Fourth International Workshop on Advanced Computational Intelligence
Wuhan, Hubei, China; October 19-21, 2011

Functional Network Analysis of Insight in Resting-state Brain Activity

Meng Hu, John Kounios, Mark Beeman and Hualou Liang, Senior Member, IEEE

***Abstract*—Insight occurs when problem solutions arise suddenly and is associated with an ‘‘Aha!’’ experience. While much research on insight has focused on event-related, goal-directed neural responses, there is growing interest in the spontaneous, resting-state brain activity. A recent study using high-density electroencephalograms (EEG) has demonstrated a dependence of task-related processing on the preceding resting state, but based on the power spectrum of individual electrodes in different frequency bands. In the current study, we sought to test the influence of resting-state functional networks on subsequent problem-solving strategy. We examined healthy subjects at rest who were subsequently directed to solve a series of anagrams to assess resting-state EEG network activity, as measured by coherence and Granger causality. Subjects were divided into two groups based on the proportion of anagram solutions derived with self-reported sudden insight versus analytic search. In this work, we mainly focused on gamma-band (30 – 40 Hz) activity, as it has been predominantly implicated in a wide variety of cognitive processes, and more importantly associated with insight solutions. Coherence analysis revealed that, within the gamma frequency band, there was a large-scale distributed resting-state network over the right hemisphere, with a network hub centering at the right anterior temporal lobe, for sudden insight relative to analytic search. Further analysis of the observed network with Granger causality indicated that there is a significant directional influence, originated from the network hub at the right anterior temporal lobe. These findings indicate that the spatial focus of the insight effect is at the right anterior temporal lobe, a result consistent with the hypothesis of right-lateralized hemispheric asymmetry.**

I. INTRODUCTION

People usually solve problems in two general cognitive strategies: analytic search and sudden insight. A search strategy involves systematic evaluation of possible problem states intervening between the current state and the goal state, and the use of available operators to transform one state into another. Insight refers to the sudden awareness of the solution to a problem (i.e., the ‘Aha!’ moment), with little or no conscious access to the processing leading up to that solution [1]. As insight involves conceptual reorganization, it is often thought of as a form of creativity and can result in important innovations [2]. Therefore, understanding the neural mechanisms of insight may lead to methods for facilitating innovation.

Electroencephalography (EEG) has been long used to study the brain activity due to its high time resolution, noninvasive monitoring and low cost [3]-[5]. Previous EEG studies on insight [6]-[7] have shown that EEG power exhibits significant insight-related changes at approximately the moment when the insight solution becomes available. This result, however, inspired the more profound question of whether there preexist the biases in fundamental neural processes that influence the likelihood of using one strategy rather than the other. A recent study [8] showed that resting-state EEG power indeed influences the adoption of cognitive strategies people use to solve problems. While resting EEG power reflects synchronous local activity measured at individual electrodes, little is known about how network connectivity during a resting state modulates subsequent problem-solving strategy. It has been extensively reported large-scale networks of brain areas connected by functional associations at particular frequency-bands may provide important information about various cognitive states [9]-[11]. Thus, in this study, we perform functional network analysis of resting-state EEG data to examine how resting-state brain networks influence problem-solving strategy.

Among brain rhythms, oscillatory activity in the gamma frequency range (30 – 40 Hz) is widely observed in the cortex in relation to a variety of cognitive processes such as memory [12], attention [13] and object recognition [14] etc. Research contrasting problem solving by insight and by analytic search strategies has identified insight solutions with a sudden burst of gamma-band oscillatory EEG activity. The location of this burst of EEG activity closely matches functional magnetic resonance imaging (fMRI) activation in the right anterior superior-temporal gyrus [6]. We therefore restrict the present resting-state network analysis to the gamma frequency range.

To assess brain network connectivity, power and coherence spectral analyses of the resting-state EEG activity were first used to identify gamma-band brain networks, and Granger causality spectral analysis to evaluate the patterning of directional influence in those networks. Granger [15] defined causal influence in terms of stochastic processes: one stochastic process is causal to a second if the autoregressive predictability of the second process at a given time point is improved by including measurements from the immediate past

M. Hu is with the School of Biomedical Engineering, Science & Health Systems, Drexel University, Philadelphia, PA 19104 USA.

J. Kounios is with the Department of Psychology, Drexel University, Philadelphia, PA 19104 USA.

M. Beeman is with the Department of Psychology, Northwestern University, Evanston, IL, USA.

H. Liang is with the School of Biomedical Engineering, Science & Health Systems, Drexel University, Philadelphia, PA 19104 USA (e-mail: hualou.liang@drexel.edu).

978-1-61284-375-9/11/$26.00 @2011 IEEE

of the first. Granger causality has been shown to be suitable for the study of directionality in neuronal interactions by assessment on neurophysiological data in both the time and frequency domains [16], [17], as well as on simulated simple systems where the direction and relative strength of Granger causal influence could be reliably established [15]. In this work, we made use of an open-source software package for analyzing brain circuits, namely Brain-System for Multivariate Auto-Regressive Time series analysis (BSMART) [18], to conduct power, coherence and Granger causality analysis.

The combined use of power and coherence spectral analysis in this study provides evidence that subjects with a tendency to solve problems with insight exhibited a significant large-scale resting-state network within the gamma frequency band over the right hemisphere compared to those who used an analytic search strategy. The further use of Granger causality analysis indicates that that there is a significant directional influence, emanating from a network hub in the right anterior temporal lobe.

II. MATERIALS AND METHODS

A. Resting-state EEG

After obtaining consent, but before giving task instructions, we measured 128-channel EEGs from subjects for about 3 min during rest state preceding work on a set of cognitive tasks. Subjects were told to close their eyes, relax, and not move their eyes.

The resting-state EEGs were sampled at 250 Hz and then band-pass filtered between 0.2 and 100 Hz. Artifacts were detected by visual inspection and excised. Channels with excessive artifact were replaced by linear interpolation using neighboring electrodes, and then downsampled to 19-channel (FP1, FP2, F7, F3, FZ, F4, F8, T3, C3, CZ, C4, T4, T5, P3, PZ, P4, T6, O1 and O2, according to International 10-20 System) for the present analysis.

B. Experiment

After the resting-state EEGs were acquired, subjects were given instructions concerning the anagram task [8]. On each trial, a .5 s fixation plus-sign warning signal was followed by an anagram displayed at the center of a video monitor (replacing the plus sign) until the subject either responded with a computer-mouse button-press or the trial timed out (16 s after the onset of the anagram). Subjects were instructed to press a button with their right index finger immediately upon deriving the solution (thereby terminating display of the anagram), and .5 s later they viewed a message which prompted them to verbalize the solution. After each solution (correct and incorrect), subjects were prompted to press a button to indicate whether the solution was (a) derived with insight, (b) derived without insight, or (c) not sure. Insight was explained to subjects as occurring when the solution pops into awareness suddenly (i.e., an “Aha! moment”), as opposed to resulting from deliberate, conscious, rearrangement of the letters of the anagram. All subjects indicated that they were intuitively familiar with this distinction. Subjects were also told to make both insight and noninsight responses (across trials). This was done in order to minimize ceiling or floor effects resulting from response bias or stereotyped responding. When a subject did not respond with a button-press by the 16 s deadline, the trial was terminated and the next trial initiated. Subjects were given a block of 14 practice trials before proceeding to the experimental trials.

Twenty-six right-handed, native English-speaking, subjects participated. Two subjects (one high insight and one low insight) were omitted due to the most EMG artifact. Subjects were divided into high-insight (twelve subjects) and low-insight (twelve subjects) groups by performing a median split on the ratio of insight to noninsight correct anagram solutions. All subjects signed an informed consent form. The study was approved by Drexel University’s Institutional Review Board.

C. Functional network analysis with coherence

1) Coherence: Coherence, the frequency domain equivalent of temporal cross-correlation, gauges the degree of interdependency between two sites as a function of frequency. We used the BSMART open-source Matlab toolbox (http://www.brain-smart.org/) to conduct the coherence analysis. The BSMART toolbox is intended for analysis of multichannel neural signals recorded in cognitive experiments. A unique feature of BSMART is that it carries out analyses based on a parametric method involving the Adaptive Multivariate AutoRegressive (AMAR) modeling technique [19], which simultaneously takes all channels into account, thus favoring the understanding of the interactions of different channels belonging to the same integrated system. Here we briefly describe the calculation of coherence in BSMART.

Let $X(t)=\left[X_1(t), X_2(t), \ldots, X_k(t)\right]^T$ be a k-dimensional random process, where k can be the number of channel in data set and T stands for matrix transposition. Assuming stationarity of the process $X(t)$, one can describe $X(t)$ by a pth-order autoregressive process: $E(t)=\sum_{m=0}^{p} A_m X(t-m)$, where A_m, m = 1, 2, … , p are $k \times k$ coefficient matrices and $E(t)$ is a k-dimensional, zero mean, uncorrelated noise vector. The Levinson, Wiggins, Robinson (LWR) algorithm [17] is then employed to estimate the A_m matrices and the covariance matrix of the noise vector (Σ) from the Yule-Walker equations of the model. The model order p can be determined by the Akaike information criterion (AIC) [17]. In this work, we set the model order as 3. Once the model coefficient matrices A_m and the covariance matrix of the noise Σ are estimated, the transfer function

$H(f) = \left(\sum_{m=0}^{p} A_m e^{-im2\pi f} \right)^{-1}$ can be obtained and the spectral matrix of the time series data can be calculated by $S(f) = X(f)X^*(f) = H(f)\Sigma H^*(f)$, where * denotes matrix transposition and complex conjugation. With the spectral matrix $S(f)$, coherence is defined as:

$$C_{i,j}(f) = \frac{S_{i,j}(f)}{\sqrt{S_{i,i}(f)S_{j,j}(f)}},$$

where $S_{i,j}(f)$ is the (i, j)th element of $S(f)$ can be used to measure the amount of interdependency between two channels *i* and *j*. The values of coherence range from zero to one, where zero indicates no interdependence between two channels, while one indicates maximum interdependence.

2) Testing for statistical significance of differences between coherence: The functional network connectivity in resting-state brain can be represented by the coherences between resting-state EEG signals from different electrodes. For each subject, resting-state EEG is fed into the AMAR model in BSMART to obtain coherences in frequency domain between all channel-pairs. The gamma-band coherence is then obtained by the simple average of the coherence within the gamma band. To identify the insight-related gamma-band functional network in resting-state brain, we used two-sample *t* – tests to detect the significant channel-pairs, in which two groups (high-insight vs. low-insight) show astatistically significant difference ($p < 0.05$). Fisher's z-transform was first applied to normalize the coherence values into an approximately Gaussian distribution before the statistical test, as coherence values are constrained between 0 and 1.

D. Granger causality analysis

1) Granger causality: Coherence analysis alone does not address the question of the predictability of activity at one channel from that at another. Therefore, Granger causality spectra [23] were computed to evaluate the relative strengths of influence, in the Granger sense of predictability, between two channels in both directions at the gamma frequency range. The basis for evaluating the direction of influences between regions is the concept of Granger causality [15]. Once the multivariate autoregressive time series representation is identified, these time series can be used to assess causality based on the definition of Granger causality. Essentially, for two simultaneously measured time series, one series is said to be causal to the second if the residual error for the second series at one moment in time is reduced if including past measurements from the first series.

In this work, we use the BSMART toolbox to conduct the Granger causality analysis. In fact, after the AMAR model is established, Granger causality from channel *j* to channel *i* can be readily derived in the frequency domain with the spectral matrix $S(f)$, the transfer function $H(f)$ and the noise covariance Σ. Specifically, Granger causality is defined as:

$$I_{j\to i}(f) = -\log\left(1 - \frac{\left(\Sigma_{j,j} - \frac{\Sigma_{i,j}^2}{\Sigma_{j,j}}\right)\left|H_{i,j}(f)\right|^2}{S_{i,i}(f)}\right)$$

The logarithm is taken to preserve certain favorable statistical properties. Similarly, the causality spectrum from *i* and *j* can be obtained by switching the indices *i* and *j* in the above equation.

2) Granger causality significance testing: Granger causality is computed in both directions for all channel pairs of the identified network of coherence. The gamma-band Granger causality is then obtained by computing the mean Granger causality between 30 and 40 Hz. By comparing the Granger causality values between two directions, we designate the direction with significantly higher Granger causality value ($p < 0.05$) than the opposite as the causal influence of the channel-pair.

III. RESULTS

In this section, twenty-four subjects' resting-state EEG are analyzed with coherence and Granger causality to investigate how the gamma-band resting-state brain network influences the problem-solving strategy. Coherence was first performed to identify the gamma-band functional network connectivity in resting-state brain. The results show that the high-insight group exhibited significantly stronger gamma-band functional network connectivity than the low-insight group in eight channel-pairs: F4 – T4, C4 – T4, P4 – T4, O2 – T4, O2 – PZ, T4 – FZ, T4 – CZ and T4 – PZ, as shown in Fig. 1. From this figure, we can see that all significant channel-pairs are located on the right hemisphere or the midline, and most of which are connected to a network hub, channel T4.

Since an insight-related gamma-band functional network is

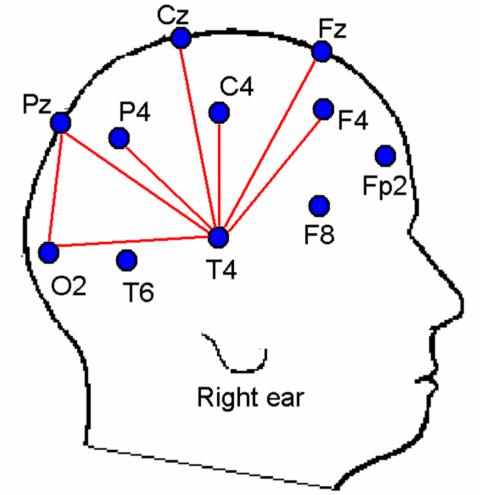

Fig. 1. Insight-related gamma-band functional network in the resting-state. Each node refers to an EEG electrode while each line corresponds to the channel-pair whose coherences differed significantly between high-insight and low-insight groups ($p < 0.05$). This network shows that the high-insight group exhibits a significantly stronger gamma-band functional network connectivity over right hemisphere compared to the low-insight group.

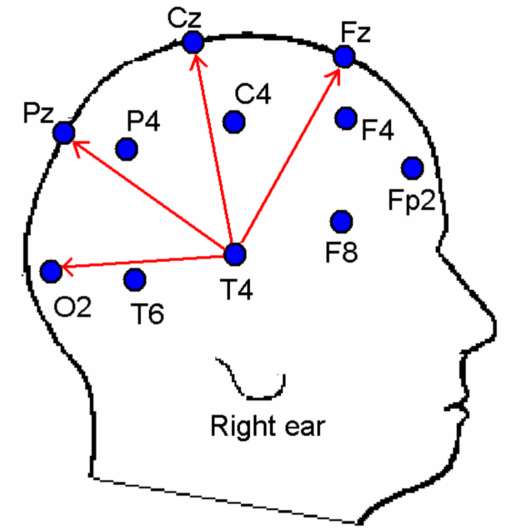

Fig. 2. Patterning of causal influence in the identified functional network shown in Fig. 1. The dominant direction of causal influence in a channel-pair (indicated by the arrow) is determined by comparing the Granger causalities of the opposite directions ($p < 0.05$). This figure shows significant causal influence from T4 to other channels in the network.

revealed in the high-insight group, we subsequently performed Granger causality analyses to investigate the patterning of causal influence in the identified resting-state network. Our results reveal a striking network pattern of causal influence, where all influences are observed originating from channel T4 outwardly to all other channels (Fig. 2). This result extends the coherence analyses and suggests that the brain region beneath the T4 electrode may serve as the information hub related to insight solving.

IV. DISCUSSIONS AND CONCLUSION

In this paper, we focus on investigating how the gamma-band resting-state brain network influences problem-solving strategy, i.e., analytic search or sudden insight. Coherence was employed to identify gamma-band functional network connectivity during the resting-state. Our results show that the high-insight group exhibited significantly stronger right-hemisphere gamma-band functional network connectivity, which indicates striking functional hemispheric asymmetry. These results suggest that the enhanced right-hemisphere gamma-band resting-state brain network is closely associated with the tendency to solve problems by insight. Previous research has shown that the right hemisphere primarily processes remote associations among concepts [20]. One prominent view describes creativity as the ability to utilize nonprepotent remote associations among problem elements to discover nonobvious solutions to a problem [21]. Hence, it is reasonable to speculate that the enhanced right-hemisphere gamma-band resting-state network may facilitate the processing of remote associations, thus favoring the emergence of the sudden insight when the problem is encountered.

Given the identified resting-state network, we performed Granger causality analysis to reveal the patterning of causal influence in the network. Our results show that significant directional influences are observed originating from channel T4 outwardly to all other channels, indicating that the right anterior temporal area (beneath electrode T4) plays a role of information hub for the communication between different brain areas. An fMRI study on insight also shows that the insight effect only reliably occurs in the right anterior superior-temporal gyrus [6]. Although the specific working mechanism of the right temporal area as the information hub still remains unclear for insight, the close association between the right anterior temporal area and insight has been manifested by these previous studies.

Could the obtained right-hemisphere resting-state network with a hub in the anterior temporal lobe be mainly influenced by electromyogenic (EMG) artifact? While this possibility is difficult to rule out completely, several problems arise with this hypothesis. First, the observed network effect is exactly what one would predict based on prior studies. For example, Jung-Beeman et al. [6] found a burst of gamma-band activity at this same electrode (though it was called T8 instead of T4) when a person solves a problem with insight. Second, EMG usually peaks at very high frequencies (e.g., 70 - 100 Hz) [22], but the analysis reported here focuses mainly on neural activity in the gamma frequency range (30 – 40 Hz). Finally, resting-state network we discovered is exclusively localized at the right hemisphere. If the network were due to the EMG, it is not clear why an EMG effect would be restricted only to the right hemisphere.

In summary, we have identified an insight-related right-hemisphere resting-state network with a hub in the anterior temporal lobe. By Granger causality analysis, we have further shown a significant directional influence from this right anterior temporal hub to all other electrodes in the identified network. These findings indicate that the spatial focus of the insight effect is at the right anterior temporal lobe, a result consistent with the hypothesis of right-lateralized hemispheric asymmetry.

ACKNOWLEDGMENT

This work is partially supported by NIH.

REFERENCES

[1] R. W. Smith and J. Kounios, “Sudden insight: all-or-none processing revealed by speed-accuracy decomposition,” *J. Exp. Psychol. Learn*, vol. 22, no. 6, pp. 1443-1462, 1996.

[2] R. S. Friedman and J. Forster, “Effects of motivational cues on perceptual asymmetry: Implications for creativity and analytical problem solving,” *J. Pers. Soc. Psychol*, vol. 88, pp. 263-275, 2005.

[3] W. J. Ray and H. W. Cole, “EEG alpha activity reflects attentional demands, and beta activity reflects emotional and cognitive processes,” *Science*, vol. 228, pp.750-752, 1985.

[4] S. Makeig, M. Westerfield, T. P. Jung, S. Enghoff, J. Townsend, E. Courchesne and T. J. Sejnowski, “Dynamic brain sources of visual evoked responses,” *Science*, vol. 295, pp. 690-694, 2002.

[5] S. Makeig, S. Debener, J. Onton and A. Delorme, “Mining event-related brain dynamics,” *Trends Cogn. Sci.*, vol. 8, no. 5, pp. 204-210, 2004.

[6] M. Jung-Beeman, E. M. Bowden, J. Haberman, J. L. Frymiare, S. Arambel-Liu, R. Greenblatt, P. J. Reber and J. Kounios, “Neural activity when people solve verbal problems with insight,” *PLoS. Biol.*, vol. 2, pp. 500-510, 2004.

[7] J. Kounios, J. L. Frymiare, E. M. Bowden, J. I. Fleck, K. Subramaniam, T. B. Parrish and M. J. Jung-Beeman, “The prepared mind: Neural activity prior to problem presentation predicts subsequent solution by sudden insight,” *Psychol. Sci.*, vol. 17, pp. 882-890, 2006.

[8] J. Kounios, J. I. Fleck, D. L. Green, L. Payne, J. L. Stevenson, M. Bowden and M. Jung-Beeman, “The origins of insight in resting state brain activity,” *Neuropsychologia*, vol. 46, pp. 281-291, 2008.

[9] H. Liang, M. Ding and S. L. Bressler, “On the tracking of dynamic functional relations in monkey cerebral cortex,” *Neurocomputing*, vol. 32-33, pp. 891-896, 2000.

[10] H. Liang, M. Ding, R. Nakamura and Steven L. Bressler, “Causal influences in primate cerebral cortex during visual pattern discrimination,” *Neuroreport*, vol. 11, no. 13, pp. 2875-2880, 2000.

[11] H. Liang, S. L. Bressler, M. Ding, W. A. Truccolo and R. Nakamura, “Synchronized activity in prefrontal cortex during anticipation of visuomotor processing,” *Neuroreport*, vol. 13, no. 16, pp. 2011-2015, 2002.

[12] M. J. Jutras,, P. Fries and E A. Buffalo, “Gamma-Band Synchronization in the Macaque Hippocampus and Memory Formation,” *J. Neurosci.*, vol. 29, no. 40, pp. 12521-12531, 2009.

[13] G. G. Gregoriou, S. J. Gotts, H. Zhou and R. Desimone, “High-frequency, long-range coupling between prefrontal and visual cortex during attention,” *Science*, vol. 324, pp. 1207-1210, 2009.

[14] A. Keil, M. M. Muller, W. J. Ray, T. Gruber and T. Elbert, “Human gamma band activity and perception of a gestalt,” *J. Neurosci.*, vol. 19, pp. 7152-7161, 1999.

[15] C. W. J. Granger, “Investigating causal relations by econometric models and crossspectral methods,” *Econometrica*, vol. 37, no. 3, pp. 424-438, 1969.

[16] M. Ding, Y. Chen, S. L. Bressler, “Granger causality: basic theory and application to neuroscience,” in: *Handbook of Time Series Analysis: Recent Theoretical Developments and Applications*, B. Schelter and M. Winterhalder, Ed. WILEY-VCH Verlag GmbH & Co. KGaA, 2006, pp. 437-460.

[17] M. Kaminski and H. Liang, “Causal influence: advances in neurosignal analysis,” *Crit. Rev. Biomed Eng*, vol. 33, no. 4, pp. 347-430, 2005.

[18] J. Cui, L. Xu, S. L. Bressler, M. Ding and H. Liang, “BSMART: a Matlab/C toolbox for analysis of multichannel neural time series,” *Neural networks*, vol. 21, pp. 1094-1104, 2008.

[19] M. Ding, S. L. Bressler, W. Yang and H. Liang, “Short window spectral analysis of cortical event-related potentials by adaptive multivariate autoregressive (AMVAR) modeling: data preprocessing, model validation, and variability assessment by bootstrapping,” *Biol. Cybern.*, vol. 83, no. 1, pp. 35-45, 2000.

[20] M. Jung-Beeman, “Bilateral brain processes for comprehending natural language,” *Trends Cogn. Sci.*, vol. 9, pp. 512–518, 2005.

[21] S. A. Mednick, “The associative basis of the creative process,” *Psychol. Rev.*, vol. 69, pp. 220-232, 1962.

[22] I. I. Goncharova, D. J. McFarland, T. M. Vaughan and J. R. Wolpaw, “EMG contamination of EEG: spectral and topographical characteristics,” *Clin. Neurophysiol*, vol. 114, pp. 1580-1593, 2003.