2007; Sauseng et al., 2005a, 2005b; Worden et al., 2000), and literature on the role of theta-band oscillations in central executive functions, working memory, and task switching (Sauseng et al., 2010; Sauseng et al., 2005a, 2005b; Schack et al., 2005; Wu et al., 2007). Changes in beta-band power in motor cortex contralateral to a hand being moved are associated with motor activity (Pfurtscheller et al., 1996; Pfurtscheller et al., 2003). Beta-band oscillations in multiple brain regions, including prefrontal and parietal cortices, are associated with insightful problem-solving and perceptual decision-making (Donner et al., 2009; Sheth et al., 2009; Siegel et al., 2011). We predicted that a functionally connected brain network, involving changes in oscillatory power covarying across at least some of the brain regions specified above, and potentially also covarying across frequency bands, would exhibit a stronger signal when the evidence supported accepting the focal hypothesis.

Materials and methods

Ethics approval for all experiments reported here was obtained from the UBC Clinical Research Ethics Board and the Vancouver Coastal

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