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Differences in theta coherence between spatial and nonspatial attention using intracranial electroencephalographic signals in humans

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Abstract

A number of previous studies revealed the importance of the frontoparietal network for attention and preparatory top-down control. Here, we investigated the theta (7–9 Hz) coherence of the right frontoparietal networks to explore the differences in connectivity changes for the right frontoparietal regions during spatial attention (i.e., attention to a specific location rather than a specific feature) and nonspatial attention (i.e., attention to a specific feature rather than a specific location) tasks. The theta coherence in both tasks was primarily maintained at a preparatory state, decreases after stimulus onset, and recovers to the level of the preparatory state after the response time. However, the theta coherence of the frontoparietal network during spatial attention was immediately maintained after cue-onset, whereas for the case of nonspatial attention, it was immediately decreased after cue-onset. In addition, the connectivity of the right frontoparietal network, including the middle frontal gyrus and superior parietal lobe, were significantly higher for spatial attention rather than for nonspatial attention, suggesting that the dorsal parts of right frontoparietal network are more engaged in spatial-specific attention from the preparatory state. These findings also suggest that these two attention systems involve the use of different regional connectivity patterns, not only in the cognitive state, but in the preparatory state as well.

KEYWORDS

attention network, frontoparietal network, intracranial electroencephalography, nonspatial attention, spatial attention

1 | INTRODUCTION

Attention is a cognitive function that enhances goal-relevant sensory information and inhibits goal-irrelevant sensory information, thereby improving the ability to detect targets (Gunduz et al., 2011). A number of studies of attention networks revealed that the frontoparietal network is the main network for attention control (Petersen & Posner, 2012; Scolari, Seidl-Rathkopf, & Kastner, 2015). There are two well-known attention control networks: the dorsal attention network and ventral attention network (Corbetta & Shulman, 2002; Petersen & Posner, 2012). The dorsal attention network, which contains the intraparietal sulcus (IPS) and frontal eye fields (FEFs), is a goal-directed top-down control network that mediates the voluntary allocation of attention to spatial or nonspatial features derived from task demands (Buschman & Miller, 2007; Vossel, Geng, & Fink, 2014). Ventral attention networks, which contain the temporoparietal junction and ventral frontal cortex (VFC), is the stimulus-driven bottom-up attention network that engages in detecting unexpected stimuli and shifts in attention (Buschman & Miller, 2007; Vossel et al., 2014).

In the cognitive state (after cue-onset), the frontoparietal network is an important factor in controlling spatial feature-based attention (Giesbrecht, Woldorff, Song, & Mangun, 2003; Shulman et al., 2010; Szczepanski, Konen, & Kastner, 2010) as well as nonspatial, feature-based attention (Giesbrecht et al., 2003; Greenberg, Esterman,

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Wilson, Serences, & Yantis, 2010; Liu, Hospadaruk, Zhu, & Gardner, 2011; Liu, Slotnick, Serences, & Yantis, 2003). The posterior parietal cortex contains subpopulations of neurons that are involved in the control of spatial and nonspatial feature-specific (color-specific) attention (Greenberg et al., 2010). Within the frontoparietal networks, different and common parts of the parietal lobe contribute to spatial and nonspatial attention, respectively (Husain & Nachev, 2007; Nachev & Husain, 2006; Park et al., 2016; Schenkluhn, Ruff, Heinen, & Chambers, 2008). Some subregions of the frontoparietal network are known to be specifically involved in controlling spatial attention (Giesbrecht et al., 2003). The superior parietal lobe (SPL) may play a role in the allocation of spatial attention and visually guided movement to spatial locations (Culham & Valyear, 2006; Nachev & Husain, 2006). Different neuronal subpopulations in the IPS and FEF are used to attend different features (Liu et al., 2011). The inferior parietal lobule (IPL) plays a role in tasks that are nonspatial or that are not necessarily spatially lateralized (Husain & Rorden, 2003; Nachev & Husain, 2006). Our previous study revealed that, after cue-onset, spatial attention is more lateralized to the right (nondominant) hemisphere, with maximum activity in the right SPL. However, nonspatial attention involves wider brain networks, including the bilateral parietal, frontal, and temporal regions, with maximum activity occurring in the right parietal lobe. These findings suggest that the amount and pattern of networks that are involved in the right frontoparietal regions differ between spatial and nonspatial attention (Park et al., 2016). Regarding connectivity analysis, it has been reported that theta coherence in the frontoparietal network is engaged in attention control during the cognitive state (Brazdil et al., 2013; Clayton, Yeung, & Cohen Kadosh, 2015; Daitch et al., 2013; Dombrowe & Hilgetag, 2014).

An efficient preparatory state (before cue-onset) may be necessary for attention tasks. Successful top-down control during attention tasks may be achieved by encoding rules, prioritizing the features of the target stimuli and reducing the influence of irrelevant stimuli. Several studies have reported that specific frontoparietal networks are involved for each attention task in these preparatory top-down controls (Micheli, Kaping, Westendorff, Valiante, & Womelsdorf, 2015; Phillips, Vinck, Everling, & Womelsdorf, 2014). A recent study indicated that the theta (5–10 Hz) coherence between the frontal midline and parietal region would be strong if task-relevant stimuli were processed in a top-down controlled or automated manner in the preparatory state (Phillips et al., 2014). In addition, alpha (8–15 Hz) coherence between the frontal and occipitoparietal cortices is related to the top-down control of spatial attention (Bonnefond & Jensen, 2012). These findings suggest that low frequency coherence such as theta might have important roles in the performance of spatial and nonspatial attention tasks from the preparatory states in the right frontoparietal regions. However, to date, the differences in theta coherence between these two attention tasks in the right frontoparietal networks from the preparatory state to the cognitive state have not yet been elucidated.

Populations of cortical neurons produce meso- and macroscopic neural dynamics and influence each other by rhythmic activation and inhibition. These neuronal dynamics of rhythmical activities are reflected in oscillations (Buzsáki, 2006). Frequency coherence or phase synchronization between oscillations in two brain regions indicates that temporal relationships exist between activations in those regions (Buzsaki & Draguhn, 2004; Fell & Axmacher, 2011; Fries, 2005). Regarding connectivity analysis, phase synchronization is considered to be one of fundamental mechanisms for neural communication and is related to the performance of various cognitive functions in the brain (Cavanagh, Cohen, & Allen, 2009; Engel, Fries, & Singer, 2001; Fries, Reynolds, Rorie, & Desimone, 2001).

In summary, to achieve successful attention control, top-down attention controls in the right frontoparietal networks may be important during both the preparatory and cognitive states. In addition, previous studies have reported that theta coherence in frontoparietal networks is involved in attention control during both preparatory and cognitive states (Brazdil et al., 2013; Clayton et al., 2015; Daitch et al., 2013; Dombrowe & Hilgetag, 2014; Phillips et al., 2014). However, to date, analyses of differences in theta coherence in right frontoparietal networks with respect to attention tasks in both states from the preparatory state to the cognitive state have not been reported. In the present study, we hypothesized that the right frontoparietal areas may have different connectivity patterns, especially in theta coherence, between spatial (location-based) and nonspatial (feature-based) attention in both the cognitive and preparatory states. To further investigate this hypothesis, we examined intracranial electroencephalographic (iEEG) signals of epileptic patients who had intracranial electrodes implanted in their right frontal and parietal regions and when they performed spatial and nonspatial attention tasks composed of the same stimulus paradigm. We analyzed the theta phase coherence of the iEEG signals of the right frontoparietal region during the spatial and nonspatial attention tasks to investigate the difference in connectivity between the two tasks from the preparatory state (before cue-onset) to the cognitive state (after cue-onset).

2 | MATERIALS AND METHODS

2.1 | Subjects

Five epileptic patients (two males and three females, all of whom were right handed with language dominance in the left hemisphere, 31 ± 15.4 years) with an intracranial implantation on the right hemisphere were included in this study. Prior to this study, the patients had intracranial electrodes, such as subdural grid and strip electrodes implanted, in order to define the exact location of the epileptic foci. The implanted electrodes (Ad-Tech Medical Instrument Corp., Racine, WI) were 4 mm in diameter and 10 mm in interelectrode distance. The location of the grid and strip electrodes were decided based on the results of a noninvasive presurgical workup that included volumetric brain magnetic resonance imaging (MRI), fluorodeoxyglucose positron emission tomography (FDG-PET), and scalp electroencephalography (EEG) monitoring. After finishing a video-EEG monitoring study to localize the seizure foci with intracranial electrodes, seizures were controlled by anticonvulsant medications. The experimental paradigm for this study was conducted approximately 5–7 days after electrode implantation, by which time all of the patients had recovered sufficiently to allow them to perform these experiments (Park et al., 2016).

All procedures of the study were approved by the Asan Medical Center, Seoul, Korea.

2.2 | Confirmation of electrode locations

The locations of the electrodes were confirmed using preoperative T1 MRI data and postoperative computed tomography (CT) data. We performed image registration between the CT data and the MRI data using the FMRIB software library (http://www.frmib.ac.uk/fsl) and transformed the locations of the electrodes into the Talairach coordinate system using the Curry software package (Compumedics, Charlotte, NC). Finally, the Talairach coordinates of the electrodes were projected onto the MNI template (provided by the Montreal Neurological Institute) (Figure 1).

2.3 | Experimental paradigm

The spatial (location-based) and nonspatial (feature-based) attention task paradigms developed earlier (Malhotra, Coulthard, & Husain, 2009) were used in this study (for details see fig. 1 in Park et al. (2016)). Both task paradigms have the same stimuli protocol. During both tasks, a stimulus that had five different patterns was presented randomly on one of five locations on the vertical middle line of the screen. The interstimulus interval was 2 s and each stimulus lasted for 1 s. During the tasks, the participants were asked to focus their attention on the computer screen while keeping their eyes open. In the nonspatial task, participants were asked to press the space bar button as quickly as possible when one of the two target patterns appeared on any one of the five locations. However, in the spatial task, participants had to press the space bar button as quickly as possible when any stimulus pattern was presented on one of the two target locations. In each task, 500 stimuli were presented over a period of approximately 16 min. Each pattern and location was presented 100 times, and therefore each task had 200 target stimuli and 300 nontarget stimuli. Before the test sessions, the participants were given enough brief practice sessions to ensure that they understood the task paradigms and were familiar with the procedures. After practice sessions, the two tasks were performed in random order.

2.4 | Data recording

iEEG signals were recorded continuously throughout each task using a Stellate Harmonie System (Stellate, Montreal, Canada) and a Neurofax EEG-1200 System (NIHON KOHDEN, Tokyo, Japan). The sampling rate for the iEEG data was 1,000 samples per second and a surface electrode at Pz on the scalp was used as a reference electrode.

2.5 | Data processing

MATLAB (Version 2016b; MathWorks, Natick, MA) and EEGLAB toolbox (eeglab 13_5_4b; Swartz Center for Computational Neouroscience, La jolla, CA) were used to analyze the iEEG signals. A time-frequency decomposition was performed using a wavelet transform. Wavelet transform was applied to continuous iEEG signals at 2–40 Hz and the window length used for the wavelet transform was increased on a log scale from 3 cycles at the lowest frequency to 12 cycles at the highest. The time-frequency decomposition was computed on every 1 ms time bin and 1 Hz frequency bin and the transformed data were segmented into 2,000 ms epochs from 600 ms before the stimulus onset to 1,400 ms after the stimulus onset. Several studies reported that the effect of a scalp reference signal on a coherence analysis of the iEEG signals is negligible (Lipsman et al., 2014; Towle et al., 1998; Zaveri, Duckrow, & Spencer, 2000). Thus, we did not apply any re-reference methods before analyzing the phase coherence in this study.

2.6 | Analysis of phase coherence

To analyze the phase coherence between each electrode signal, we computed the squared weighted phase lag index (swPLI) using the imaginary parts of the cross-spectrum. The cross-spectrum between two signals is given by $x_i = z_{1,i} \cdot z_{2,i}^*$, where, $z_{1,i}$ and $z_{2,i}$ denote the Fourier coefficients for channels 1 and 2 in the i-th trial, and $*$ denotes a complex conjugate operator. The Fourier coefficients of each signal
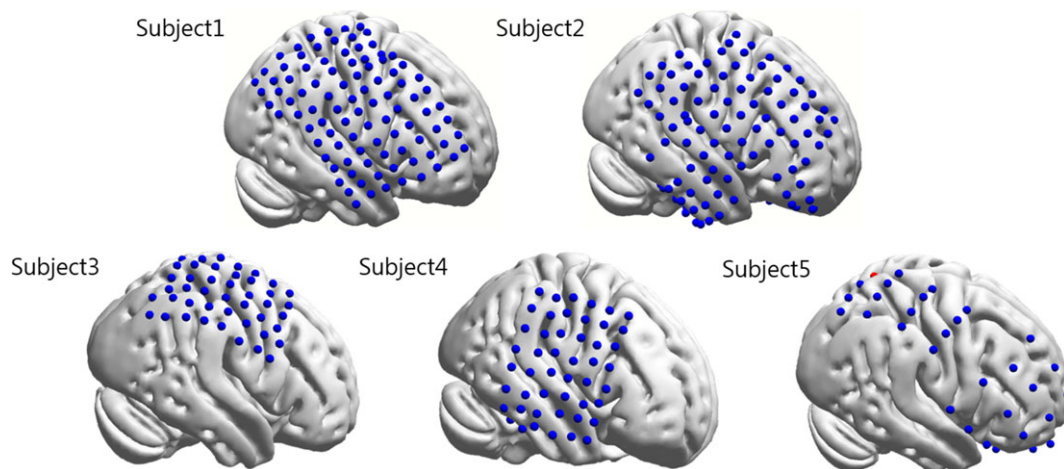

FIGURE 1 Locations of grid electrodes on the Montreal Neurological Institute standard model. For each patient, the locations of grid electrodes were extracted through the coregistration of preoperative T1 magnetic resonance imaging (MRI) and postoperative computed tomography (CT) images. The locations extracted for each patient were normalized and projected onto the Montreal Neurological Institute standard model [Color figure can be viewed at wileyonlinelibrary.com]

were obtained using a wavelet transform. The swPLI uses the product of the imaginary part of the cross-spectrum of two distinct trials. The swPLI is defined as:

$$swPLI = \frac{\sum_{i=1}^{N}\sum_{j \neq i}^{N} Im(X_i) \cdot Im(X_j)}{\sum_{i=1}^{N}\sum_{j \neq i}^{N} |Im(X_i) \cdot Im(X_j)|}$$

Where i and j indicate the number of trials, N is the total number of trials and the Im operator denotes the imaginary part of a complex number. The swPLI has a high robustness to false coherence caused by volume conduction or a common reference (Vinck, Oostenveld, van Wingerden, Battaglia, & Pennartz, 2011). In addition, the swPLI is the debiased wPLI estimator. If the sample size is more than 30 trials, sample size bias is negligible (Vinck et al., 2011). Only the correct trials were used to calculate the swPLI, which was computed on every 20 ms time bin and a 1 Hz frequency bin. To confirm that the swPLI of each time-frequency bin was significantly higher than zero, we computed p-values using the standard errors of jackknife estimates. A false discovery rate (FDR) correction algorithm was used to avoid multiple comparison problems. We set the alpha value to 0.05 and the false discovery portion to 0.2 to infer the statistical significance of each swPLI value (Phillips et al., 2014).

2.7 | Counting electrode pairs with significant cluster

2.7.1 | Defining dominant frequency range for the analysis of connectivity patterns

We clustered adjacent time-frequency bins that had significant swPLI values (FDR corrected p-value <0.05) at each 400 ms time period ranging 2–40 Hz with 200 ms interval to find the dominant frequency ranges which have maximum clusters at each windows across all frontoparietal electrode pairs. We found that 70.98% of maximum clusters were contained in low frequency range (2–9 Hz) and the number of maximum clusters was the peak at 8 Hz (Supporting Information Figure S1). Thus we used a frequency ranging from 7 to 9 Hz to investigate the differences between the two tasks and changes in the coherence and connectivity of the right frontoparietal network.

2.7.2 | Determining the significant cluster sizes by permutation test

To define significant cluster sizes exceeding a statistical threshold(Maris & Oostenveld, 2007; Micheli et al., 2015), we analyzed a time-frequency window of 400 ms time bins ranging 7–9 Hz frequency bins and clustered adjacent time-frequency bins that had significant swPLI values (FDR corrected p-value <0.05). We performed a permutation test to determine statistically significant cluster sizes ($p < 0.05$) using following steps: (a) Select a time-frequency window randomly (7–9 Hz and 400 ms duration) from the epoched Fourier coefficients of each electrodes. (b) Calculate p-values of the swPLI using the jackknife estimation method and generate statistical mask (uncorrected p-value <0.05) in the window. (c) Analyze the maximum cluster size in the window. (d) Repeat steps (a)–(c) for 5,000 iterations in each task. Within each subject, permutation test was performed 10,000 iterations across all frontoparietal electrode pairs. The probability that the maximum cluster size was more than six bins was less than 5% across all subjects (Supporting Information

Figure S2). Thus, we used six bins as a threshold cluster size to define a significant pair in a window.

2.7.3 | The ratio of significant pairs (Sig.P.Ratio)

The ratio of significant pairs (Sig.P.Ratio) between each brain region in a time-frequency window was calculated by dividing the total number of significant electrode pairs between the regions for all subjects by the total number of electrode pairs between the regions for all subjects. The Sig.P.Ratio was calculated at 200 ms intervals (overlap 50%) from −600 to 1,400 ms. We divided the time period of −600–1,400 ms into the preparatory period (−400–0 ms), the cue-onset period (−200–200 ms), the postcue period (0–400 ms) and the preresponse period (200–600 ms).

The binomial test was applied to confirm whether the Sig.P.Ratio in the window was significantly different from the chance level. The median Sig.P.Ratio of each region pair across all windows was used as the chance level for binomial testing using MATLAB and the Statistics Toolbox Release 2016b (MathWorks Inc., Natick, MA). A one-sided test was used in this study. In addition, we applied Pearson's Chi-square test and Fisher Exact test using IBM SPSS statistics 21 (IBM Corporation, New York, NY) to test whether the Sig.P.Ratio for a specific region pair was different between the two tasks for the same window. The complete analytical process is illustrated in Figure 2.

3 | RESULTS

3.1 | Behavior performance

The mean response time across all subjects was 0.78 ± 0.16 s for the nonspatial attention task and 0.71 ± 0.24 s for the spatial attention task. The ratio of correct trials was high in both tasks across all subjects (95.52 ± 5.57% for the nonspatial attention task and 96.4 ± 2.97% for the spatial attention task), and all subjects had a sufficient number of correct trials (more than 30), thus permitting the sample size bias of the swPLI to be neglected (Vinck et al., 2011). There were no statistical differences for the mean response time or for the ratio of correct trials between the nonspatial and spatial attention tasks ($p > 0.05$, Wilcoxon rank sum test).

3.2 | Mean swPLI

As shown in Figure 3a,b, the mean swPLI was calculated by averaging the swPLIs of all electrode pairs between the frontal and parietal regions. To investigate whether the theta (7–9 Hz) swPLI was different with respect to the attention task, the differences in theta swPLI between the two tasks were tested using the Mann–Whitney U test (Figure 3c). In both attention tasks, the mean swPLI in the theta band (7–9 Hz) was maintained until cue-onset (white dashed lines), decreased after cue-onset, and recovered after the response time (average response time: yellow dashed-dotted lines). The patterns of the theta band mean swPLI were similar for the two tasks; however, the mean swPLI value for the theta band before cue-onset was higher for the spatial attention task than for the nonspatial attention task. At some time bins, before and after cue-onset, a significant
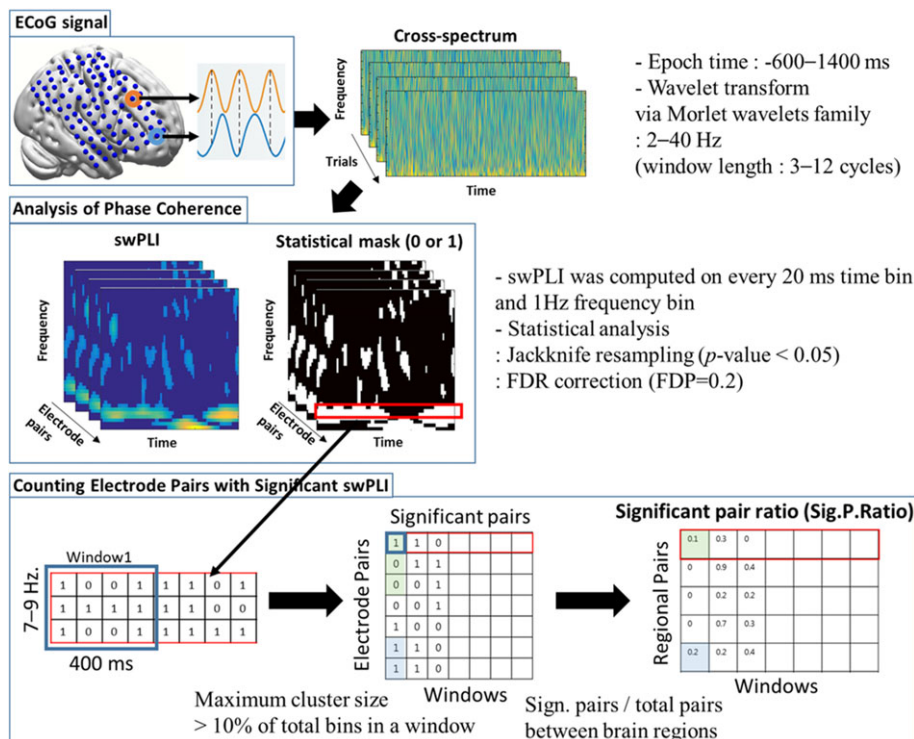
FIGURE 2 Schematic design of the analysis. The Fourier coefficients of each signal and cross-spectrum between each electrode pair were achieved by wavelet transform. To analyze phase coherence, the swPLI was computed for every 20 ms time bin and 1 Hz frequency bin, and the jackknife resampling method and FDR correction method were used to confirm the statistical significance of each swPLI value. If the maximum cluster size of an electrode pair within a time-frequency window containing 400 ms time bins and 7–9 Hz frequency bins exceeded 10% of the time-frequency window size, the electrode pair was defined as a significant pair for the time-frequency window. The ratio of significant pairs (Sig. P.Ratio) was defined as the ratio of significant electrode pairs among total number of electrode pairs between each region [Color figure can be viewed at wileyonlinelibrary.com]

difference was found in the theta swPLI of the frontoparietal networks between the two tasks (Mann–Whitney U test, $p < .05$) (Figure 3c). However, because nearly all of the electrode pairs had a low swPLI close to zero, the swPLI had a low mean and a high standard deviation in both tasks. Significant differences in the theta swPLI between two tasks were caused by only about 10% of the total electrode pairs that had a significantly high theta swPLI.

3.3 | Transient changes of connectivity

To confirm the existence of transient changes in connectivity for each brain region during both attention tasks, we analyzed the Sig.P.Ratios between the regions at each window and used binomial tests to investigate whether the Sig.P.Ratio at each window was significantly higher than the median Sig.P.Ratio across all windows in the region pair. Figure 4b,c show the Sig.P.Ratios for each task and Figure 4d,e
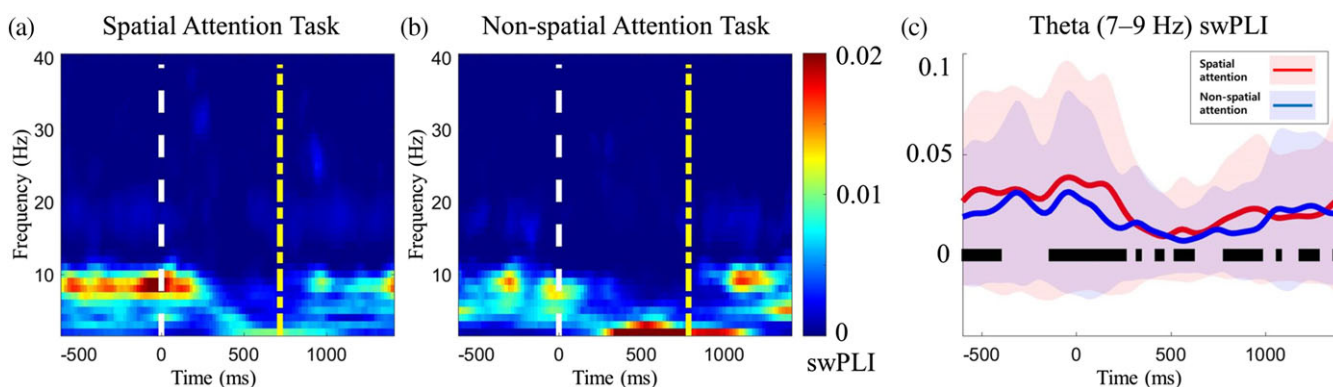

FIGURE 3 (a,b) mean swPLI. The swPLI of each electrode pair between the frontal and parietal lobes was calculated from 600 ms before cue-onset to 1,400 ms after cue-onset at each frequency and averaged for all pairs. White dashed lines represent the cue-onset time and yellow dashed-dotted lines represent the mean response time. (c) Mean and standard deviation of 7–9 Hz theta swPLI of frontoparietal electrode pairs. Solid line denotes the mean theta swPLI and the shaded area shows the standard deviation of each task. Black thick lines on the zero line represent time periods when the theta swPLI were significantly different between the two tasks (Mann–Whitney U test, $p < .05$) [Color figure can be viewed at wileyonlinelibrary.com]

represent the region pairs that had a significantly higher Sig.P.Ratio (binomial test, $p < 0.05$).

3.3.1 | Spatial attention task

During the preparatory period, the Sig.P.Ratios of region pairs between the right frontal (superior frontal gyrus [SFG], middle frontal gyrus [MFG], inferior frontal gyrus [IFG]) and the right parietal lobes (MFG–SPL, IFG–SPL, SFG–IPL, MFG–IPL, IFG–IPL) were significantly

higher than the median Sig.P.Ratio for each region pair (Figure 4d). The region pair between the right SPL and IPL also had a significantly higher Sig.P.Ratio than the median Sig.P.Ratio of the region pair. These significant changes in all of the region pairs between the right frontal and right parietal lobe were maintained up to the cue-onset period. It is particularly noteworthy that the Sig.P.Ratios between the right frontal and right parietal lobe (MFG–SPL, IFG–SPL, IFG–IPL) increased during the cue-onset period (Figure 4b,d). Although the Sig.
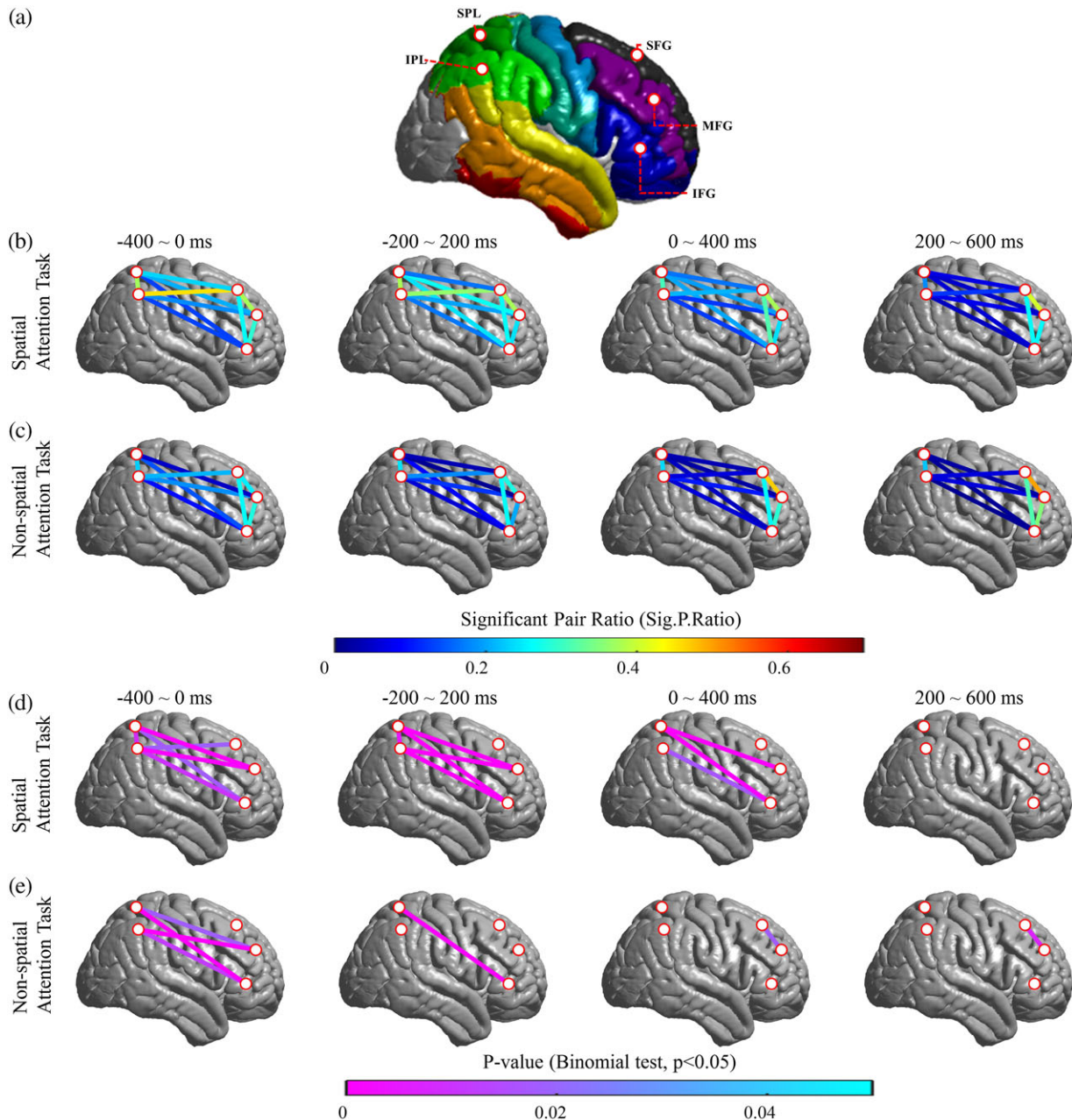

FIGURE 4 Sig.P.Ratio between each brain region in each time-frequency window (7–9 Hz, 400 ms). The Sig.P.Ratio represents the ratio of electrode pairs that have significant phase coherence in each time-frequency window. The Sig.P.Ratio was calculated for every 200 ms interval from −600 to 1,400 ms. (a) Brain regions used for Sig.P.Ratio analysis: superior frontal gyrus (SFG), middle frontal gyrus (MFG), inferior frontal gyrus (IFG), superior parietal lobe (SPL), inferior parietal lobe (IPL). (b,c) The Sig.P.Ratio between brain regions in four time-frequency windows for each task; the time duration for each window is −400–0 ms (preparatory period), −200–200 ms (cue-onset period), 0–400 ms (postcue period), 200–600 ms (preresponse period). The color of the lines denotes the Sig.P.Ratio between brain regions. (d,e) The region pairs that have significantly higher Sig.P.Ratio than the median Sig.P.Ratio across all windows (−600–1,400 ms) in the region pair (binomial test, $p < 0.05$) in the spatial and nonspatial attention tasks, respectively; the color of the lines denotes the p-value of the binomial test [Color figure can be viewed at wileyonlinelibrary.com]

P.Ratios between the right frontal and right parietal lobe during post-cue period and preresponse period were lower than those in the preparatory period and the cue-onset period, the Sig.P.Ratios between these region pairs (MFG–SPL, IFG–SPL, IFG–IPL) were maintained until the postcue period (Figure 4d).

3.3.2 | Nonspatial attention task

During the preparatory period, the Sig.P.Ratios of the region pairs between the right frontal (MFG and IFG) and right parietal (SPL and IPL) regions were significantly higher than the median Sig.P.Ratio of each region pair, although they were lower than the Sig.P.Ratios for the spatial attention task (Figure 4c,e). Unlike the spatial attention task, a clear decrease in the Sig.P.Ratios of the region pairs was observed immediately after the preparatory period when compared to the value for the Sig.P.Ratios during the preparatory period. However, Sig.P.Ratios within the right frontal regions between the SFG and the MFG increased during the postcue period and a high value was then maintained until the preresponse period (Figure 4c,e).

3.4 | Difference in Sig.P.Ratio between tasks

To identify statistical differences in the connectivity between two tasks from the preparatory period to the preresponse period, we applied the Pearson's Chi-square test for each brain region pair to determine if one task had a significantly higher Sig.P.Ratio than the other within the same window. Figure 5 shows the difference in the Sig.P.Ratio between the tasks.

3.4.1 | The preparatory period (−400–0 ms)

Region pairs between the SPL and frontal lobe (SFG, MFG), between the IPL and the SFG and between the SPL and IPL had significantly higher Sig.P.Ratios for the spatial attention task than for the nonspatial task.

3.4.2 | The cue-onset period (−200–200 ms)

Region pairs between the frontal and parietal lobe (MFG–SPL, IFG–SPL, SFG–IPL, MFG–IPL, and IFG–IPL) showed significantly higher Sig.P.Ratios for the spatial task than for the nonspatial attention task.

3.4.3 | The postcue period (0–400 ms)

Region pairs between the SPL and frontal lobe (MFG, IFG), and between the IPL and IFG remained significantly higher than the Sig.P.Ratios for the spatial attention task.

3.4.4 | The preresponse period (200–600 ms)

During the preresponse period, region pairs between the MFG and IFG showed higher Sig.P.Ratios for the nonspatial attention task than for the spatial attention task. The Sig.P.Ratio between the IPL and IFG of the spatial attention task was significantly higher than that of the nonspatial attention task.

4 | DISCUSSION

In this study, we investigated phase coherence for the right frontoparietal networks during spatial and nonspatial attention tasks in humans using iEEG. The important findings in the present study were that theta coherence of the right frontoparietal regions during the preparatory state (preparatory period) was highly maintained in both tasks, but was higher for the spatial task than for the nonspatial task. In addition, during the cognitive state (postcue period), theta coherence of the right frontoparietal network including MFG–SPL and IFG–SPL was also maintained in the spatial attention task, but not in the nonspatial attention task. These findings suggest that the two attention tasks involve the use of different right frontoparietal networks in both the preparatory state and the cognitive state and that the spatial
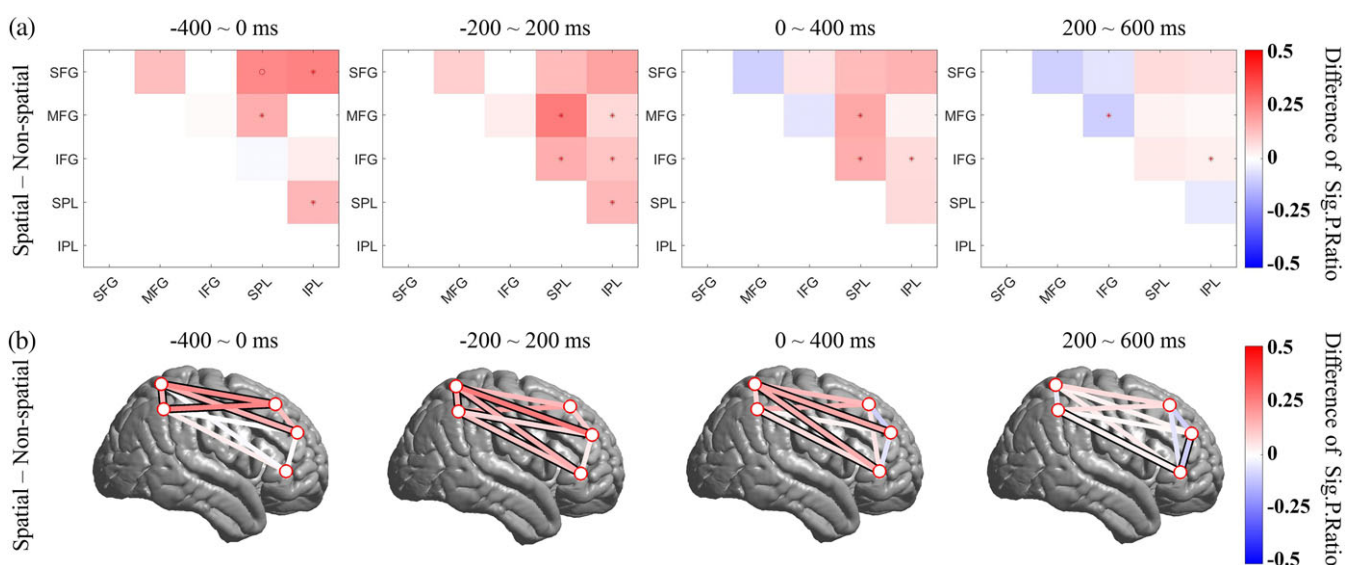

FIGURE 5 Difference in Sig.P.Ratio between spatial and nonspatial attention tasks. If the Sig.P.Ratio of the spatial attention task is higher than that of the nonspatial attention task, the region pair is represented in red and in the opposite case, in blue. (a) The red asterisks and circles indicate that the Sig.P.Ratio of the region pair is significantly different between the two tasks (red asterisk: Chi-square test $p < 0.05$; red circle: Fisher's exact test $p < 0.05$). (b) The lines with black outline indicate that the Sig.P.Ratio of the region pair is significantly different between the two tasks (red asterisk: Chi-square test $p < 0.05$; red circle: Fisher's exact test $p < 0.05$) [Color figure can be viewed at wileyonlinelibrary.com]

attention task utilizes the right frontoparietal network to a significant extent, especially for the right SPL, when compared to the nonspatial attention task.

Previous studies have revealed that, while performing the tasks after cue-onset, the right frontoparietal network is important for both tasks, and that spatial attention, when compared to nonspatial attention, is lateralized to a greater extent to the right hemisphere (Park et al., 2016). However, it is not entirely clear whether—and if so, to what extent—a difference in connectivity in the right frontoparietal network from the preparatory state to the cognitive state exists between the two tasks. To further investigate these issues, in the present study, we only included patients who were implanted with intracranial electrodes on the right frontal and parietal regions and investigated changes in theta coherence and connectivity between the two tasks. The findings indicate that the spatial attention task is more dependent on the right frontoparietal network, especially the fronto-SPL network, during the entire task process when compared to the nonspatial attention task. These results are consistent with findings reported in previous studies, which suggest that the SPL may play a role in spatial attention (Culham & Valyear, 2006; Nachev & Husain, 2006; Park et al., 2016).

It is interesting to note that the mean value of the swPLI for the theta band before cue-onset (preparatory state) was higher in the case of the spatial attention task than in the nonspatial attention task. We conclude that this may be because the spatial attention task, when compared to the nonspatial attention task, requires more engagement of the right frontoparietal network, even from the preparatory state, to efficiently perform a goal-directed top-down spatial attention task.

The right frontoparietal network was maintained after cue-onset during the spatial attention task, suggesting that, from the preparatory period to the postcue period, the spatial attention task is dependent on the right frontoparietal network. In contrast, a marked decrease of the swPLI and the Sig.P.Ratio after cue-onset during the nonspatial attention task suggests that the nonspatial attention task was less dependent on the right frontotoparietal network. This difference in the swPLI between two tasks cannot be attributed to the difference in difficulty between the tasks, because no significant difference was found in the mean response time and ratio of correct trials between the tasks.

It was curious to find that the swPLI and connectivity in both tasks was higher during the preparatory state than during the cognitive state. During the tasks from the preparatory state to the cognitive state, the participants were asked to keep their eyes open, thus the differences of swPLI and connectivity between the preparatory state and cognitive state cannot be attributed to the effect of eye opening and closure. Rather, it may be attributed to the partial contribution of the resting state networks during the preparatory state, which may be explained by the fact that the human brain, when at rest, exhibits frequency specific electrophysiology of stronger theta (4–8 Hz) and alpha (8–12 Hz) band-limited power in the dorsal attention network (Hacker, Snyder, Pahwa, Corbetta, & Leuthardt, 2017).

4.1 | Functional roles of theta coherence

The theta frequency range (6–10 Hz) showed prominent changes during the two attention tasks in the present study. These findings are compatible with the fact that lower frequencies in the alpha and beta range are known to mediate top-down effects (Bastos et al., 2012). Many previous studies reveled the important roles of the theta oscillation during the attention tasks (Brazdil et al., 2013; Clayton et al., 2015; Daitch et al., 2013; Dombrowe & Hilgetag, 2014; Phillips et al., 2014). Thus, we used a theta frequency of 7–9 Hz to investigate the difference and changes in the coherence and connectivity of the right frontoparietal network between the two tasks.

In both tasks, regional theta coherence was maintained during the preparatory period and recovered after the response time. During the preparatory period, the Sig.P.Ratios between the right frontal and parietal regions in both tasks were also significantly higher than the level of chance. These findings suggest that theta coherence between the right frontal and parietal regions during the preparatory state are engaged for task-relevant attention control. These results are consistent with previous studies, which suggest that theta (5–10 Hz) coherence appears to update task rules, prepare a task-relevant response (Phillips et al., 2014), engage in the retrieval of memories and task-relevant information, update information in the working memory and control task information (Liebe, Hoerzer, Logothetis, & Rainer, 2012; Polania, Nitsche, Korman, Batsikadze, & Paulus, 2012; Rutishauser, Ross, Mamelak, & Schuman, 2010; Sauseng, Klimesch, Schabus, & Doppelmayr, 2005; Womelsdorf, Johnston, Vinck, & Everling, 2010). Other studies have also revealed that theta coherence is observed on the frontoposterior network during an attention control task (Clayton et al., 2015) and the orientation of attention (Brazdil et al., 2013; Daitch et al., 2013; Dombrowe & Hilgetag, 2014).

4.2 | Similarities and differences in the theta coherence network between spatial and nonspatial attention tasks

In both tasks, some region pairs between the right frontal and parietal regions had significantly large Sig.P.Ratio values during the preparatory period. During this period, all of the participants were required to sustain their attention on detecting the cue-onset in both tasks. Therefore, common attention networks may be needed to engage in the preparatory period. It is assumed that frontoparietal networks observed in this study, such as the IPL and frontal region pairs (IPL–MFG, IPL–IFG), had significantly higher Sig.P.Ratios during the preparatory period in both tasks, but that there was no significant difference in Sig.P.Ratios between the two tasks, reflecting the common structures for attention networks in both tasks. These findings are consistent with previous studies involving healthy subjects and patients with hemineglect that the IPL and the VFC were revealed as major regions for sustaining attention (Adler et al., 2001; Foucher, Otzenberger, & Gounot, 2004; Hjaltason, Tegner, Tham, Levander, & Ericson, 1996; Singh-Curry & Husain, 2009; Vandenberghe, Gitelman, Parrish, & Mesulam, 2001). The right IPL has a particularly crucial role in maintaining attention (Malhotra, Parton, Greenwood, & Husain, 2006; Sturm, Thimm, Kust, Karbe, & Fink, 2006; Thimm, Fink, Kust, Karbe, & Sturm, 2006).

Conversely, the SPL and frontal region pairs (SPL–SFG, SPL–MFG) had significantly higher Sig.P.Ratios in the case of the spatial attention task than in the nonspatial task during the preparatory

period, suggesting that the SPL-frontal network specifically functions regarding spatial attention from the preparatory state. Networks between the SPL and frontal regions are also thought to be a part of the orienting networks (Petersen & Posner, 2012). Various studies have revealed that the dorsal attention network, which consists of the FEF and SPL/IPS, is involved in top-down visuospatial orienting attention (Corbetta & Shulman, 2002; Fan, McCandliss, Fossella, Flombaum, & Posner, 2005; Phillips et al., 2014). Additionally, some studies have reported the dorsal attention network has a spatial-specific orienting function (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Giesbrecht et al., 2003; Hopfinger, Buonocore, & Mangun, 2000; Kastner, De Weerd, Desimone, & Ungerleider, 1998; Scolari et al., 2015; Yantis et al., 2002) and our previous study (Park et al., 2016) support these findings.

Sig.P.Ratios for the frontoparietal networks during the preparatory period were maintained until the cue-onset period in the spatial attention task. In contrast, the Sig.P.Ratios for the frontal and parietal region pairs decreased immediately after the preparatory period in the case of the nonspatial attention task. It appears that for the spatial attention task, orienting networks involved in the preparatory state are also engaged in the detection of cue-onset at target locations to which participants attend. However, in the nonspatial attention task, participants must recall target patterns and compare them to stimulus patterns after cue-onset.

In the present study, Sig.P.Ratio after cue-onset in the nonspatial attention task was significantly higher within the frontal regions (MFG–IFG) than that of the spatial attention task. The higher Sig.P. Ratio within the frontal lobe in the nonspatial attention task is not due to the working memory load of the frontal lobe because the response time and ratio of correct trials were similar in both of the two tasks. Rather, it may be due to the wider contribution of brain regions not confined to the frontoparietal network in the nonspatial attention task.

One of the methodologic issues in phase analysis study is to decide an optimal referencing method for the connectivity analysis using iEEG data. In the present study, we used Pz electrode as a reference electrode. There may be some arguments about using surface reference electrode in iEEG analysis. Several re-reference methods (such as, common average reference[CAR], bi-polar derivation, and region average re-reference) can be used in studies for phase synchronization analysis with intracranial EEG (iEEG; Buschman & Miller, 2007; Foster, Kaveh, Dastjerdi, Miller, & Parvizi, 2013; Micheli et al., 2015; Phillips et al., 2014; Voytek et al., 2010). However, these studies have cautioned that if the re-reference signal not only contained common noise signals but also contained neuronal signals, re-referencing results in a cancelation of the neuronal signals and also produce erroneous connectivity estimations (Bastos & Schoffelen, 2016; Trongnetrpunya et al., 2016). In addition, in the present study, each participant had different numbers and locations of intracranial electrodes, which covered several different brain areas as well as the right frontoparietal area depending on clinical need to evaluate the epileptic foci. Thus, we considered that re-reference methods such as CAR or Laplacian reference may not be adequate because these re-references have the different effects across the subjects. Several coherence studies of iEEG revealed that the effect of scalp reference signals on coherence measurements is negligible because scalp EEG signals are considerably smaller than iEEG signals (Lipsman et al., 2014; Towle et al., 1998; Zaveri et al., 2000). Thus we concluded that the use of scalp reference electrode in the present study is a valid method to analyze the coherence measurement. Additionally, we had re-analyzed the mean swPLI between frontoparietal electrode pairs with two re-reference methods (CAR and Laplacian method) to compare the effect on phase coherence according the references (Supporting Information Figure S3). In spite of differences in the mean swPLI among re-reference methods, the patterns of the mean swPLI using re-reference methods were similar to the patterns of the mean swPLI using Pz reference. These results suggested that the patterns of the theta coherence in the present study were not caused by the scalp reference.

4.3 | Limitations

This study has several limitations. First, the number of patients was small and the brain regions that were covered by the electrodes were not the same for each patient. The participants were presurgical epilepsy patients, and the placement of the electrodes was determined by clinical need; subdural electrodes did not cover the entire brain area. Consequently, the results of this study do not fully take all attentional networks into consideration. However, the results of this study were obtained by comparing iEEG data for the right frontoparietal regions for nonspatial and spatial attention tasks performed by the same patients and not by comparing the difference in iEEG data among the patients. Therefore, we conclude that the number of patients in this study and the difference in the location of electrodes among patients would distort our results.

Second, electrodes showing infrequent or rare interictal epileptiform discharges were included in the study, and electrodes that showed a consistent noisy signal or frequent interictal epileptiform discharges were excluded. We do not think that the infrequent epileptiform discharges distorted our results because they appeared to occur infrequently across the two tasks. Finally, we do not consider the use of antiepileptic drugs to be a potential confounding factor in this study because we compared iEEG data between spatial and nonspatial attention tasks performed by the same participants.

5 | CONCLUSION

The findings in the present study suggest that right frontoparietal networks have different connectivity patterns for theta phase coherence for spatial and nonspatial attention in both the preparatory and cognitive state. In particular, the current study revealed that theta phase coherence in the right frontoparietal network, especially between the SPL and frontal lobe, are more engaged in spatial-specific attention from the preparatory state to the cognitive state.

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