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Neural oscillations dissociate between self-related attentional orientation versus evaluation

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A B S T R A C T

To investigate the theory that self-reflection on one's personality traits engages distinct neural mechanisms of self-related attentional orientation and self-related evaluation, we recorded electroencephalograms from adults while they made trait judgments about themselves and an age- and gender-matched friend, or judgments of word valence. Each trial consisted of a cue word that indicated a target person for trait judgments or instructed valence judgments, followed by a trait adjective to be evaluated. Using a wavelet analysis, we calculated time–frequency power over each electrode and phase synchrony between electrode pairs associated with self-, friend- or valence-cues and with trait adjectives during trait or valence judgments. Relative to friend- and valence-cues, self-cues elicited increased synchronous activity in delta (2–4 Hz), theta (5–7 Hz), alpha (8–13 Hz), beta (14–26 Hz), and gamma (28–40 Hz) bands, and increased large-scale phase synchrony in these frequency bands. Self-related evaluation compared to friend-related evaluation during trait judgments induced stronger desynchronization in alpha, beta and gamma band activities, and decreased phase synchrony in alpha and gamma band activities. Our findings suggest that self-related attentional orientation and self-related evaluation engage distinct neural mechanisms that are respectively characterized by synchrony and desynchrony of neural activity in local assemblies and between long-distance brain regions.

Introduction

Self-reflection is an important feature of human thought and plays a key role in human behavior. The neural substrates underlying self-reflection have been investigated extensively by combining functional magnetic resonance imaging (fMRI) (for review, see Han and Northoff, 2009; Heatherton, 2011; Northoff et al., 2006) with the self-referential task that requires judgments of one's own personality traits (Rogers et al., 1977). Increased blood-oxygen-level-dependent (BOLD) signals in the cortical midline structure, including the medial prefrontal cortex (MPFC) and posterior cingulate cortex (PCC), have been observed during trait judgments of the self compared to a celebrity (Fossati et al., 2003; Han et al., 2008; Heatherton et al., 2006; Kelley et al., 2002; Ma and Han, 2011; Ma et al., in press; Macrae et al., 2004; Moran et al., 2006; Zhu et al., 2007; Zysset et al., 2002), indicating that these brain regions are involved in self-reflection on personality traits. While the self-referential task requires both orienting attention to the self and evaluating one's own personality traits, the previous fMRI findings did not dissociate the neural substrates involved in self-related attentional orientation and self-related evaluation due to the low time resolution of the BOLD signal and the paradigms employed by fMRI studies.

Previous fMRI studies of self-referential processing have primarily employed two behavioral paradigms. The first paradigm used a block design in which participants performed a self-judgment task in one block of trials and a celebrity-judgment task in another (e.g., Han et al., 2008, 2010; Ma et al., in press; Wang et al., 2012; Zhu et al., 2007). This paradigm required an attentional shift toward the self or a celebrity between successive blocks of trials but not between successive trials, and thus cannot dissociate the neural activity related to self-related attentional orientation versus self-related evaluation. The second paradigm utilized an event-related design in which each trial consisted of a cue word that defines the judgment task and trait adjective for evaluation (e.g., Heatherton et al., 2006; Kelley et al., 2002; Moran et al., 2006). In this paradigm, the judgment task varied across trials such that participants had to shift their attention toward either the self or the other first and then to evaluate whether the trait adjective described the target person. However, as the cue word and trait adjective were presented simultaneously in this paradigm (e.g., Heatherton et al., 2006; Kelley et al., 2002), the previous fMRI research using this event-related design was unable to separate the neural substrates involved in self-related attentional orientation versus self-related evaluation either.

To disentangle the neural mechanisms involved in self-related attentional orientation and self-related evaluation, it is necessary to record the neural activity that is elicited by cue words and trait adjectives in the self-referential task, separately. This requires a technique to record neural activity with a high temporal resolution.

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Electroencephalogram (EEG) has a temporal resolution of a millisecond and has been used in recent studies of neural activity underlying self-referential processing (e.g., Fields and Kuperberg, 2012; Magno and Allan, 2007; Mu and Han, 2010; Shestyuk and Deldin, 2010; Watson and Dritschel, 2007). Using a block design, Mu and Han (2010) found that phase-locked event-related potentials (ERPs) showed an increased positivity at 200–400 ms after stimulus onset over the frontal area (P2) and an enlarged positivity at 400–1000 ms over the frontal/central areas (P3) during trait judgments on the self compared to a celebrity. Shestyuk and Deldin (2010) also used a block design to investigate ERPs sensitive to the valence of self-referential words and found that positive versus negative words evoked larger amplitudes of the P2 and a late positive component. Magno and Allan (2007) used an event-related design to examine the neural activity associated with autobiographical memory. On each trial, the cue "self" or "friend" was presented first, followed by a word that served as an autobiographical memory cue. The self or friend cue instructed participants to retrieve a specific personal episode that was related to the autobiographical memory cue. Similarly, Magno and Allan (2007) identified neural correlates of self-referential processing by contrasting ERPs evoked by autobiographical memory cues in the self versus friend conditions and found that retrieval of one's own specific personal episodes elicited an increased positive shift of the ERPs at 100–1700 ms. Fields and Kuperberg (2012) also reported increased positivity over the frontal/central region to neutral words imbedded in a sentence when referenced to the self compared to others.

Self-referential processing has also been associated with modulations of non-phase-locked neural oscillations. Using the wavelet analysis (Kronland-Martinet et al., 1987), Mu and Han (2010) analyzed non-phase-locked time–frequency (TF) power linked to trait adjectives referenced to the self or to a celebrity at the theta (5–7 Hz), alpha (8–13 Hz), beta (14–27 Hz), and gamma (28–40Hz) bands. The found that, relative to other-referential trait adjectives, self-referential trait adjectives induced event-related synchronization (ERS) of theta-band activity over the frontal area at 700–800 ms and of alpha-band activity over the central area at 400–600 ms. In contrast, event-related desynchronization (ERD) associated with self-referential trait adjectives was observed in beta band activity over the central/parietal area at 700–800 ms and in gamma-band activity over the frontal/central area at 500–600 ms. These findings suggested that both ERS and ERD of neural oscillations were engaged in the self-referential processing but did not distinguish neural activity elicited by cues that shifted attention to the self or to others from that elicited by trait adjectives during evaluation of self or others. Thus it remains unclear whether self-related attentional orientation and self-related evaluation are mediated by distinct neural mechanisms.

The current study used a modified event-related design to disentangle the neural activity underlying self-related attentional orientation versus evaluation during the self-referential task. In Experiment 1, trials consisted of an instruction cue followed by a trait adjective (Fig. 1). A cue word, which was either "self," a friend's name, or "valence," was presented first. Self-cue and friend-cue instructed participants to make judgments of whether the following trait adjective described the self or the friend, respectively. Valence-cue indicated judgments of valence (positive vs. negative) of the following trait adjective. We recorded EEG to both cue words and trait adjectives during trait and valence judgments. This allowed us to analyze whether the neural activity linked to the process of both self-related attentional orientation by comparing EEGs to self-cue and friend-cue and the neural activity associated with self-related evaluation by comparing EEGs to trait adjectives during self- or friend-judgments. Valence-cues and valence-judgment provided a baseline to control for semantic processing and motor responses. To assess the degree to which neural activity in response to the cues in Experiment 1 reflected semantic processing of the self-, friend-, and valence-cues, Experiment 2 presented participants with only the cue words and asked them to perform a semantic discrimination task on the cue words. The neural activity that was elicited by the cue words in Experiment 1, but not modulated by the same cue words in Experiment 2, was specifically associated with self-related attentional orientation.

Similar to our previous research (Mu and Han, 2010), the current study used the wavelet analysis to calculate non-phase-locked TF power with a high temporal resolution elicited by cue words and trait adjectives, separately. We compared the non-phase-locked neural activity to the cue words and trait adjectives referenced to the self versus a friend to dissociate neural oscillations involved in self-related attentional orientation and self-related evaluation of personality traits. It has long been known that ERD of non-phase-locked neural activity is associated with increased cellular excitability in thalamo-cortical systems (Steriade and Llinas, 1988) and is interpreted as an electrophysiological correlate of activated cortical areas involved in processing of sensory or cognitive information (Pfurtscheller, 1992). An increased ERD may reflect the involvement of a larger neural network or more cell assemblies in information processing. ERS reflects the synchronized activity of a large number of neurons (Pfurtscheller et al., 1996). ERS of low frequency band activity (e.g., alpha band) occurs during an idling brain state or during expectation of sensory stimuli whereas ERS of high frequency band activity (e.g., gamma band) is associated with a binding of sensory information or sensorimotor integration (see Pfurtscheller and Lopes da Silva, 1999 for review). Mu and Han's (2010) findings suggest that complicated neural processes are engaged in self-referential processing. However, the block design used in the study did not allow us to test whether the ERS and ERD activity was engaged in self-related attentional orientation or self-related evaluation, or both. If, for example, the alpha band ERS arose from an inner-directed attentional demand during the self-referential processing, whereas the alpha band ERD reflects enhanced task demand during evaluation of self-related trait adjectives (Mu and Han, 2010), the ERS and ERD activity may temporally dissociate

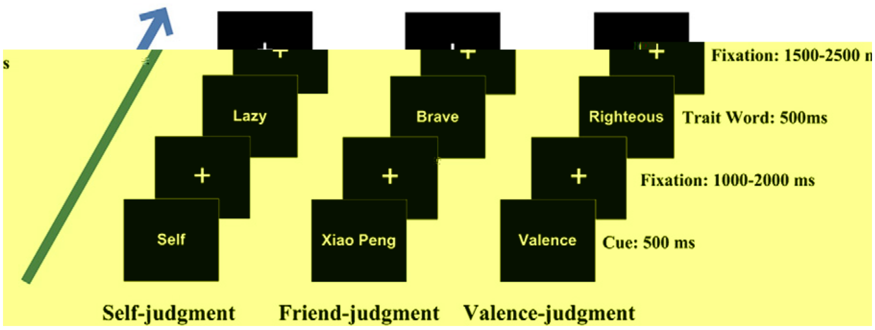

Fig. 1. Illustration of the event-related design in Experiment 1. Each trial consisted of a cue of upcoming task demand, followed by a trait adjective for trait judgments on oneself or a friend or for valence judgments. Both cue words and trait adjectives were in Chinese.

between cue words that induce self-related attentional orientation and trait adjectives that initiate self-related evaluative processing. Thus we tested whether ERS and ERD in multiple frequency bands are respectively induced by self-cue (relative to friend-cue) and self-judgments (relative to friend-judgments).

In addition, since fMRI studies have shown that self-referential processing activates multiple brain regions including the MPFC and PCC and leads to enhanced functional connectivity between the MPFC and the occipital cortex (e.g., Ma and Han, 2011), the current study also investigated whether self-related attentional orientation and self-related evaluation are characterized by distinct patterns of functional integration of large-scale neuronal assemblies during the self-referential task. This was assessed by calculating phase synchrony between electrode pairs using the phase-locking-value (PLV) method (Lachaux et al., 1999). In this method, synchronous neural activity is characterized by a constant phase lag between two electrodes throughout all trials. There has been evidence that phase synchrony in gamma band activity between different brain regions is involved in perception (Rodriguez et al., 1999), conscious recollection (Burgess and Ali, 2002), and emotional processing (Martini et al., 2012). Increased synchrony between prefrontal and posterior association areas in the theta band has also been observed during a working memory task (Sarnthein et al., 1998). We calculated phase synchrony between electrode pairs in different brain regions related to self-cue versus friend-cue and trait adjectives for self- versus friend-judgments to assess whether self-related attentional orientation and self-related evaluation are mediated by different patterns of large-scale integration of neural activity.

Materials and methods

Subjects

Twenty-six healthy adults (13 males, 13 females, aged between 19 and 27 years) participated in Experiment 1. Eighteen healthy adults (13 males, 5 females, aged between 18 and 24 years) participated in Experiment 2. All subjects were right-handed and had normal or corrected-to-normal vision. Informed consent was obtained from each subject before the study. This study was approved by a local ethics committee.

Stimuli and procedure

Both cue words and trait adjectives were presented in Chinese. Each of the trait adjectives consisted of two Chinese characters. Each Chinese character subtended 2.0°×2.0° of visual angle at a viewing distance of 80 cm. A total of 300 adjectives from an established personality trait adjective pool (Liu, 1990) were used in Experiment 1. The adjectives were classified into 10 lists of 30 words (half positive and half negative) that were pseudo-randomly selected for different judgment tasks for each participant. Word frequency was matched in each condition.

The name of an age- and gender-matched friend was given by each subject prior to the study. In Experiment 1, each trial started with a cue word of 'self', a friend's name in two Chinese characters, or 'valence' at the center of the screen for 500 ms, which was followed by a fixation cross that was presented randomly between 1000 and 2000 ms at the center of the screen. A trait adjective was then presented for 500 ms followed by a fixation cross with a duration that varied randomly between 1500 and 2500 ms at the center of the screen (Fig. 1). Self-cues and friend-cues instructed subjects to judge whether the following trait adjective was able to describe oneself or the friend. The valence-cue required subjects to judge the valence (positive vs. negative) of the following adjective. Subjects were asked to respond as accurately and quickly as possible by pressing one of two buttons with the left or right thumb. The assignment of 'yes/no' responses to the left or right buttons was counterbalanced across subjects. There were seven blocks of 30 trials, with 10 trials for self judgments, 10 trials for friend judgments, and 10 trials for valence judgments. The order of different judgment tasks was counterbalanced across blocks.

In Experiment 2, only cue words were presented and subjects performed a discrimination task on 'self', a friend's name in two Chinese characters, or 'valence', which were randomly presented in four blocks of 120 trials. Each block consisted of equal numbers of the three cue words. Each trial consisted of a cue word at the center of the screen for 500 ms, which was followed by a fixation cross with a duration that varied randomly between 500 and 800 ms. Subjects were asked to identify the words (self, a friend' name or valence) by pressing one of the three keys on a keyboard. The assignment of the three words to corresponding fingers (index/middle/fourth fingers) and hands (left/right) for responses was counterbalanced across subjects. Instruction emphasized both response speed and accuracy.

EEG recording

EEG was continuously recorded from 62 Ag/AgCl scalp electrodes that were mounted on an elastic cap according to the extended 10–20 system. All channels were referenced to the right mastoid. The electrode impedance of each electrode was kept below 5 kΩ. To monitor eye movement, both horizontal and vertical electro-oculograms were also recorded from electrodes placed 1.5 cm lateral to the left and right external canthi and electrodes placed above and below the left eye. The EEG data were sampled at 250 Hz and filtered with a 0.01–100 Hz band-pass filter, then re-referenced to the algebraic average of the electrodes at the left and right mastoids for off-line analysis. Trials contaminated by eye blinks, eye movements, or muscle potentials exceeding ±60 μV at any electrode and trails containing behavioral errors were excluded from further analysis. There were 82% and 73% artifact-free trials with correct responses in Experiment 1 and Experiment 2, respectively.

TF power analysis

We first calculated ERPs to cue words and trait adjectives in each condition (self-, friend- and valence-judgments) with averaging epochs from 200 ms before to 1000 ms after stimulus onset. In order to obtain non-phase-locked neural activities, we subtracted the ERPs in each condition from the corresponding EEG epoch to remove the phase-locked EEG activity from the raw data. Neural oscillations including spectra power and phase synchrony were quantified based on wavelet decomposition of the signal between 2 and 80 Hz in 1 Hz steps. The signal was then convolved by the complex Morlet wavelet $w(t, f_0)$ (Kronland-Martinet et al., 1987) with a Gaussian shape in time (SD σ_t) and frequency (SD σ_f) domains around its central frequency f_0:

$$w(t, f_0) = Ae^{(-t^2/2\sigma_t^2)} \cdot e^{2i\pi f_0 t}$$

with $\sigma_f = 1/2\pi\sigma_t$. Wavelets were normalized so that their total energy was 1. The normalization factor A was equal to: $(\sigma_t\sqrt{\pi})^{-1/2}$. The time-varying energy $E(t, f_0)$ was defined as the square norm of the result of the convolution of a complex wavelet $w(t, f_0)$ with the signal $s(t)$: $E(t, f_0) = |w(t, f_0) \times s(t)|^2$. Convolution of the signal by a family of wavelets provided a TF representation of the signal. A wavelet family was characterized by the number of cycles of wavelets (NCW), a constant ratio (f_0/σ_f) which should be chosen in practice greater than 5 (Grossmann et al., 1989). To achieve better temporal and frequency resolution, we used a linearly increased NCW (at 2 Hz, the NCW was 3; at 40 Hz, the NCW was 10; at 80 Hz, the NCW was 20) in accordance with the previous studies (Delorme and Makeig, 2004; Wu et al., 2007). Relative to using a constant NCW, using the linearly increased NCWs provided better temporal resolution at low frequencies and better frequency resolution at high frequencies.

With the linearly increased NCW used in our study, the wavelet duration was 119.7 ms and the spectral band width was 1.3 Hz at 2 Hz. The wavelet duration was 19.9 ms and the spectral band width was 8.0 Hz at 80 Hz.

The TF representation of each condition was first calculated by averaging the non-phase-locked neural oscillations over the trials in each condition for each subject. The TF values used for further statistical analyses was the percentage increase or decrease of spectral power in specific time windows relative to the baseline over −200 to 0 ms before the stimulus onset (Pfurtscheller and Aranibar, 1979). Considering temporal resolutions of both low and high frequency bands, we chose 50 ms as a time unit and this resulted in 20 time intervals from 0 to 1000 ms. The TF representations around 50 Hz was excluded from data analysis due to the 50 Hz electricity system in China. The remaining frequencies were divided into seven successive sub bands: delta (2–4 Hz), theta (5–7 Hz), alpha1 (8–10 Hz), alpha2 (11–13 Hz), beta (14–26 Hz), gamma1 (28–40 Hz), and gamma2 (60–80 Hz), similar to our previous study (Mu and Han, 2010). To investigate the modulations of TF power varying across different regions of the scalp, electrodes over the scalp were divided into four regions based on their anterior–posterior and middle–lateral locations: the midline region with three clusters (frontal: FZ, FCZ; central: CZ, CPZ; parietal: PZ, POZ), the anterior region with two clusters (left: F1, F3, F5, FC1, FC3, FC5; right: F2, F4, F6, FC2, FC4, FC6), the central region with two clusters (left: C1, C3, C5, CP1, CP3, CP5; right: C2, C4, C6, CP2, CP4, CP6), and the posterior region with two clusters (left: P1, P3, P5, PO3, PO5, O1; right: P2, P4, P6, PO4, PO6, O2).

To examine the differences in TF powers between self- and friend-cues, we conducted a repeated-measures analysis (ANOVA) with Cue (self-cue vs. friend-cue) and Region (frontal, central, parietal for electrodes along the midline) or Hemisphere (left and right for lateral electrodes) as within-subject variables. To investigate the difference between general person processing and semantic processing, we performed the ANOVAs with Cue (friend-cue vs. valence-cue) and Region/Hemisphere as within-subject variables. Similar ANOVAs with Judgment (self vs. friend or friend vs. valence) and Region/Hemisphere as within-subject variables were conducted to assess the differences in TF powers related to trait/valence judgments.

To confirm the distinct pattern of neural activities related to cue and trait adjectives during self-judgments, we conducted the ANOVAs of each frequency band activity with Stage (cue/trait word), Task (self/friend) and Region/Hemisphere as within-subject variables. To assess whether the differences in TF power observed in Experiment 1 can be explained simply by perceptual and semantic processing of cue words, we performed the ANOVAs of TF power to cue words in Experiment 2 with Cue (self-cue vs. friend-cue or friend-cue vs. valence-cue) and Region/Hemisphere as within-subject variables. All P-values of ANOVAs were adjusted using Greenhouse–Geisser correction for nonsphericity.

Phase synchrony analysis

Similar to the previous research (Doesburg et al., 2008; Gross et al., 2004; Lachaux et al., 1999; Luo et al., 2004; Rodriguez et al., 1999), we used the same Morlet wavelet transform to estimate whether the phase synchrony across electrodes over different scalp sites in the time windows and frequency bands of interests (TFOI) that significantly differentiated between self- and friend-cues and between self- and friend-judgments also changed as a function of self-related attentional orientation and evaluation. We estimated the phase-locking-value (PLV) defined as the absolute value of the sum of the phase differences between two electrodes. The PLV of signals from electrodes j and k at time t and frequency f across N epochs was calculated as:

$$PLV_{j,k,t} = N^{-1}\left|\sum_{N} e^{i[\Phi_j(f,t)-\Phi_k(f,t)]}\right|$$

PLV is a value between 0 and 1. 0 represents randomly dispersed phases among all trials and 1 represents fully phase locked oscillations in all trials between electrodes j and k.

We chose 21 representative electrodes for phase synchrony analyses, which yielded 210 pairs (21×20/2) located in the frontal (F3, F4, FZ), fronto-central (FC3, FC4, FCZ), central region (C3, C4, CZ), centro-parietal (CP3, CP4, CPZ), parietal (P3, P4, PZ), parieto-occipital (PO3, PO4, POZ), and occipital (O1, O2, OZ) regions. The phase synchrony between each pair of electrodes was computed using paired t-tests. To control the type-I error during multiple comparisons, we used nonparametric permutation tests to correct P values (Kaiser et al., 2004; Maris and Oostenveld, 2007). The PLVs of two conditions for comparison were randomly shuffled 1000 times. The t-test for each random partition was calculated. This procedure repeated 1000 times for each time–frequency unit, leading to 1000 T values. After sorting the 1000 T values, we selected the 95 th percentile as our threshold for correction. The observed PLVs whose T values fell within 95 th percentile (P<.05) were considered significant.

Results

Behavioral performance

The ANOVA of reaction times (RTs) in Experiment 1 showed a significant main effect of Judgment ($F_{(2, 50)}$ = 3.54, P<.05). Post hoc analyses confirmed that RTs to self-judgments were slightly longer than those to valence judgments (909 vs. 892 ms, $t_{(25)}$ = 3.02, P<.01) whereas there was no significant difference in RTs between self and friend judgments (909 vs. 906 ms, $t_{(25)}$ = 0.34, P>.05) and between friend and valence judgments ($t_{(25)}$ = 1.82, P>.05). The RT results suggest that task difficulty was comparable between self- and friend-judgments and between friend- and valence-judgments.

The ANOVA of RTs in Experiment 2 showed a significant main effect of Cue (self/friend/valence, $F_{(2, 34)}$ = 16.54, P<.01). Post hoc analysis confirmed faster responses to self-cue compared to friend-cue (456 vs. 477 ms, $t_{(17)}$ = −2.85, P<.05) and valence-cue (456 vs. 496 ms, $t_{(17)}$ = −7.59, P<.0001). RTs were shorter to friend-cue than to valence-cue ($t_{(17)}$ = −2.40, P<.05). Accuracy was higher to self-cue (78%) and friend-cue (78%) relative to valence-cue (73%) ($t_{(17)}$ = 3.49 and 2.98, Ps<.01) but did not differ between self-cue and friend-cue ($t_{(17)}$ = −0.51, P>.05).

Non-phase-locked neural activity in Experiment 1

To assess the neural oscillatory activities involved in self-specific processing (self vs. friend) and general person processing (friend vs. valence), we conducted ANOVAs of TF power in each frequency band related to cue words and trait adjectives, respectively.

Synchronous activity related to self-cue

As shown in Fig. 2, relative to friend-cue, self-cues elicited increased ERS in multiple frequency bands. These included increased delta band activity at 600–800 ms over the posterior regions to self-cue compared to friend-cue ($F_{(1, 25)}$ = 4.41, P<.05, η^2 = .15). Similarly, self- vs. friend-cue induced increased theta band activity over the anterior regions at 200–300 ms ($F_{(1, 25)}$ = 4.81, P<.05, η^2 = .16) and at 600–700 ms ($F_{(1, 25)}$ = 6.66, P<.05, η^2 = .21) and over the central regions at 300–400 ms ($F_{(1, 25)}$ = 6.27, P<.05, η^2 = .20). Beta band activity increased significantly to self- vs. friend-cue over the anterior region at 50–100 ms ($F_{(1, 25)}$ = 6.90, P<.05, η^2 = .22). Gamma1 band activity also increased significantly to self- compared to friend-cue over the midline and central regions at 100–400 ms (central, $F_{(1, 25)}$ = 5.82, P<.05, η^2 = .19; midline, $F_{(1, 25)}$ = 7.04, P<.05, η^2 = .22) and over the posterior region at 300–500 ms ($F_{(1, 25)}$ = 9.08, P<.01, η^2 = .27).

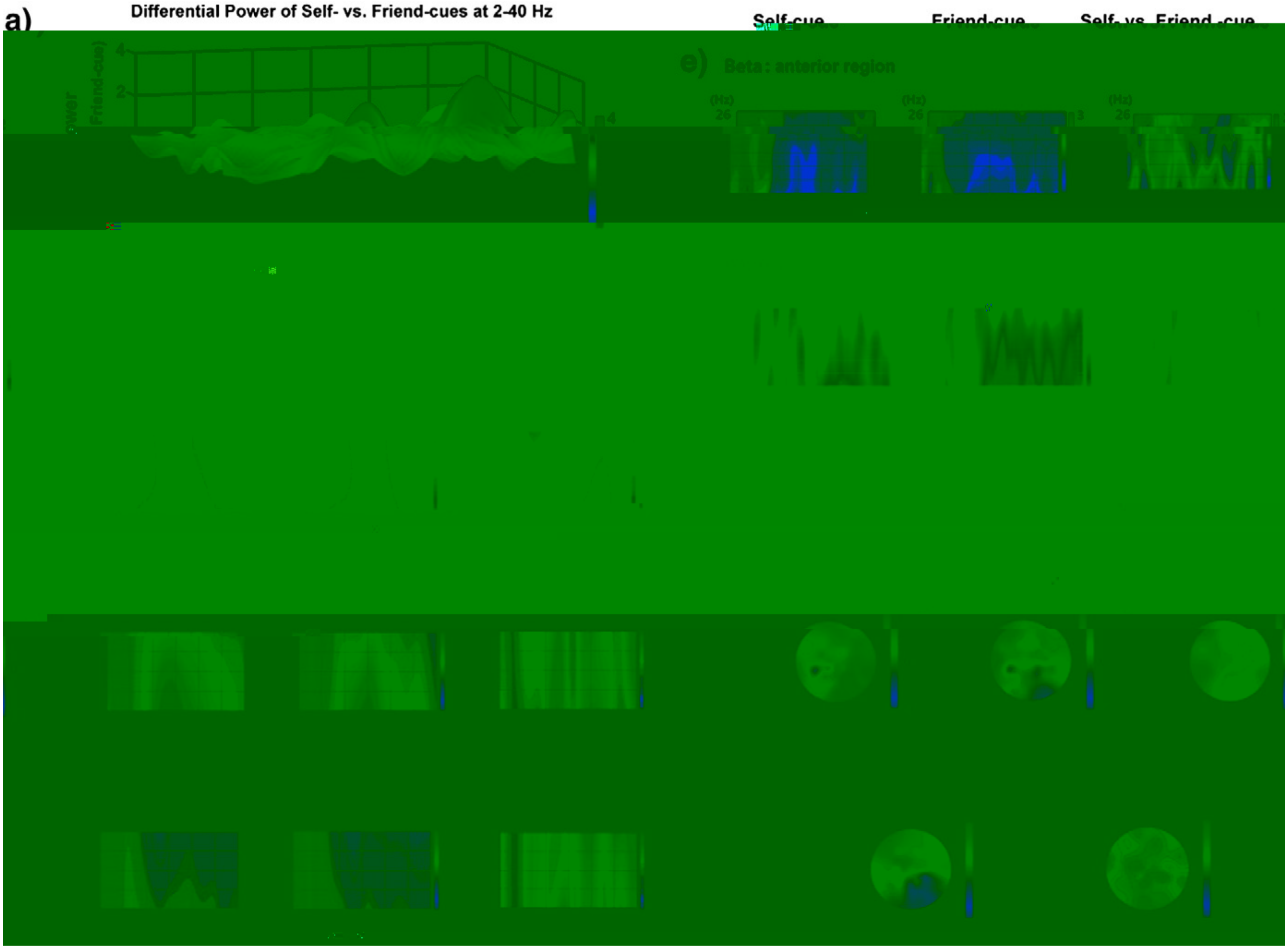

Fig. 2. The total synchronous TF power induced by self-cues compared to friend-cues. a) The differential TF power induced by self-cues vs. friend-cues at the left frontal electrode F5 showed increased spectral power at 2–40 Hz from 0 to 1000 ms after the onset of cue words. b) Delta band activity related to self-cue and friend-cue at the posterior electrode P1. c) Theta band activity related to self-cue and friend-cue at the left frontal electrode F5. d) Alpha1 band activity related to self-cue and friend-cue at the left central electrode CP3. e) Beta band activity related to self-cue and friend-cue at the left anterior electrode F5. f) Gamma1 band activity related to self-cue and friend-cue at the central electrode C1. g) The topographies illustrate the distribution of the differential power to self- vs. friend-cues in a 50 ms time window at the maximum difference in each band. The scale for TF power indicates normalized differential power. Red color represents event-related synchronization and blue color represents event-related desynchronization.

Significant interactions of Cue × Region were observed in alpha1 band activity at 300–400 ms over the central region ($F_{(2, 50)}=9.53$, $P<.01$, $\eta^2=.28$) and in beta band at 50–100 ms at the midline electrodes ($F_{(2, 50)}=5.783$, $P<.05$, $\eta^2=.19$). Post-hoc analyses showed that increased activity was observed with self-cues relative to friend-cues in the left central region in alpha1 band ($F_{(1, 25)}=5.32$, $P<.05$, $\eta^2=.18$) and in the frontal sites in beta band ($F_{(1, 25)}=5.55$, $P<.05$, $\eta^2=.18$). Self- vs. friend-cue failed to modulate neural oscillations in the alpha2 and gamma2 bands ($Ps>.05$).

ANOVAs of delta band activity to friend-cue and valence-cue showed a significant interaction of Cue × Hemisphere at 600–1000 ms in the posterior regions ($F_{(2, 50)}=8.61$, $P<.01$, $\eta^2=.24$). Post-hoc analyses showed that, relative to valence-cue, friend-cue induced decreased delta band activity in the right posterior regions at 600–700 ms ($F_{(1, 25)}=8.61$, $P<.01$, $\eta^2=.24$). There were also significant interactions of Cue × Hemisphere in alpha1 band over the anterior regions at 700–900 ms ($F_{(2, 50)}=4.86$, $P<.05$, $\eta^2=.15$) and in the alpha2 band over the anterior regions at 800–900 ms ($F_{(2, 50)}=7.15$, $P<.05$, $\eta^2=.20$). Post-hoc analyses revealed that friend- vs. valence-cue increased alpha band activity over the right anterior region (alpha1, $F_{(1, 25)}=6.85$, $P<.05$, $\eta^2=.22$; alpha2, $F_{(1, 25)}=8.89$, $P<.01$, $\eta^2=.26$). Neither the main effect of Cue nor Cue × Region interaction was significant in other band activities ($Ps>.05$).

Desynchronous activity related to evaluation of one's own personality traits

Neural oscillations associated with self-referential evaluation were identified by comparing the neural activity evoked by trait judgments on oneself vs. a friend. Relative to friend-judgments, self-judgments induced decreased activity in multiple band activities (alpha1: the central region, $F_{(1, 25)}=6.25$, $P<.05$, $\eta^2=.20$ at 300–400 ms; the midline scalp site, $F_{(1, 25)}=6.58$, $P<.05$, $\eta^2=.21$ at 300–400 ms; the posterior region, $F_{(1, 25)}=7.47$, $P<.05$, $\eta^2=.23$ at 300–500 ms; beta: the anterior region, $F_{(1, 25)}=7.79$, $P<.01$, $\eta^2=.24$ at 200–500 ms; the midline scalp site, $F_{(1, 25)}=6.81$, $P<.05$, $\eta^2=.21$ at 200–400 ms; the central region, $F_{(1, 25)}=6.32$, $P<.05$, $\eta^2=.20$ at 200–300 ms; gamma1: the anterior region, $F_{(1, 25)}=4.55$, $P<.05$, $\eta^2=.15$ at 300–400 ms, Fig. 3). Increased activity to self- vs. friend-judgments was observed only in the delta band activity at 100–300 ms over the posterior region ($F_{(1, 25)}=5.33$, $P<.05$, $\eta^2=.18$). ANOVAs of other frequency band activities failed to show significant effect of Judgment ($Ps>.05$).

Relative to valence-judgments, friend-judgments only showed increased gamma1 band activity in the anterior (300–400 ms, $F(1, 25) = 5.69$, $P < .05$, $\eta^2 = .19$; 700–800 ms, $F(1, 25) = 14.80$, $P < .01$, $\eta^2 = .37$) and the posterior regions (300–400 ms, $F(1, 25) = 6.64$, $P < .05$, $\eta^2 = .21$). Neither the main effect of Judgment nor its interaction with Hemisphere was significant ($Ps > .05$).

Distinct patterns of neural oscillations to self-cue and self-related trait adjectives

To further confirm the distinct pattern of neural oscillations related to cue and trait adjectives in the self and friend conditions, we conducted ANOVAs with Stage (cue vs. trait word), Task (self vs. friend), and Region/Hemisphere as within-subject variables. There was a significant main effect of Stage in multiple bands. Increased neural oscillations to Judgments vs. Cue stage were observed in delta band at 400–1000 ms (anterior, $F(1, 25) = 29.02$, $P < .001$, $\eta^2 = .54$; central, $F(1, 25) = 46.86$, $P < .001$, $\eta^2 = .65$; posterior, $F(1, 25) = 54.77$, $P < .001$, $\eta^2 = .69$; midline, $F(1, 25) = 69.56$, $P < .001$, $\eta^2 = .74$), beta band at 900–1000 ms (central, $F(1, 25) = 14.04$, $P < .001$, $\eta^2 = .36$; posterior, $F(1, 25) = 22.71$, $P < .001$, $\eta^2 = .48$), and gamma band at 800–900 ms (central, $F(1, 25) = 4.66$, $P < .05$, $\eta^2 = .16$). More importantly, we found significant Stage × Task in theta band activity at 300–400 ms over the central region ($F(1, 25) = 5.42$, $P < .05$, $\eta^2 = .18$, Fig. 4a), in the alpha1 band activity at 300–1000 ms over the central and posterior regions (central, $F(1, 25) = 8.94$, $P < .01$, $\eta^2 = .26$; posterior, $F(1, 25) = 5.42$, $P < .05$, $\eta^2 = .18$, Fig. 4b), in the beta band activity over the anterior region (50–100 ms, $F(1, 25) = 9.48$, $P < .01$, $\eta^2 = .28$; 200–400 ms, $F(1, 25) = 8.17$, $P < .01$, $\eta^2 = .25$, Fig. 4c) and the central region (200–400 ms, $F(1, 25) = 6.04$, $P < .05$, $\eta^2 = .20$), in the gamma1 band activity over the central regions (100–200 ms, $F(1, 25) = 4.09$, $P = .05$, $\eta^2 = .14$; 300–500 ms, $F(1, 25) = 9.27$, $P < .01$, $\eta^2 = .27$, Fig. 4d). These results confirmed the opposite effects of self-cue and self-judgment on the neural oscillations in multiple frequency band activities.

Post-hoc analyses were conducted to further confirm the differences in neural oscillations between self-cue and self-judgment and between friend-cue and friend-judgment. Relative to self-judgment, self-cue induced increased power in the theta band over the central area (300–400 ms, $F(1, 25) = 31.92$, $P < .0001$, $\eta^2 = .56$), in the alpha1 band activity over the central (300–1000 ms, $F(1, 25) = 14.84$, $P < .001$, $\eta^2 = .37$) and posterior regions (300–1000 ms, $F(1, 25) = 14.64$, $P < .001$, $\eta^2 = .37$), in the beta band over the anterior regions (0–100 ms, $F(1, 25) = 7.85$, $P < .01$, $\eta^2 = .24$; 200–300 ms, $F(1, 25) = 4.62$, $P < .05$, $\eta^2 = .16$), and in the gamma1 band over the central region (300–500 ms, $F(1, 25) = 6.60$, $P < .05$, $\eta^2 = .21$). In contrast, relative to friend-judgment, friend-cue led to decreased power in the beta band over the anterior (200–400 ms, $F(1, 25) = 9.84$, $P < .01$, $\eta^2 = .28$) and central regions (200–400 ms, $F(1, 25) = 5.23$, $P < .05$, $\eta^2 = .17$), and in the gamma1 band over the central region (100–200 ms, $F(1, 25) = 4.57$, $P < .05$, $\eta^2 = .16$). There was no significant difference in the lower band activity between friend-cue and friend-judgments ($P > .05$).

Phase synchrony of neural oscillations to self-cue

To investigate the functional integration of large-scale neuronal assemblies modulated by self-related attentional orientation, we analyzed phase synchronization in the TFOI that significantly differentiated between self-cue and friend-cue. The PLVs generated from electrode pairs in the TFOI associated with self- vs. friend-cues were compared using paired t-tests with nonparametric permutation tests corrections. Fig. 5a illustrates the significant differences in phase synchronization between self-cues and friend-cues. Relative to friend-cues, self-cues yielded increased phase synchronization in the theta band between the left central electrodes and the bilateral posterior electrodes and between the right central electrodes and the frontal electrodes at 300–400 ms (mean $t(25) = 3.08$, corrected $P < .05$) and in the alpha1 band between the right parietal region and the central regions at 300–400 ms ($t(25) = 2.92$, corrected $P < .05$). Self-cues also

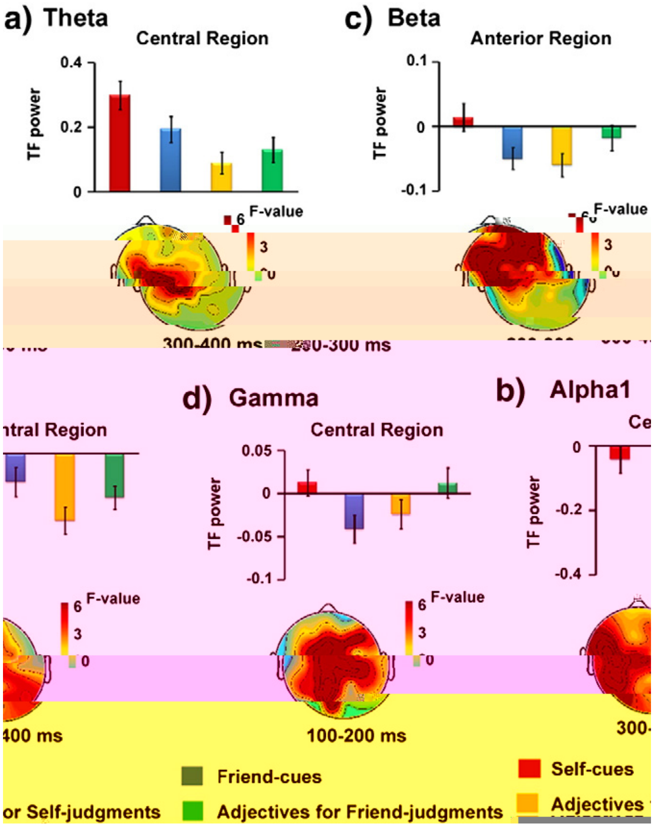

Fig. 4. Ill s a ion of dis inc a e s of ne al oscilla ions o self-c e and self- ela ed ai adjec i es. Each anel sho s a ba cha of s ec a o e o c e o ds and ai adjec i es d ing self- and f iend-j dgmen s. The o og a h sho s dis ib ion of F al es ha indica e a significan in e ac ion of S age Task in a) he a band ac i i a he cen al egion a 300–400 ms, b) al ha1 band ac i i a he cen al egion a 300–400 ms, c) be a band ac i i a he an e io egion a 200–300 ms, and d) gamma band ac i i a he cen al egion a 100–200 ms.

ind ced g ea e hase s nch oni a ion be een he midline and os e io egions a 400–500 ms in gamma1 band ac i i ((25) = 3.41, co ec ed P<.05). Ho e e he e as no significan diffe ence in hase s nch on in he TFOI ela ed o f iend-c e and alence-c e (Ps > .05).

Phase desynchrony of neural oscillations to evaluation of one's own personality traits

To assess he he f nc ional in eg a ion of la ge-scale ne onal assemblies as also in ol ed in self- ela ed e al a ion d ing ai j dgmen s, e cond c ed hase s nch oni a ion anal ses in he TFOI ha significan l diffe en ia ed be een self- and f iend-j dgmen s on e sonali ai s. Rela i e o f iend-j dgmen s, self-j dgmen s ind ced dec eased hase s nch on in al ha1 band be een he an e io and os e io elec odes o e he midline and lef hemis he e a 300–400 ms ((25) = −3.22, co ec ed P<.05) and in he gamma1 band be een he f on al and cen o a ie al elec odes a 300–400 ms ((25) = −3.18, co ec ed P<.05, Fig. 5b). TFOI anal ses of hase des nch on in o he f e enc bands did no sho an significan diffe ence be een self- and f iend-j dgmen s (Ps > .05). We also com a ed hase s nch on of ne al oscilla ions ela ed o f iend- s. alence-j dgmen s. This onl sho ed inc eased hase s nch oni a ion in gamma1 band be een an e io and os e io elec odes a 300–400 ms ((25) = 2.88, co ec ed P<.05).

Non-phase-locked neural activity in Experiment 2

To assess he he he ne al oscilla o ac i i o self-c e obse ed in E e imen 1 migh a ise f om sim le c e-ind ced e ce al and seman ic ocessing, e com a ed TF o e ela ed o self-c e and f iend-c e in E e imen 2, hich e i ed simila e ce al and seman ic ocessing inde enden of self- ela ed a en ional o ien a ion. The anal ses did no sho significan diffe ences in an f e enc band ac i i be een self-c es and f iend-c es (Ps > .05). We onl fo nd ha , ela i e o alence-c e, self-c e ind ced dec eased he a band ac i i a 400–700 ms o e he an e io (F (1, 17) = 8.28, P = .01, η^2 = .33) and cen al (F (1, 17) = 8.53,

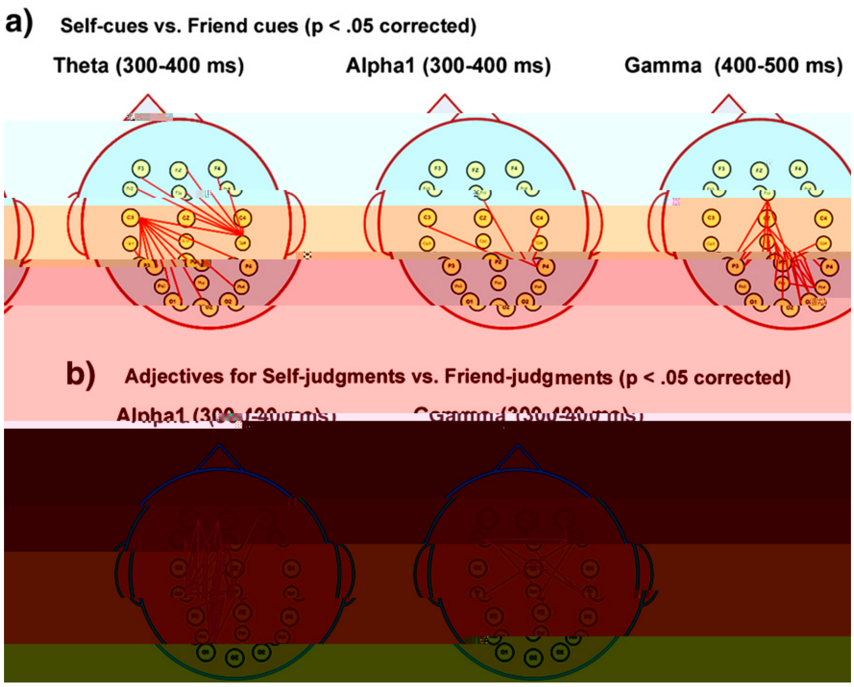

Fig. 5. a) Ill s a ion of inc eased hase s nch on ela ed o self-c es com a ed o f iend-c es in he he a (300–400 ms), al ha1 (300–400 ms), and gamma1 (400–500 ms) band ac i i . b) Ill s a ion of dec eased hase s nch on ind ced b self- s. f iend-j dgmen in he al ha1 (300–400 ms), and gamma1 (300–400 ms) bands.

$P<.01$, $\eta^2=.33$) regions, whereas friend-cue induced decreased theta activity at 400–600 ms over the anterior (F (1, 17) = 5.20, $P<.05$, $\eta^2=.23$) and central (F (1, 17) = 4.83, $P=.04$, $\eta^2=.22$) regions. TFOI analyses of phase synchrony failed to show any significant difference between self-cue and friend-cue and between friend-cue and silence-cue ($Ps>.05$).

Discussion

The current study examined whether self-related attentional orientation and self-related evaluation engage distinct neural oscillatory mechanisms during personality trait judgments. We modified a canonical self-reference task (Rogers et al., 1977) by inserting a time lag between the cues orienting one to a trait/silence judgment task and the trait adjectives that initiated evaluative processes. We found that neural oscillations linked to self-related attentional orientation was characterized mainly by enhanced synchronous activity and increased phase synchrony in multiple frequency bands. In contrast, self-related evaluation of trait adjectives mainly induced decreased neural oscillations and phase desynchrony in multiple frequency bands. Our findings provide evidence for distinct neural oscillatory mechanisms underlying self-related attentional orientation and self-related evaluation during self-reflection on personality traits.

Neural oscillations and self-related attentional orientation

It is not difficult for a healthy adult to decide whether a trait adjective describes himself or herself. What cognitive processes are engaged during self-reflection on one's own personality traits? According to Klein et al. (2002), an adult has a great deal of information about his or her own behavior, which helps to form summary representations of one's own important traits in order to retrieve them quickly when needed. To decide whether a trait is self-descriptive, one may also have to recall episodes that are inconsistent with the trait in question. In the paradigm used in our study, self-cue that indicated self-related trait judgments directed attention toward the database of trait summaries about oneself. Because of the unique position of the self among people and the significance of quick self-reflection for social interaction, the inward-directed attention, compared to attention to others, may engage increased neural activity in a specific brain region and enhanced coactivation of neural activity between multiple coordinated brain regions.

Indeed, we found that, relative to friend-cue that required judgments on a familiar other, self-cue elicited stronger neural oscillatory activity in multiple frequency bands. Increased delta band activity to self-cue was evident over multiple brain regions and increased beta and gamma band activities related to self-cue were found over the fronto-central areas. Increased alpha1 band activity to self-cue versus friend-cue was most salient over the left than right temporal regions. In contrast, friend-cue elicited decreased delta band activity over the right parietal and occipital regions relative to silence-cue. Although friend-cue also led to increased alpha band activity compared to silence-cue, this effect was evident only over the right fronto-central regions, which was different from the increased alpha1 band activity to self-cue over the left central region. The distinct patterns of neural oscillatory modulations to self-cue versus friend-cue cannot be attributed to the differences in perceptual and semantic processing because a simple semantic discrimination task performed on the same cue words in Experiment 2 did not elicit differential modulations of neural oscillatory activity to self-cue and friend-cue. Although the cue words in Experiment 2 did not instruct trait judgments on the self and a friend, the word 'self' may induce greater alertness relative to a friend's name and the word 'silence,' thus leading to faster behavioral responses to self-cue than friend-cue and silence-cue. However, such effects, if any, did not necessarily induce increased synchronous neural oscillations as shown in Experiment 2. The functional significance of self-cue for inward-directed attention during trait judgments seemed to be critical for the modulations of neural oscillatory activity.

Previous EEG studies have shown evidence for the association between internally directed attention and increased neural oscillations in both low and high frequency bands. Attention to internal processing during mental calculation tasks increased delta synchronization (Fernandez et al., 1995; Harmony et al., 1996) and mental simulation of jogging enhanced theta band activity (Li et al., 2007). Internally directed attention such as mental arithmetic and mental imagery also increased alpha band synchronization (Cooper et al., 2003; Otrekhova et al., 2001), possibly due to an active inhibition of other mental activity. Similarly, in our study, self-cue instructed participants to direct their attention to their own internal traits and to inhibit cognitive processes unrelated to the self in order to prepare for self-related evaluative processes. Our results thus suggest that inward-directed attention to one's own personality traits is also mediated by increased delta, theta and alpha synchronous activity following self-cues.

It has been hypothesized that high frequency band activity (e.g. gamma oscillations) plays an important role in filling up the gap between single neurons and neural assemblies (Basar et al., 2000). Such activity has been linked to multiple processes such as attention (Gruber et al., 1999; Herrmann and Knight, 2001; Muller et al., 2000), sensory memory (Haenschel et al., 2000), and recollection and the process of familiarity (Burgess and Ali, 2002; Tallon-Baudry, 2009). Beta and gamma oscillations are also associated with conscious perception. Tallon-Baudry et al. (1996, 1997) observed a large increase in gamma band activity when participants consciously perceived shapes or objects. Other researchers also reported that gamma-band

band activity are common for self-related evaluative processes that are engaged in both the self-referential task in the block design in our previous work (Mu and Han, 2010) and the event-related design in the current study.

Besides the functional role in conscious processing (Varela et al., 2001), high frequency band activity is also engaged in memory processes. For example, increased gamma band oscillations were observed with a larger stimuli that matched working memory contents (Debener et al., 2003). Stimuli with representations in long-term memory also induced greater gamma responses compared to stimuli that subjects had never seen before (Herrmann et al., 2004a, 2004b). Thus it has been suggested that gamma oscillations play a key role in the comparison of memory contents with stimulus-related information (Herrmann et al., 2004a, 2004b). We previously suggested that the decreased gamma band activity reflects less effort required for the comparison of memory contents with self-related stimuli compared to other-related stimuli (Mu and Han, 2010), possibly due to the existence of a self-related trait summary (Klein et al., 2002). In contrast, trait judgments of others may require searching for evidence from episodic memory and thus induce greater synchronization in localized neuronal pools. Thus, our current findings suggest that the decreased oscillatory activity in the gamma band is associated with self-related evaluation and possibly reflects a reduced effort for memory retrieval during reflection of one's own, compared to a friend's, personality traits.

Our phase synchronization analysis also revealed event-related changes in phase synchronization elicited by trait adjectives. The coherent neural oscillations between long-distance brain regions decreased during trait judgments of the self relative to a friend, and this effect was observed in multiple frequency bands and across a large scale of brain regions. Recent research suggests that phase synchronization of neural activity also has a role in both working memory and long-term memory (see Fell and Axmacher, 2011, for review). For example, phase synchronization in the theta band between frontal and temporal–parietal regions and in the alpha band between midline parietal and left temporal/parietal sites increased as a function of memory load (Payne and Kounios, 2009). Enhancement of gamma band phase synchronization was observed between occipital and frontal sites during recall of previously learned associations between different line drawings (Gruber et al., 2001). If the large-scale phase synchronization induced during trait judgments subserves memory processes, our results suggest that, relative to trait judgments on the self, trait judgments on a close other may require stronger long-range neural integration in order to retrieve information from memory. This is consistent with the proposal that less memory effort is required for trait judgments of the self compared to a friend because of the presence of a self-related trait summary (Klein et al., 2002).

Conclusion

The current study developed a paradigm to separate self-related attentional orientation from self-related evaluation during a self-referential task. Neural oscillations related to these two components of self-referential processing during trait judgments were identified by analyzing EEG activity to self-cue and trait adjectives for self-judgments that were separated by a time interval. We showed that self-cue elicited increased spectral power and phase synchronization in multiple frequency band activities compared to friend-cue, suggesting that enhanced synchronous neuronal activity was recruited when shifting attention toward the self. However, trait adjectives during self vs. friend judgments were associated with decreased alpha/beta/gamma band oscillations and weakened phase synchronization in multiple frequency band activity. Our findings suggest that distinct neural oscillatory mechanisms are engaged in self-related attentional orientation and self-related evaluation. Neural communication in local assemblies and between long-distance brain regions together contributes to self-related attentional orientation and evaluation during the self-referential task.

Although the current work suggests that multiple brain regions and their functional connections are involved in self-related attentional orientation and evaluation, our EEG results did not uncover the exact anatomical structures involved in self-related processing in different time windows due to the low spatial resolution of EEG signals. Future fMRI research should map self-related attentional orientation and evaluation onto specific brain regions and variations of functional connectivity between these brain regions. Finally, since there has been evidence that self-concept and the underlying neural mechanisms are sensitive to sociocultural experiences (Han and Northoff, 2009; Han et al., in press; Markus and Kitayama, 1991), it would be interesting to investigate whether and how the neural activity underlying self-related attentional orientation and evaluation is influenced by social desirability bias and sociocultural contexts.

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