Default mode network and attention network in unconscious processing

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***Abstract*—The critical role of unconscious processing in problem solving had been proved by previous empirical evidence. However, we still could not understand how unconscious mind process information differently from the conscious mind. One previous study utilized an event-related potential approach to demonstrate the different processes we went through during processing unconscious cue and conscious cue. In addition to this sequential and localized processing view, this study reanalyzed the data from that study and aimed to investigate how the default mode network and attention network reacted to and engaged in the processing of an unconscious cue. Functional connectivity was measured and graph theory was utilized to obtain the network dynamics. The results showed that compared to the no cue condition, the conscious cue condition did not exhibit a different communication pattern within the default mode network and the attention network. But after the presentation of the unconscious cue, the default mode network and attention network both reacted with enhanced communication within the network. It suggests that if a stimulus is presented below the perceptual threshold, it will activate the default mode network, which might support the divergent activation of the cue. The attention network might be engaged to monitor the default mode network and inhibit some unwanted divergent activation.**

Keywords—unconscious processing, default mode network, attention network, local efficiency, global efficiency

I. INTRODUCTION

Unconscious mind, a term introduced by Freud, was defined as a large reservoir of thoughts beneath our conscious awareness [1]. It has been long questioned whether unconsciousness really plays an important role in human thoughts and how it can be scientifically measured. A series of studies have shown that unconscious information processing can facilitate the generation of a creative solution. Maier found that during solving a two-string problem, subjects frequently figured out the solution after a subtle cue (an experimenter casually brushing against one of the strings, setting it gently into motion) was displayed [2]. The author reported this process to be unconscious, since no subject was able to report the experimenter's actions. In 2006, Dijksterhuis and Meurs replicated this finding with a more well controlled experiment paradigm [3]. Their results displayed that when subjects got distracted from a problem solving task and engaged in a demanding irrelevant working memory task, they actually performed better after returning to the original problem solving task. The authors suggested that the mental operation happening at an unconscious level imposed by heavy working memory load facilitated solutions to creative problems. The authors announced the unconscious thought theory [4], stating that thinking and memory searching during unconscious processes are more diffused or divergent than that during conscious processes, rendering it to be more conductive in creative idea generations [5,6]. In addition to the previous empirical evidence, Gao and Zhang utilized an event-related potential approach and the sandwich mask technique to demonstrate the effectiveness and capacity of the unconscious processing and revealed the specific event-related potential (ERP) components and the underlying brain generators for unconscious processing [7].

In this study the modern network view towards cognitive processing was adopted instead of the sequential and localized processing view. According to this modern paradigm, cognition is the consequence of dynamic interactions among "functionally connected" discrete brain regions, instead of the product of any individual brain region [8]. These "functionally connected" discrete brain regions formed large-scale networks, identified by their different functions, such as the default mode network, the attention network, etc. The default mode network is a network active when an individual is awake and at rest. It plays a critical role in monitoring internally oriented tasks, including daydreaming and retrieving memories [9]. It is typically deactivated during most stimulus-driven cognitive tasks. But how it will act during unconscious processing of information remains a question. The attention network is crucially involved in the selection of sensory contents by attention [10]. It provides the top-down modulation which inhibits irrelevant activities and induces control over lower-level perceptual processes. Its role during unconscious processing is of interest as well.

Therefore, the data from Gao and Zhang [7] was reanalyzed in this study to evaluate the functional connectivity in the default mode network and the attention network. In addition, graph theory was utilized to exhibit their network dynamics to reveal how they were engaged in the unconscious processing.

II. METHOD

A. Participants, Stimuli and Procedure

Data were collected from 20 College students (seven men and thirteen women, mean age 20 years, range 20–24 years). A classic divergent thinking problem task was used. The stimuli used were 180 object names and 180 cues (a cue is remotely distant from a problem in semantic relatedness and able to trigger an unusual use of the object.) selected based on the preliminary experiment results. This experiment employed a within-subject design with 3 conditions: unconscious cue condition, conscious cue condition and no-cue condition. In the unconscious cue condition, the cue was sandwich-masked,

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so the participants cannot see the cue clearly or report it. In the conscious cue condition, the cue was presented long enough for the participants to process with awareness. Figure 1 displays the sequences of trial presentations for the three different conditions. Please see [7] for more details.

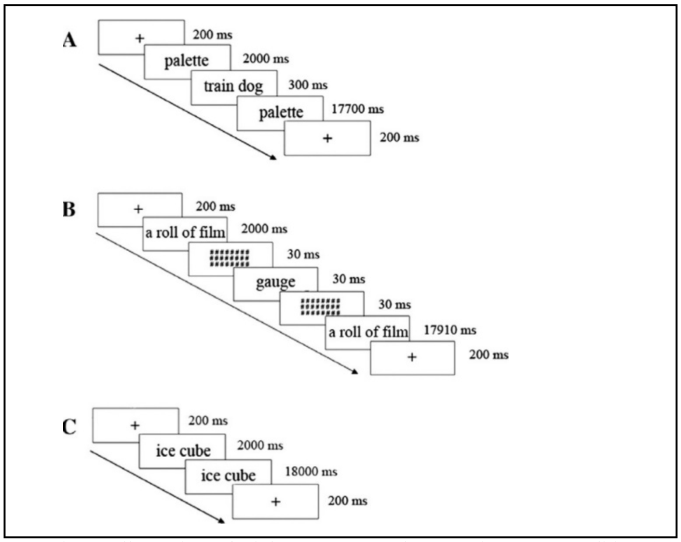

Fig. 1. Illustration of trial sequences under conscious cue condition (A), unconscious cue condition (B), and no cue condition (C).

B. *Electroencephalogram recording and analysis*

Dense array EEG was recorded using a HydroCell GSN 128-channel net and Net Amps 300 amplifier (EGI Inc., Eugene, Oregon, USA). Recording was conducted with sampling rate of 500 Hz, with a 200 Hz anti-aliasing low pass filter, Cz as a reference (ground electrode between Cz and Pz), and was digitalized with 24-bit precision. Impedance was kept below 50 kΩ throughout the recording.Continuous EEG signal was re-referenced to the linked mastoids, filtered with high-pass (0.1 Hz) and low pass (30Hz) FIR filter, and segmented around the end of the display of object names from -200 ms to 5100 ms (200 msperiod preceding cue onset as baseline). Independent component analysis (ICA) was performed to remove artifacts [11].

C. *Brain functional connectivity network analysis*

For source estimation, the forward model was calculated using the symmetric boundary element method (BEM) [12] and default MNI MRI template (Colin 27). The inverse model was estimated using the weighted Minimum Norm Estimate (wMNE) [13]. After estimating the activation time-courses at 15,002 vertices (an equilateral triangle in the tessellation of the cortical surface), 148 anatomical regions of interest (ROIs; 74 in each hemisphere) were generated based on the Destrieux atlas [14] and mean activity of each area was used to calculate functional connectivity.

Time frequency decomposition was conducted on source-based EEG single trials with Morlet wavelet (EEGlab newtimef function). For every subject, condition, and ROI, a 3D matrix of 70 (frequency points) × 200 (time points) × 'number of trials' (which varied between subjects) was obtained. The functional coupling was evaluated with imaginary part of coherence (iCoh) computed for each frequency and time points between all possible pairs of ROIs.

The ROIs for the default mode network and attention network were selected based on He and his colleagues' findings [15]. To measure the related brain functional connectivity network characteristics, these full iCoh adjacency matrices were converted into sparse, undirected, weighted graphs, which were further analyzed with graph measures. The threshold was adjusted for each full adjacency matrix to make sure the density of each graph (defined as the proportion of existing edges out of all possible edges) equals 0.20. The global efficiency is the average inverse shortest path length in the network. The local efficiency is the global efficiency computed on node neighborhoods [16]. These two measures provide information of the communication efficiency in the brain. On a global scale, efficiency quantifies the exchange of information across the whole network, while the local efficiency quantifies a network's resistance to failure on a small scale.

D. *Statistical analysis*

Global and local efficiency across 70 frequency points, 200 time points were compared between unconscious cue condition, conscious cue condition and no cue condition, utilizing cluster-based permutation test. The number of randomizations was set as 10000. The family-wise alpha level was set to 0.05. For each permutation, all t-scores corresponding to uncorrected p-values below the threshold of 0.05 were formed into clusters. The sum of the t-scores in each cluster is the "mass" (tmass) of that cluster. The most extreme cluster mass in each of the 10001 sets of tests was recorded to estimate the distribution of the null hypothesis.

III. RESULTS

The dynamics of the default mode network and attention network locked to the presentation of cues were obtained and compared among unconscious cue condition, conscious cue condition and no cue condition. The results showed that compared to no cue condition, the conscious cue condition did not exhibit a different communication pattern within either of the two large-scale brain networks. However, the unconscious-hint condition exhibited a unique pattern within these two large-scale brain networks.

Up to around 500 ms after the presentation of the unconscious cue, the local efficiency of the default mode network was significantly higher than the no cue condition, within the theta band (tmass = 188.4, P = 0.005) (Figure 2, 1st row). The communication between neighbouring nodes in the default mode network was enhanced. Up to around 800 ms after the presentation of the unconscious cue within the beta bands, and up to around 2000 ms within the theta and alpha band, the global efficiency of thedefault mode network was significantly higher than the no cue condition (tmass = 909.4, P = 0.001; tmass = 812.5, P = 0.001)(Figure 2, 2nd row). The communication within the whole default mode network was enhanced. Up to 800 ms after the presentation of the unconscious cue, the local efficiency of the attention network was significantly higher than the no cue condition within the theta and alpha band (tmass =

336.8, P = 0.001) (Figure 2, 3rd row). The communication of the neighboring nodes within the attention network was enhanced. Up to around 700 ms after the presentation of the unconscious cue, the global efficiency of the attention networkwas significantly higher than the no cue condition within the theta and alpha bands (tmass = 661.2, P = 0.002) (Figure 2, 4th row). The communication within the whole attention network was enhanced.

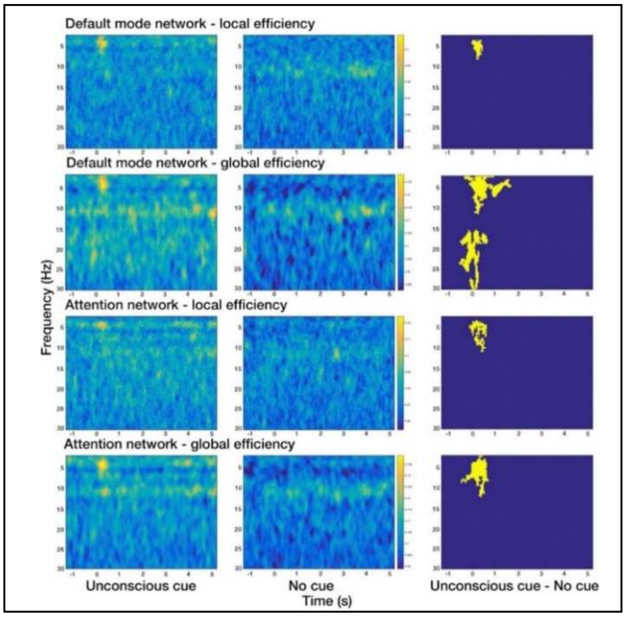

Fig. 2. Local and global efficiency dynamics of the default mode network and attention network, and the difference between the unconscious cue condition and the no cue condition. In the difference graphs (third column), the yellow parts indicate the time-frequency regions significantly different between the 2 conditions.

IV. DISCUSSION

The results showed that compared to the no cue condition, the conscious cue condition did not exhibit a different communication pattern within the default mode network and the attention network. This could be due to that the cue was given after the divergent problem above the perceptual threshold, rendering it to be an additional piece of information to the problem. Therefore, no different pattern of large-scale brain network emerged. But after the presentation of the unconscious cue, the default mode network and attention network both reacted with enhanced communication within the network. The default mode network is believed to be typically deactivated during most stimulus-driven cognitive tasks [9], however, it seems that if a stimulus is presented below the perceptual threshold, it will activate the default mode network. Since the default mode network is tightly associated with daydreaming and memory retrieving, this result suggests that the default mode network might be involved in the unconsciousprocessing and divergent activation of the cue [7]. This will facilitate the generation of a creative solution in the end. On theother hand, the attention network was also actively involved. It is known to play a key role in inducing control over low-level perceptual processing, also over default mode network [17]. Meanwhile, it provides a gating top-down modulation inhibiting irrelevant activities [17,18]. In this case, the attentionnetwork might be engaged to monitor the default mode network and inhibit some unwanted divergent activation as well.

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