NeuroImage 119 (2015) 13–19

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/ynimg

Beta oscillations and reward processing: Coupling oscillatory activity and hemodynamic responses

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ARTICLE INFO

Article history:
Received 16 December 2014
Accepted 21 May 2015
Available online 10 June 2015

Keywords:
Reward
Beta oscillations
fMRI
Time–frequency
JointICA

ABSTRACT

Diverse cortical and subcortical regions are synergically engaged during reward processing. Previous studies using time–frequency decomposition of Electroencephalography (EEG) data have revealed an increase of mid-frontal beta oscillatory activity (BOA) after reward delivery, which could be a potential mechanism in the coordination of the different areas engaged during reward processing. In order to evaluate this hypothesis, twenty subjects performed a monetary gambling paradigm in two separate sessions (EEG and fMRI). Time–frequency oscillatory EEG data and fMRI activity were fused using Joint Independent Component Analysis (ICA). The present results showed that mid-frontal BOA elicited by monetary gains is associated with the engagement of a fronto–striatal–hippocampal network previously involved in reward-related memory enhancement, supporting the role of this activity during reward processing.

Introduction

Learning on the bases of reward is critical to anticipate potential outcomes and optimize decision-making. This fundamental process requires the dynamic interplay of distributed neural substrates involved in reward, attention and memory (Dayan and Balleine, 2002). In this vein, previous studies have shown that fronto–striatal–hippocampal interactions play an important role in the enhancement of both long and short-term memory formation induced by rewards (Wittmann et al., 2005, 2008; Adcock et al., 2006; Murty and Adcock, 2013). The optimal engagement of such extensive network requires of an integrative mechanism that allows the selective recruitment and rapid coordination of the brain structures involved in it. One potential mechanism to achieve such efficient neuronal communication is the synchronization of separated brain areas to a common rhythm of neuronal firing (von Stein and Sarnthein, 2000). Concretely, Beta Oscillatory Activity (BOA) has recently been suggested to be a key component mediating the cross-talk between reward, memory and attention processes following rewarding events (Marco-Pallarés et al., 2014).

Previous Electroencephalography (EEG) and Magnetoencephalography (MEG) human studies using time–frequency (TF) decomposition have revealed a mid-frontal BOA elicited by positive outcomes (20–30 Hz, peaking 200–400 ms after positive feedback; Cohen et al., 2007; Marco-Pallarés et al., 2008; Marco-Pallarés et al., 2009; Cunillera et al., 2012; HajiHosseini et al., 2012; Leicht et al., 2013; Luft et al., 2013; Padrao et al., 2013) and reward-predicting cues (Bunzeck et al., 2011; Kawasaki and Yamaguchi, 2013; Apitz and Bunzeck, 2014). This gain-related signal has been associated to the engagement of reward-related brain networks due to the fact that BOA shows a similar pattern in response to rewards than that observed in midbrain dopaminergic and striatal neurons. Interestingly, several studies have supported this view. Indeed, BOA has been shown to be sensitive to individual differences in the Catechol-O-methyltransferase enzyme (COMT) polymorphism (Marco-Pallarés et al., 2009), which is related to differences in dopamine levels. Similarly, administration of dopaminergic agonists also modulates BOA in response to reward-predicting cues and reward outcomes (Apitz and Bunzeck, 2014). In line with these results, Leicht and colleagues (2013) showed that individual differences in BOA predicted participants' sensation seeking trait, strongly related to increased dopaminergic activity (Blanchard et al., 2009). All in all, these studies point out the relevance of the mesolimbic system in the modulation of cortical BOA.

Although most of these studies have focused on local power results, several authors have hypothesized that this activity may be related to long-rage communication driven by phase synchronization (Cohen et al., 2011; Marco-Pallarés et al., 2014). In particular, Marco-Pallarés and colleagues (2014) have proposed that BOA may reflect the

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http://dx.doi.org/10.1016/j.neuroimage.2015.05.095
1053-8119/

transmission of fast motivational value signals from cortical structures to downstream regions in order to enhance the encoding of positive or novel events. Accordingly, BOA has also been related to working memory improvements in rewarding motivational contexts (Kawasaki and Yamaguchi, 2013), a process mediated by fronto–striatal–hippocampal loops (Murty and Adcock, 2013). Thus, according to Marco-Pallarés and colleagues' model, BOA would reflect the interplay between attentional (orienting attention to relevant on-going goals), motivational (enhancing encoding) and memory circuits (storing information). However, this assumption has never been tested.

Uncovering cerebral networks underlying BOA would involve the use of a combination of neuroimaging techniques with both high temporal precision—needed to derive BOA ranges—and also optimal spatial resolution, along with the ability to assess distant brain regions with no a priori constrains. A possible approach to tackle the aforementioned technical difficulties is the use of a combined EEG-fMRI analysis which would take advantage of the optimal temporal and spatial precision provided by each neuroimaging technique, respectively (Carlson et al., 2011). Independent Component Analysis (ICA)—a multivariate, data-driven approach— has emerged as a promising method to extract and combine temporal information from EEG and spatial information from fMRI. In particular, Joint ICA (Calhoun et al., 2006) selects independent components from different neuroimaging techniques simultaneously, using, for example, EEG data in the temporal domain and fMRI activation maps in the spatial domain (Calhoun et al., 2009). In the present study—by performing a multimodal Joint ICA EEG-fMRI analysis—we aimed to test the hypothesis that mid-frontal BOA is associated with reward-related networks.

Materials and Methods

Participants

Twenty students (M = 22.9 years old, SD = 2.9, 15 women) participated in the experiment. All participants were paid 10€ per hour plus an amount of monetary bonus depending on participants' performance. All participants gave written informed consent and all procedures were approved by the local ethical committee.

Experimental Procedure

Each participant performed a separated fMRI and EEG session (as in the EEG-fMRI gambling setup of Carlson et al., 2011). Participants performed the same gambling task in both sessions adapted to EEG and fMRI setups. The EEG session was performed in a different room to that of the scanner. The order of the two sessions was counterbalanced across participants and was separated by at least 1 day (M = 8.2, SD = 7.5 days).

Participants were engaged in a gambling task (see Fig. 1), similar to the one used in the study by HajiHosseini et al. (2012). Each trial started with a figure (pre-cue) which indicated whether the next cue would be informative (information pre-cue followed by informative cue) or not (non-information pre-cue followed by non-informative cue). If the trial was informative, one of two possible cues appeared ($p = 0.5$); a cue indicating either high probability (hp) or low probability (lp) of monetary wins. However, if the pre-cue indicated that the trial was non-informative, one of two different cues with no relationship with the probability of winning or losing or the final result of the trial (gain or loss) was randomly presented ($p = 0.5$). In other words, cues in the non-informative trials provided no information and were displayed to maintain a consistent structure across the two conditions (information vs. non-information). In the fMRI task, the pre-cue and cue lasted 8 s with a pseudorandom jitter from a fixed distribution between −1 and 1 s at 125 ms steps. This jitter was added both to the pre-cue and subtracted from the cue (i.e., the pre-cue lasted 4 s plus the jitter and the cue 4 s minus the jitter, for a total of 8 s). In the EEG task, the time between the pre-cue and the cue signals and the time between the cue signal and the presentation of the cards was set to 1.5 s (for a total of 3 s).

After the presentation of the cue (high probability, low probability, or the non-informative random cue), four blank cards appeared on the screen. Subjects were instructed to select a card among four by pressing one of four buttons (two buttons in each hand). After the response choice, the selected card was marked and after 2 s all cards turned to either green or red. If the subject had selected a green card, he/she won 50 euro cents whereas if the participant had selected a red card, he/she lost 50 euro cents. If a participant did not respond after 2 s, a message prompting him/her to respond faster was presented and no money was lost/won (no red/green cards were shown). In high probability trials, three cards turned green and one turned red, whereas in low probability trials three cards turned red and one turned green. In non-informative conditions, the same pattern of results occurred: in half of the trials three cards turned red and one green and in the other half three turned green and one red. After the presentation of feedback, a blank screen was presented for 2 s, indicating the beginning of a new trial. The feedback indicating the win or the loss remained in the screen for 2 s in the fMRI task and 1.5 s in the EEG task. In addition, in the fMRI task, a jitter between −1 and 1 s at 125 ms steps, was added to the selection of the card and subtracted from the blank screen separating the different trials (i.e., the selection of the card lasted 2 s plus the jitter and the time between trials lasted 2 s minus the jitter).

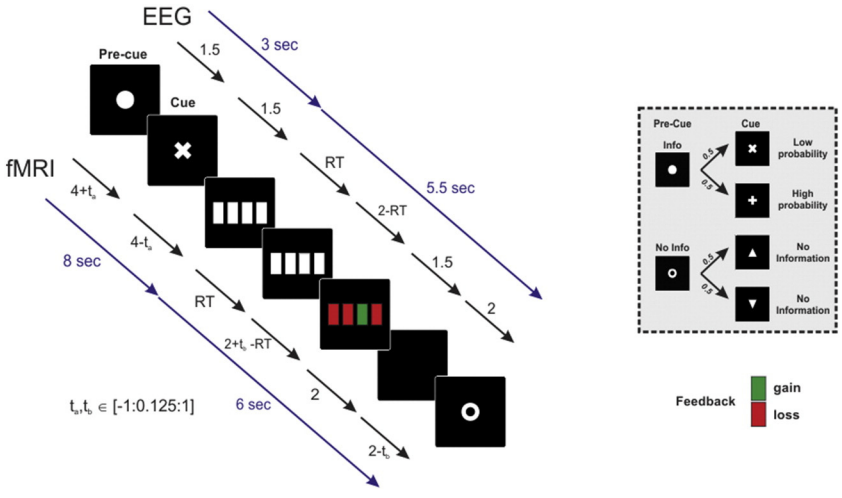

Fig. 1. Gambling task. Experimental setup for the gambling task with the different timings and jitter for the two modalities (EEG, fMRI).