International Journal of Psychophysiology 91 (2014) 172–177

Contents lists available at ScienceDirect

International Journal of Psychophysiology

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

Resting-state EEG theta activity and risk learning: sensitivity to reward or punishment?

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ARTICLE INFO

Article history:
Received 24 April 2013
Received in revised form 18 October 2013
Accepted 22 October 2013
Available online 29 October 2013

Keywords:
Resting-state EEG
Theta/beta ratio
Decision-making
Reinforcement learning
Reward–punishment sensitivity

ABSTRACT

Increased theta (4–7 Hz)–beta (13–30 Hz) power ratio in resting state electroencephalography (EEG) has been associated with risky disadvantageous decision making and with impaired reinforcement learning. However, the specific contributions of theta and beta power in risky decision making remain unclear. The first aim of the present study was to replicate the earlier found relationship and examine the specific contributions of theta and beta power in risky decision making using the Iowa Gambling Task. The second aim of the study was to examine whether the relation were associated with differences in reward or punishment sensitivity. We replicated the earlier found relationship by showing a positive association between theta/beta ratio and risky decision making. This correlation was mainly driven by theta oscillations. Furthermore, theta power correlated with reward motivated learning, but not with punishment learning. The present results replicate and extend earlier findings by providing novel insights into the relation between thetabeta ratios and risky decision making. Specifically, findings show that resting-state theta activity is correlated with reinforcement learning, and that this association may be explained by differences in reward sensitivity.

1. Introduction

The resting state electroencephalogram (EEG) is composed of different frequency components and found to be relatively stable over time (Corsi-Cabrera et al., 2007; Williams et al., 2005). Furthermore, resting state EEG is not merely an epiphenomenon and is proposed to reflect electrophysiological predisposition of human behavior (Allen et al., 1993; Coan and Allen, 2004; Davidson, 1992; Harmon-Jones and Allen, 1997; Hofman and Schutter, 2012; Sutton and Davidson, 2000). For example the ratio between resting state theta (4 7 Hz) and beta activity (13–30 Hz) oscillations have been found to predict risk-taking behavior (Schutter and Van Honk, 2005), and self-reported approach motivation. The use of this metric has its origin in Attention Deficit Hyper Activity Disorder (ADHD) research, where increased theta activity and decreased beta activity are often found in patients compared to healthy controls (Clarke et al., 2002b; Clarke et al., 2003; di Michele et al., 2005; Snyder and Hall, 2006). In ADHD, abnormalities in the theta and beta bands found to be related to responsiveness to drug treatment (Clarke et al., 2002a; Clarke et al., 2002b; Clarke et al., 2003), and normalizing these abnormalities is a common target for biofeedback treatment of this condition (see Loo and Makeig, 2012 for a review and discussion of limitations). The increase in theta and decrease in beta power in ADHD have originally been interpreted as reflecting hypoarousal. The findings in healthy populations, however, showing that increased theta/beta ratio is associated with increased risk taking may suggest that there is a specific link between resting state theta and beta activity and reward related motivation (Schutter and Van Honk, 2005). Such a link is directly of interest for ADHD since this condition is often associated with increased risk taking behavior (Drechsler et al., 2007; Duarte et al., 2012; Garon et al., 2006; Malloy-Diniz et al., 2007; Miller et al., 2013) and aberrant reward processing (Ernst et al., 2003; Holroyd et al., 2008; van Meel et al., 2005).

In the earlier study by Schutter and van Honk, theta/beta ratio was found to inversely correlate with learning performance in the Iowa Gambling Task (Schutter and Van Honk, 2005). In this task people learn to make choices based on the balance between reward and punishment outcomes. Different decks of cards are associated with different reward/punishment contingencies. Advantageous decks are characterized by frequent low gains, and infrequent low losses, resulting in a net gain. Disadvantageous decks are associated with frequent high gains, but infrequent higher losses, leading to long term loss (Bechara et al., 1994). Individuals with a high resting-state theta/beta ratio more slowly learned to choose advantageous decks as compared to individuals with low theta/beta ratio (Schutter & van Honk, 2005). This finding suggests that resting-state theta/beta ratio is associated with the propensity to take risky decisions, and may reflect differences in the underlying punishment and reward sensitivity. In keeping with this idea we recently found that event related EEG responses (ERPs) to gambling outcome information were correlated with resting-state theta/beta ratio. Individuals who had a high

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http://dx.doi.org/10.1016/j.ijpsycho.2013.10.013

theta/beta ratio showed less pronounced differences between reward and loss outcomes, as compared to individuals with a low theta/beta ratio (in individuals with high self-reported behavioral inhibition; Massar et al., 2012). Taken together these findings provide support for the idea that resting-state theta/beta ratio is particularly associated with activity in reward related brain circuits.

Although the theta/beta ratio provides a concise measure of abnormalities in both frequency bands, theta and beta EEG likely reflect activity in different brain circuits. Scalp recorded theta EEG has widespread cortical (local) generators (Raghavachari et al., 2006; Tsujimoto et al., 2006), an important source of frontal theta activity is in the anterior cingulate cortex (di Michele et al., 2005; Scheeringa et al., 2008; Womelsdorf et al., 2010). This portion of theta activity is thought to be related to the subcortical septal–hippocampal system which is associated with motivational processes (Gray and McNaughton, 2000; Mitchell et al., 2008). In agreement we found that resting state theta, that was localized to the dorsal ACC, was correlated with reward/loss related ERP amplitudes during a gambling task (Massar et al., 2012). Beta activity similarly, is generated in widespread cortical and subcortical areas. It is thought to reflect activity of inhibitory GABA-ergic interneurons. Functionally, beta activity is found to increase in situations in which the active motor or cognitive state needs to be maintained, inhibiting the interference of novel stimuli or motor plans (Buschman and Miller, 2007; Engel and Fries, 2010; Jenkinson and Brown, 2011). Comparably, it has been suggested that beta in resting state reflects top–down inhibition of motivational drives (Hofman et al., 2013; Putman et al., 2010; Schutter and Van Honk, 2005). In the present study we aimed to replicate these findings, by replicating the association between resting-state theta/beta ratio and risky decision making. Resting-state EEG was measured from thirty-one participants before they performed the IGT. If resting-state EEG profile is indeed indicative of risky decision making, we would expect to replicate the findings of a negative correlation between the theta/beta ratio and IGT learning performance. Moreover we aimed to distinguish the separate contributions of theta and beta activities by analyzing their relations with IGT performance separately.

A second matter of interest is that learning in the IGT cannot unequivocally be ascribed to one specific cognitive or motivational operation (Buelow and Suhr, 2009). Disadvantageous decisions in the IGT are associated with both high gains and high losses. Therefore, impaired learning in this task could be due to an excessive drive to obtain rewards (reward sensitivity), or alternatively to a decreased propensity to avoid punishment (punishment sensitivity; Bauer et al., 2013; Bechara et al., 2002; van Honk et al., 2002). Reward processing and punishment processing are partially governed by different brain circuits (Seymour et al., 2007; Yacubian et al., 2006), therefore it is possible that resting-state EEG in a particular frequency band specifically relates to either one of these tendencies. In order to examine whether resting-state EEG was specifically related to reward or punishment sensitivity in this study, we incorporated a task that separately assesses these two motivational systems (Pessiglione et al., 2006). In this task stimuli are associated with either a chance to win money, or a chance to lose. Reward sensitivity would be expressed as the increasing propensity to choose gain-related stimuli, while punishment sensitivity is reflected in the extent to which loss-related stimuli are avoided. Resting-state EEG was measured before participants performed the two gambling tasks, and associations between resting-state EEG, IGT learning scores, and reward and punishment sensitivity were examined.

2. Methods

2.1. Participants

Thirty-one healthy participants (8 males; age: mean ± SD, 23.2 ± 5.7) were recruited from the Utrecht University campus. All participants had normal or corrected-to-normal vision. All except for four participants were right-handed. All participants signed informed consent before starting the experiment, and received payment or course credits for participation.

2.2. EEG recording

Resting state EEG was measured from 9 electrodes placed according to the international 10/20 system (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4). Vertical and horizontal EOG was recorded with electrodes placed above and below the left eye, and at the outer canthi of each eye. EEG was recorded with BioSemi ActiveTwo Ag/AgCl active electrodes, at a sampling rate of 2049 Hz, using a 512 Hz low-pass filter. As per Biosemi design online reference is done using the CMS/DRL system (Common Mode Sense/Driven Right Leg; MettingVanRijn et al., 1996). Four minutes of resting-state EEG were recorded (2 min eyes open, 2 min eyes closed). EEG data were offline referenced (average mastoids). Further analysis was done following methods described in earlier studies (Schutter and Van Honk, 2005). Data were filtered (1 Hz high-pass, 30 Hz low-pass), and divided into 4-second segments. Automatic eye movement correction was applied (Gratton et al., 1983), and segments containing muscle or other artifacts (activity exceeding ±60 μV) were excluded from further analysis. Spectral power estimation was done with a Fast Fourier transformation (Hamming window: 10%). Power values in the theta band (4–7 Hz), and beta band (13–30 Hz), and theta/beta ratios were calculated at Fz and Cz, since resting-state theta/beta ratio typically shows a peak at fronto-central scalp locations (Massar et al, 2012).

2.3. Iowa Gambling Task (IGT)

A computerized version of the Iowa Gambling Task was used (see Fig. 1). Participants were instructed to choose from four decks of cards by clicking on one deck using a mouse. After choosing a card the amount that was lost or won was presented in the middle of the screen. Unbeknownst to the subjects, two decks provided frequent large rewards, but infrequent larger losses (disadvantageous decks), adding up to a net loss over trials. The other two decks (advantageous decks) were associated with lower gains. Infrequent losses, however, were also less high, creating a positive expected value (Bechara et al., 1994). The task lasted for 100 trials, and participants were instructed to try to win as much money as possible. Performance was quantified as the percentage of advantageous choices per block of 20 trials. Learning score was quantified as the difference between the first block and the last block.

2.4. Reward-punishment task (RPT)

The reward–punishment task (RPT) was adapted from Pessiglione et al. (2006; see Fig. 1). Subjects had to learn to distinguish between symbols that were presented in pairs. For one pair, one symbol was associated with a high chance of winning 1 Euro and a lower chance of winning nothing (80% win, 20% nothing). The other symbol was associated with the reversed reward probability (20% win, 80% nothing). For a second pair, one symbol was characterized by a high probability of losing 1 Euro (80% loss, 20% nothing), while the other symbol had a reversed loss probability. Outcome feedback was provided after every trial by presenting a picture of a euro coin together with the word 'win' or 'lose' for winning and losing trials respectively. On trial in which nothing was won or lost, only the word 'nothing' was presented (without showing a euro coin). A third (neutral) pair did not yield any rewards or losses. After choosing one symbol in this neutral pair, a euro coin was presented accompanied by the word 'look', on 80% of the trials, indicating that the participant was to view the euro coin but that no money was added or subtracted. On the remaining 20% of the neutral-pair trials the word 'nothing' was presented after a choice was made, again indicating that no money was lost or won. Similar to the IGT, participants were not aware of the reinforcement schedule when starting the task, and had to learn by trial-and-error. Participants were instructed to earn as