

Vicarious Reward Response Is Positively Correlated with Functional Connectivity in the Resting State Default Mode Network

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Abstract

Some people can easily empathize with others, while others cannot. The neural mechanism underlying individual difference of how much people can empathize with others is still not clear. Vicarious reward is the phenomenon by which we vicariously experience the positive sensations or emotions of others. Beta oscillatory activity (BOA) is observed when participants experience vicarious reward. Recent studies have reported that the default mode network (DMN) is also involved in reward processing and have suggested that individual differences in the way participants respond to reward stimuli are correlated with DMN functional connectivity during the resting state. In the current study, we investigated whether DMN functional connectivity during the resting state is also correlated with BOA for vicarious reward. Participants watched a player playing a game (Kendama) and investigated the correlation of BOA amplitude and resting state DMN functional connectivity. The results revealed a significant correlation between the degree of phase synchronization within DMN components in the resting state and the amplitude of BOA while participants experienced vicarious reward. The results suggested that functional connectivity within the DMN in the resting state positively influenced vicarious reward processing while observing others receiving a reward.

Keywords

Vicarious Reward, Default Mode Network (DMN), PHASE Synchronization, Beta Oscillatory Activity (BOA), Electroencephalography (EEG)

1. Introduction

We often feel positive feelings or pleasure when observing people we like achieving positive outcomes. This experience often occurs even in the absence of a direct relationship between the observer and the observed person. The phenomenon by which we vicariously experience the positive sensations or emotions of others is called vicarious reward and constitutes a form of empathy. Vicarious reward is commonly experienced in daily life. For example, when watching a professional sports game or TV show, people often become invested in the activities of certain players or characters. When these observed individuals achieve positive outcomes, the observer also feels pleasure, even if they are not directly involved in the observed activity. An increasing number of studies have examined this kind of positive empathy or vicarious reward (Lammell et al., 2008; Gable & Reis, 2010; Rizzolatti et al., 2014; Marco-Pallarés et al., 2015; Morelli et al., 2015; Apps et al., 2016; Lockwood, 2016).

Recent studies have examined the neural correlates of vicarious reward and noted the involvement of the reward system, which exhibits activation when participants directly receive a reward (Mobbs et al., 2009; Lockwood et al., 2015; Apps et al., 2016; Apps et al., 2013; Shimada et al., 2016). Mobbs et al. (2009) conducted an experiment using functional magnetic resonance imaging (fMRI), in which participants watched a socially desirable player and socially undesirable players play a game requiring the players to make a judgment about whether an unseen card would be higher or lower than a second unseen card. The results revealed greater activation in the observer's reward system, including the ventral striatum (VS), anterior cingulate cortex (ACC) and ventromedial prefrontal cortex (vmPFC), when the socially desirable player won in a game, compared with when the socially undesirable player won. This enhanced activity was also correlated with the subjective feeling of similarity to the observed player, which indicates that observers were more likely to experience vicarious reward when they had a feeling of closeness with the observed person. Several other studies have also reported vmPFC and ACC involvement in processing rewards received by others (Burke et al., 2010; Aoki et al., 2014; Lockwood et al., 2015; Schott et al., 2008).

Previous studies investigating reward for the self using electroencephalography (EEG) reported beta oscillatory activity (BOA) in the mid-frontal region (typically around Fz, FCz and Cz; Marco-Pallarés et al., 2008; Marco-Pallarés et al., 2015; Mas-Herrero et al., 2015). Oscillatory activity while receiving a vicarious reward was also investigated in a previous study in our laboratory (Inomata et al., 2019). In that study, participants observed a two-player competitive game (rock-paper-scissors [RPS] game) while cheering for one of the players. The results revealed that BOA was elicited when the cheered-for player won, which indicates that BOA occurred when participants received vicarious reward, potentially providing a putative index of activation of the reward system for vicarious reward.

Recently, several studies reported a relationship between the default mode network (DMN) and the reward system, reporting a correlation with functional connectivity (FC) within these networks (Knyazev, 2013; Koch et al., 2018; Jung et al., 2013). The DMN is an intrinsic brain network that has been reported to be most strongly activated when a person is not focused on the outside world, and is in a state of internally focused thought (Raichle, 2015). Interestingly, several DMN regions have also been linked to social cognition (Mitchell, 2006; Gobbini et al., 2007) and empathy (Kim et al., 2017; Bilevicius et al., 2018). Thus, involvement of the DMN in vicarious reward processing might be expected because it is achieved by simulating another person's mental processes.

Koch et al. (2018) investigated the reward system of patients with obsessive-compulsive disorder (OCD) using a paradigm based on monetary reward because OCD patients are thought to have impaired reward system function resulting in patients exhibiting repetitive, compulsive behavior patterns to counteract anxiety. The results revealed that patients exhibited decreased activation in several frontal regions, including Brodmann Area 6 (BA6), BA8 and the posterior cingulate cortex (PCC, BA31) together with stronger connectivity between the PCC and the vmPFC (BA10), which are the main components of the DMN, compared with healthy controls, when participants received monetary reward (Koch et al., 2018). Jung et al. (2013) also conducted a delayed monetary reward task with OCD patients and healthy controls and compared the FC pattern between the resting state and the delayed monetary reward task. The results revealed that functional interactions between the nucleus accumbens (NA) and the medial orbitofrontal cortex (OFC) and rostral ACC persisted both in the resting state and the loss anticipation period in OCD patients, but not in healthy controls (Jung et al., 2013). These regions are also considered to be part of the DMN, indicating the involvement of the DMN in reward processing.

The DMN comprises a set of brain regions that are co-activated during passive states and show intrinsic functional correlations with one another. It can be divided into at least three subsystems that converge on hubs with specialized functions (Buckner et al., 2008). First, the medial temporal lobe subsystem provides information from prior experiences in the form of memories and associations that constitute the building blocks of mental simulation. Second, the medial prefrontal cortex (MPFC) subsystem facilitates the flexible use of this information during the construction of self-relevant mental simulation. These two subsystems converge on the third subsystem, which is the precuneus/posterior cingulate cortex (pC/PCC; Buckner et al., 2008; Knyazev, 2013). This third subsystem is thought to play a pivotal role in the DMN (Fransson & Marrelec, 2008).

The MPFC is thought to process social salience, which reflects the relationship between the self and others and is also activated during thinking about the complex interactions among people (Iacoboni et al., 2004; Schmitz et al., 2004; Mitchell et al., 2005; Mitchell, 2006; Buckner et al., 2008). Therefore, it is reasonable to assume that the second subsystem (the anterior hub of the DMN) may play a

key role in processing vicarious reward. The pC/PCC cortices, which are thought to play a pivotal role in DMN, are also thought to participate in salience detection and are positively related to the dopaminergic reward system (Knyazev, 2013). The pC/PCC is also involved in self-centered cognition and self vs. other discrimination (Vogt et al., 2006). Thus, it can be speculated that the third subsystem (the posterior hub of DMN) may also be involved in vicarious reward processing.

In the current study, we focused on the anterior hub and posterior hub of the DMN to investigate the relationship between the DMN and vicarious reward. We used EEG to investigate the neural activity associated with vicarious reward and resting state DMN. We examined EEG activity that occurred during the resting state and when participants watched another person play with a Kendama, a traditional hand-held toy in Japan. A Kendama toy has a stick with a point at one end, three cups attached, and a ball with a small hole in one end. The ball is connected to the stick with a string. In playing Kendama, the player attempts to catch the ball with a cup or a point of the stick. The experimental task comprised three sessions: a resting session with eyes open (RO), a resting session with eyes closed (RC) and a task session (Task). The RO and RC sessions enabled us to examine DMN activity during participants in the resting state so that we could investigate FC between the anterior hub and the posterior hub of the DMN for each participant. The task session enabled us to investigate EEG activity associated with vicarious reward processing. We investigated reward-related BOA for each participant. After investigating the FC of DMN and BOA of vicarious reward, the correlations between FC of DMN hubs and BOA were calculated to investigate whether FC of DMN can be used to explain individual differences between those who easily receive vicarious reward when watching others succeed and those who experience more difficulty receiving vicarious reward.

2. Materials and Methods

2.1. Participants

Twenty-one right-handed adults (seven females, aged 22.5 ± 2.09 years, mean \pm SD) participated in the experiment. Five participants were excluded from the analysis because of a high level of noise in the EEG signal (the noise detection method is described in the EEG data analysis section). Thus, 16 participants were included in the analyses. Written informed consent was obtained from all participants. The protocol was approved by the Research Ethics Committee of Meiji University and conducted according to the principles and guidelines of the Declaration of Helsinki.

2.2. Experimental Tasks

The experiment comprised three sessions: the eyes-closed resting (RC) session, the eyes-open resting (RO) session and the task session. In the RC session, par-

ticipants were instructed to close their eyes and remain quiet without focusing on any specific thought for 60 s. In the RO session, participants were instructed to stay quiet, as in the RC session, with their eyes open for 60 s. Both the RC session and RO session were performed twice, so there was a total of 120 s for each RC session and RO session

The Task session comprised 90 trials. The trials started after a 30-s rest period. Each trial comprised a jittered pre-stimulus rest period (pre-rest, 1 - 2 s), a 3.5-s movie, and a post-stimulus rest period (post-rest, 2 s). The movie clips in the Task session showed a female model playing with a Kendama. After the pre-rest period, the player appeared on the screen and did not move for 1.5 s (baseline). After the baseline period, the player pulled the ball upward using the string attached with the ball and tried to catch the ball with the cup of the Kendama stick (action period, for 1 s; **Figure 1**). Then, the results of the Kendama player kept showing for 1 s (result period) so that the participants could easily understand whether the player experienced success or failure. Thus, the outcome of the Kendama game was apparent 1 s after the onset of the player's action. In the Task session, participants were instructed to cheer for the player to be successful in the Kendama game in their mind (without saying anything aloud). The number of success trials and failure trials was matched (45 times) and the order was randomized in each session.

After the EEG experiment, participants completed Davis' Interpersonal Reactivity Index (IRI) to investigate personal traits of empathy, which is a 28-item self-report survey of seven-point Likert-type items (from -3 to +3). The 28 items provide individual scores on four subscales: perspective taking, fantasy, empathic concern, and personal distress (Davis, 1996). We also investigated the correlation between IRI scores and FC in the DMN in the resting state.

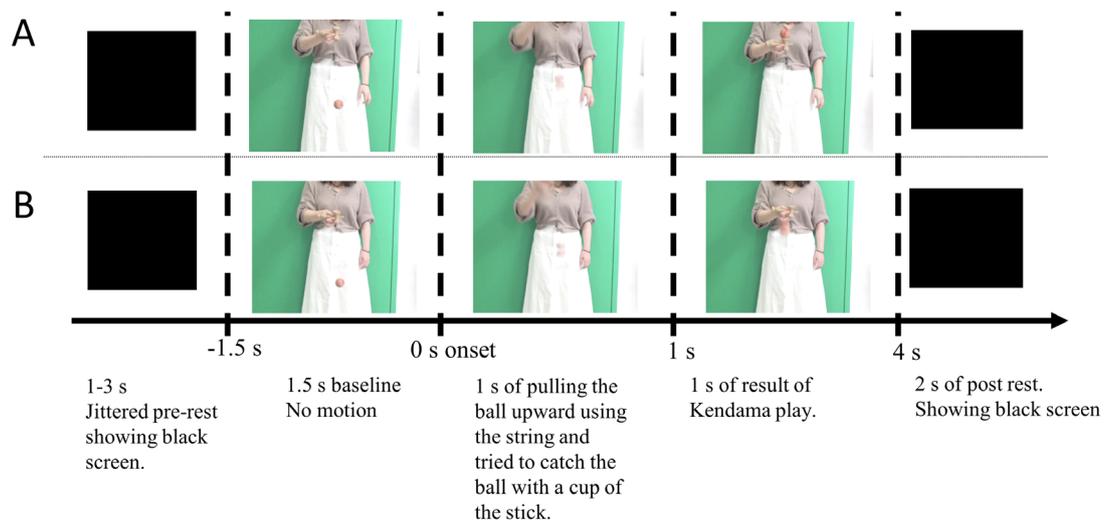


Figure 1. Schematic illustration of the experimental procedure in the Task sessions. Participants watched a 3.5-s movie clip of a person playing with a Kendama toy. (A) The player succeeded to catch the ball with a cup of the Kendama stick (success trial). (B) The player failed to catch the ball with a cup of the Kendama stick (failure trial).

2.3. EEG Data Acquisition

EEG was recorded using a 24-bit bio-signal amplification unit (g.USBamp, g.tec Medical Engineering GmbH, Austria) with a sampling frequency of 1200 Hz. The signals were recorded with active Ag/AgCl electrodes. Electrodes were mounted on an elastic cap and located at 30 positions according to the extended 10 - 20 system (Fp1, Fp2, F7, F3, Fz, F4, F8, FC5, FC3, FCz, FC4, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, PO3, PO4, O1, and O2). The ground electrode was located on the forehead and the reference was mounted on the right earlobe. Using the same amplification unit we used to record EEG, we recorded vertical electrooculography (EOG) from above and below the right eye. The electrophysiological signals were filtered with a 0.5 - 100 Hz band-pass filter.

2.4. EEG Data Analysis

All analyses were performed using Matlab 2019a (Mathworks, Sherborn, MA, USA) software. We subjected the EEG data to Jade independent components analysis (ICA) to eliminate ocular artifacts. ICA components that were most significantly correlated with the vertical EOG ($r^2 > 0.16$) were rejected. The remaining data were back projected to create EEG signals that were free from ocular artifacts. After rejecting the ocular artifacts, the RC and RO sessions were segmented into 3.5-s epochs using 0.5 s to 59.5 s EEG data. For the Task session, we segmented the EEG data into 3.5-s (baseline 1.5 s, action 1 s, result 1 s) epochs according to the Kendama trials. We set an artifact threshold of $\pm 100 \mu\text{V}$ and excluded trials in which the signal exceeded this level from further analysis. The percentage of rejected trials was 24.0% for all trials.

Prior to wavelet transformation, we re-referenced the EEG data offline to the mean of the amplitude from all electrodes. To investigate the time-frequency behavior elicited by the vicarious reward (Success/Failure) in the Task session, we computed the instantaneous amplitude and phase by convolving the EEG signal with a six-cycle complex Morlet wavelet (Kajihara et al., 2015). The frequency ranged from 1 to 40 Hz in 1-Hz steps. We applied wavelet transformation to the entire set of noise-reduced EEG data that were pre-processed in the previous section. After wavelet transformation, the time-frequency data were normalized based on the power of each frequency during the first 30-s resting period. Data were then baseline corrected using the average power of the baseline in each epoch (Hobson & Bishop, 2016). We avoided using the first half of the baseline period ($[-1, -0.5]$ s) to reduce the influence of the previous trial. In the following statistical analysis, we used the normalized and baseline-corrected data to investigate the significance of power changes with respect to the different stimuli. We categorized the frequency bands as follows: 1) theta band: 4 - 7 Hz, 2) alpha band: 8 - 14 Hz, 3) low-beta band: 15 - 30 Hz, and 4) high-beta band: 30 - 40 Hz. We investigated whether there were any changes in the power in these bands when participants experienced vicarious reward.

2.5. Vicarious Reward Processing While Watching Kendama Playing

Previous studies have reported that BOA observed at the mid-frontal electrode (typically Fz, FCz and Cz) reflects functional coupling of distributed brain regions involved in reward processing (Marco-Pallarés et al., 2008; Marco-Pallarés et al., 2015; Mas-Herrero et al., 2015; Inomata et al., 2019). We applied an a priori hypothesis about the region of interest (ROI), designating the mid-frontal electrode (Fz) as the ROI to investigate vicarious reward processing. Normalized and baseline corrected data were obtained from Fz for each success and failure trial. First, we subtracted time-frequency data of failure trials from that of success trials to determine the frequency and time point showing maximum difference between success and failure. After determining the frequency and time point, we used paired t-tests to test the significance of the power difference between success and failure trials.

2.6. EEG FC Analysis at Resting State

We selected four ROIs for the anterior hub and the posterior hub of DMN: BA24 and BA32 for the anterior hub and BA7 and BA23 for the posterior hub (Knyazev et al., 2012; Knyazev, 2013; Wacker et al., 2010). These ROIs were selected for both hemispheres in exact low-resolution electromagnetic tomography (eLORETA) software (Pascual-Marqui et al., 2011). We selected a single voxel in the center of each ROI as the representative voxel. To analyze FC between anterior hub and posterior hub of DMN, we used lagged phase synchronization as a measure of EEG FC between ROIs in anterior hub and posterior hub. Lagged phase synchronization is a method for evaluating the similarity between signals in the frequency domain, based on normalized Fourier transforms. Thus, lagged phase synchronization quantifies the non-linear relationship between two ROIs. This lagged connectivity measure is considered to be accurately corrected as it represents the connectivity of two signals after excluding the instantaneous zero-lag component such as volume conduction and low spatial resolution that usually affect other connectivity indices (Pascual-Marqui et al., 2011). After investigating the lagged phase synchronization for each ROI pairs at RC and RO session, Spearman's correlations between lagged phase synchronization for each ROI pairs and BOA power at task session were investigated for each participant.

2.7. Channel-Base Phase Synchronization Index (PSI)

Because eLORETA has potential methodological limitations due to the relatively low spatial resolution of intracortical signals, we also assessed channel-base phase synchronization which is directly observed at each electrode channels, to strengthen the eLORETA results. To identify the phase relationships between any two electrodes, we defined the phase synchronization index (PSI) for each time point and each electrode pair using the following equation (Kajihara et al., 2015; Kawasaki et al., 2014; Kawasaki et al., 2010):

$$\text{PSI}_{jk(t,f)} = \sqrt{\left(\frac{\sum_{i=1}^N \cos(\Delta\varphi_{jk}(i,f))}{N} \right)^2 + \left(\frac{\sum_{i=1}^N \sin(\Delta\varphi_{jk}(i,f))}{N} \right)^2},$$

where $\Delta\varphi_{jk}(i,f)$ is the phase difference between electrodes j and k at time t and frequency f , and the number of time points N with an interval of 1.0 s is 1,200. We selected Fz as the electrode for the anterior hub, and Pz as the electrode for the posterior hub. Previous studies investigating the relationship between extraversion and DMN activity showed that the EEG component correlated with DMN activity exists in the frontal and parietal area (Knyazev et al., 2012; Knyazev, 2013; Wacker et al., 2010). Therefore, we calculated the PSI between Fz and Pz as the DMN response. We investigated PSI values while participants were in the resting state and PSI values while participants were showing reward-related BOA in the Task session. After calculating PSI values for each participant, we investigated Spearman's correlations between PSI values in the resting state and those in the task session.

3. Results

3.1. Reward-Related Beta Oscillatory Activity While Watching Kendama Playing

To identify BOA related to vicarious reward, we applied time-frequency analysis to the mid-frontal electrode (Fz) for the Task session. We found the largest power difference between success and failure trials in the 30 - 40 Hz frequency range at 1.1 - 1.2 s after the action onset of Kendama playing ($t[15] = 3.02$, $p < 0.01$, two-tailed paired t -test), which can be regarded as the reward-related BOA evoked by the vicarious reward (Figure 2).

3.2. Correlation between IRI Score and Reward-Related BOA

We then calculated Spearman's correlation between IRI score of each dimension and BOA at the task session. We found a significant negative correlation between personal distress (PD) scores and BOA in the success trial ($\rho = -0.700$, $p < 0.05$, Bonferroni-corrected; Table 1). No other significant correlations were found between IRI scores and BOA.

3.3. Correlation between Resting-State FC and Reward-Related BOA

We investigated Spearman's correlations between resting-state FC (calculated by lagged phase synchronization) and reward-related BOA in the task session. As we selected four ROIs for the anterior hub and four ROIs for the posterior hub, we examined 16 pairs of ROI pairs for FC analysis in each frequency band. We found a significant positive correlation between FC in the left BA24-left BA7 pair in the low-beta band in the RC session and BOA on failure trials ($\rho = 0.71$, $p < 0.05$, Bonferroni-corrected; Figure 3(A)). We also found a significant positive correlation between FC in the right BA32-right BA7 pair in the high-beta band

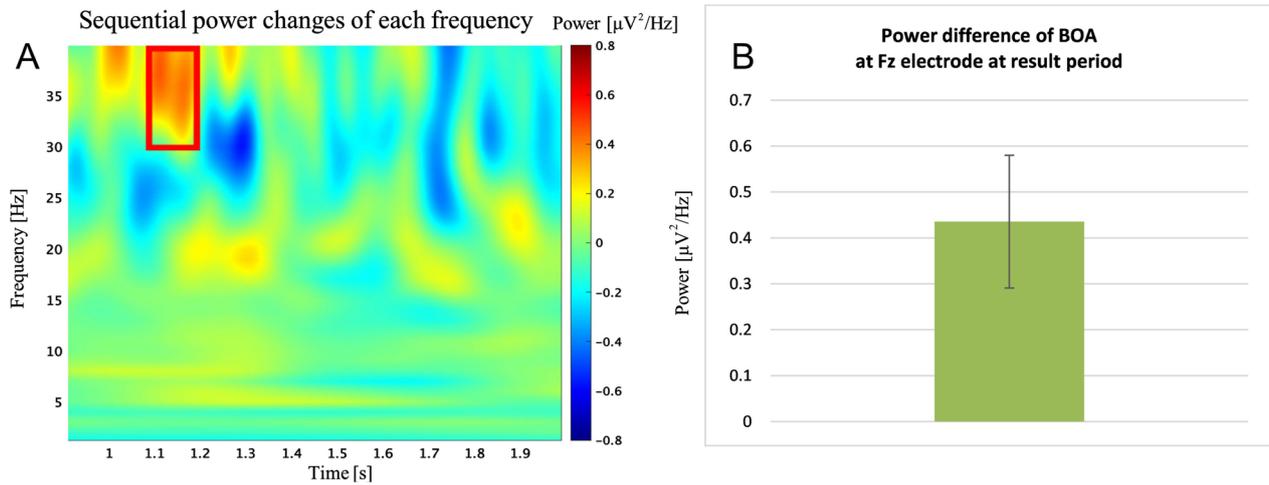


Figure 2. Averaged power difference between success and failure trials at Fz electrode. (A) Scalogram showing power difference between success and failure trials at Fz electrode. Significant power changes at 1.1 - 1.2 s after the onset of Kendama playing at 30 - 40 Hz was observed (red box). (B) A two-tailed paired t-test revealed a significant power difference between success and failure trials ($t_{[15]} = 3.02, p < 0.01$).

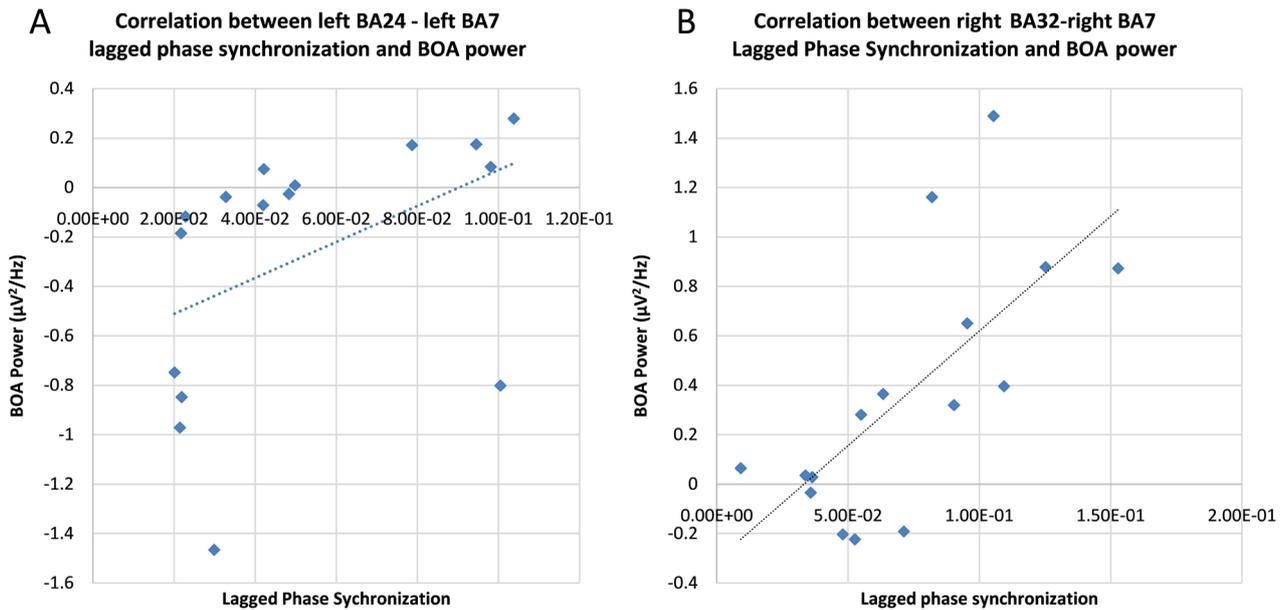


Figure 3. Spearman's correlations between FC in RC session and BOA in the Task session. (A) Correlation between FC of left BA24-left BA7 and BOA power in the failure trail. (B) Correlation between FC of right BA32-right BA7 and BOA power difference between success and failure trials.

Table 1. Spearman's correlation between IRI scores and BOA power in the task session.

Dimention	Success	Failure	Difference
	ρ	ρ	ρ
PD	-0.700	-0.231	-0.033
EC	0.046	0.327	0.037
PT	0.128	0.147	-0.140
FS	-0.232	-0.073	0.016
Total	-0.528	-0.016	-0.074

in the RC session and the BOA difference of the success and failure trials ($\rho = 0.73$, $p < 0.05$), Bonferroni-corrected; **Figure 3(B)**). No other significant correlations were found for the RC session. For the RO session, we found no significant correlations.

3.4. Channel-Base Phase Synchronization Analyses

Spearman's correlation between PSIs (Fz-Pz) of resting state and task session showed a significant correlation in the alpha and low-beta bands in the failure trials (alpha: $\rho = 0.597$, $p < 0.05$, low-beta: $\rho = 0.603$, $p < 0.05$, Bonferroni-corrected; **Table 2**).

4. Discussion

The current study revealed a BOA power difference between success and failure trials while watching Kendama, which was greatest at 0.1 - 0.2 s after the onset of the outcome of the Kendama game. The maximum difference of BOA was found in the high-beta band (30 - 40 Hz). Spearman's correlation analysis between IRI scores and BOA revealed a significant negative correlation between PD and BOA. Significant correlations of FC in the resting-state session and BOA were observed at two regions: 1) FC of left BA24-left BA7 in the RC session and BOA power at failure trial, and 2) FC of right BA32-right BA 7 in the RC session and a BOA power difference between success and failure trials. BA24 and BA32 are located at medial and dorsal portions of ACC and can thus be regarded as the anterior hub of DMN, while BA7 is located at pC and can therefore be regarded as the posterior hub. Channel-base phase synchronization analysis (Pz-Fz) also revealed a significant correlation between during the EC resting state phase synchronization and during failure trial phase synchronization in the alpha and

Table 2. Spearman's correlation of PSIs between resting state (A: RC, B: RO) and task session.

(A)		
Frequency	Success	Failure
	ρ	ρ
30 - 40 Hz	0.518	0.485
15 - 30 Hz	0.565	0.603
8 - 14 Hz	0.546	0.597
(B)		
Frequency	Success	Failure
	ρ	ρ
30 - 40 Hz	0.392	0.391
15 - 30 Hz	0.347	0.208
8 - 14 Hz	0.293	-0.009

low-beta bands. These results suggest that FC in DMN in the resting-state is related to vicarious reward processing.

Previous studies have reported that mid-frontal BOA is exhibited when an individual directly receives a reward (Marco-Pallarés et al., 2008; Marco-Pallarés et al., 2015; Mas-Herrero et al., 2015). Mas-Herrero et al. (2015) conducted a gambling task while recording brain activity using EEG and fMRI. The results revealed that the difference in BOA between gain and loss trials was maximized at 27 - 33 Hz (Mas-Herrero et al., 2015). According to their joint independent component analysis, which combined fMRI data and EEG data, this oscillatory activity was coupled with ventral striatum and hippocampus activity. These regions are components of the reward system (Schultz, 2015). The results of the current study, indicating higher beta band BOA during the delivery of vicarious reward, are consistent with these previous findings.

Subsequent investigation revealed that PD showed a significant negative correlation with BOA power in success trials. As PD measures self-oriented anxiety and interpersonal discomfort in social situations, a negative correlation with sensitivity to vicarious reward may be expected. However, it should be noted that, in some situations, PD also has a negative correlation with prosocial behavior. For example, people with high PD scores tend to exhibit excessive arousal of empathy, which can lead them to feel as if they are facing a situation eliciting anxiety or discomfort, potentially resulting in a failure to help others who are actually in the situation, if the observer seeks to avoid the situation (Decety & Ickes, 2009). Considering these previous findings, we speculate that a person who can control their level of empathy-related arousal may be able to maximize their prosocial behavior, leading to an enhanced ability to receive vicarious reward.

In the current study, FC within the DMN also exhibited a significant correlation with BOA. The ROI pair of right BA32-right BA7 exhibited a positive correlation with BOA differences between success and failure trials. Stronger FC within this region was related to larger BOA differences. This finding indicates that individual differences in the level of BOA power exhibited when participants received vicarious reward was correlated with FC within the DMN in the resting state. This result is partially in accord with previous reports of the involvement of the DMN in empathy (Bilevicius et al., 2018). Bilevicius et al. (2018) reported that four resting state networks are involved in empathy: the DMN, the salience network (SN), and the left and right central executive networks (CENs). In a study by Seeley et al. (2007), emotional empathy scores, which were measured using the International Personality Item Pool (IPIP), were positively correlated with FC between DMN components and the premotor cortex, portions of the precentral (motor) and postcentral (somatosensory) cortices. Another study suggested that differences in the strength of DMN FC were related to personality traits regarding the capacity of an individual to feel empathy for others (Kim et al., 2017). Kim et al. (2017) also reported a relationship between DMN FC and empathy in an fMRI study, revealing a significant correla-

tion between FC within the DMN and IRI scores. The results revealed that FC strength of the mPFC/ACC was positively correlated with IRI scores (except PT). The researchers concluded that because the DMN anterior hub is thought to be involved in self-referential mental simulation, low-empathy individuals may have impaired or decreased self-referential mental simulation during the resting state, whereas connectivity was better sustained in medium-empathy individuals. These studies suggest that the trait empathy can be affected by activity and/or FC within the DMN.

A similar feature that suggests personality trait is affected by DMN was reported in a study of extraversion, which is a central dimension of human personality theories (Knyazev, 2013). Knyazev (2013) conducted EEG experiments while participants were in the resting state and investigated the relationship between EEG responses and the spontaneous thoughts questionnaire (STQ). The results revealed that high self-referential positive expectations (SRPE) scores (extraverts) were associated with increased alpha power in the posterior DMN hub, whereas, in introverts, high SRPE scores were associated with an increase in alpha power in the anterior DMN hub. The results of these studies suggest that differences in personality are reflected in activity in DMN regions, and/or the strength of FC within DMN regions.

Relationships between the DMN and the reward system have also been reported. Koch et al. (2018) conducted a monetary reward task with OCD patients using fMRI and investigated regional brain activation and FC when patients received a monetary reward. The results revealed decreased activation of PCC (BA31) and stronger connectivity between the PCC and vmPFC (BA10). OCD is characterized by anxiety-provoking, involuntary, obsessive thoughts, which patients react to with repetitive, compulsive behavior patterns to counteract anxiety. Previous studies reported that altered reward processing in the reward system is involved in these behaviors (Figeo et al., 2011; Jung et al., 2011; Kaufmann et al., 2013). These studies reported that patients exhibit decreased activation of PCC and increased FC between PCC and vmPFC, indicating the involvement of the DMN in reward processing.

These findings suggest that the resting state DMN FC relates to personal trait differences like reward sensitivity, empathy sensitivity and extraversion, although causality between DMN FC and personality trait difference should be investigated more intensively in the future study.

In the current study, we found significant correlations only when participants observed failure trials. Lagged phase synchronization between left BA24 and left BA7 exhibited a positive correlation with BOA in failure trials. The results also revealed that Pz-Fz channel-base phase synchronization was significantly correlated between the resting state and failure trials. BA24 is located in the ACC, which is involved in many aspects of social cognition, such as vicarious experiences. Previous studies of empathy revealed that the ACC is involved in both vicarious pain and vicarious reward (Lockwood, 2016; Singer et al., 2004; Apps et al., 2016). BA7 is located in the precuneus and is activated during various types of

social cognition, such as comparing oneself to another person (Farrow et al., 2001; Ruby & Decety, 2003). Some previous studies have postulated that activity in the DMN anterior and posterior hubs is observed at Fz and Pz (Knyazev et al., 2012; Knyazev, 2013; Wacker et al., 2010). In the current study, the findings of channel-base phase synchronization and lagged phase synchronization analyses appear to be consistent with these previous studies. The correlated FC between these regions when observing failure trials may reflect the different functional processes of vicarious negative experience. This notion is consistent with previous studies of learning by De Pascalis et al. (2012) using EEG during a monetary task with a go/no-go paradigm, reporting significant phase synchrony in the theta, alpha, beta and gamma bands between frontal and parietal sites in loss trials (De Pascalis et al., 2012). These findings also suggest the possibility that DMN FC can predict personal trait difference, especially in negative experience.

The frequency bands in which FC exhibited significant correlations with BOA power in the current study should be noted. We observed that low beta band FC was correlated with BOA in failure trials and that high beta band FC was correlated with BOA differences between success and failure trials. Jann et al. (2010) reported that the blood oxygenation level dependent (BOLD) signal was correlated with electrophysiological activity in the alpha and beta frequency bands in the DMN. Mantini et al. (2007) reported a positive correlation between whole EEG channel activity in the alpha and beta frequency bands and BOLD signals in DMN regions. The results also revealed that BOLD signals in the anterior hub of the DMN were significantly correlated with activity in the gamma frequency band (30 - 50 Hz) of whole EEG channels, which is considered to reflect a self-referential mental state (Mantini et al., 2007). These findings suggest that negative feedback of vicarious experience may be more strongly correlated with a wide range of resting state DMN activity, whereas BOA differences between success and failure may be more strongly related to DMN anterior hub activity in the resting state.

Several limitations were involved in the current study. First, EEG source localization and ICA were performed with a 32-electrode array. Previous studies have reported that localization accuracy improves when the number of recording electrodes is increased (Laarne et al., 2000; Lantz et al., 2003). Although 32-electrode arrays are typically considered to be sufficient, measurement accuracy might have been improved by using more electrodes. Second, eLORETA software involves several restrictions, producing smooth solutions resulting in many correlated voxels that are then submitted to spatial ICA. Thus, correlated voxels are combined into one extended component with low spatial resolution. This could be a serious limitation if we were investigating the interactions between close ROIs. However, we mainly targeted the anterior and posterior DMN hubs, which were sufficiently far away from each other. It should also be noted that, in the current study, we made a priori assumptions about ROIs and only investigated the interactions between the anterior and posterior DMN hubs. Previous studies investigated the relationships between empathy and the DMN

(Kim et al., 2017; Bilevicius et al., 2018), which suggests that there might be FC between other regions in DMN, which should be investigated in future studies.

Overall, our study revealed that sensitivity to receiving vicarious reward is correlated with FC between the anterior and posterior hubs of the DMN. The ACC, a component of the anterior hub, was activated when processing vicarious experiences, and the precuneus, a component of the posterior hub, was activated when processing social interactions. It is still not clear whether DMN FC affects personal trait difference related with vicarious reward processing, which should be further investigated in the future study.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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