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THE EFFECTS OF MUSIC ON BRAIN FUNCTIONAL NETWORKS: A NETWORK ANALYSIS

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Abstract—The human brain can dynamically adapt to the changing surroundings. To explore this issue, we adopted graph theoretical tools to examine changes in electroencephalography (EEG) functional networks while listening to music. Three different excerpts of Chinese Guqin music were played to 16 non-musician subjects. For the main frequency intervals, synchronizations between all pair-wise combinations of EEG electrodes were evaluated with phase lag index (PLI). Then, weighted connectivity networks were created and their organizations were characterized in terms of an average clustering coefficient and characteristic path length. We found an enhanced synchronization level in the alpha2 band during music listening. Music perception showed a decrease of both normalized clustering coefficient and path length in the alpha2 band. Moreover, differences in network measures were not observed between musical excerpts. These experimental results demonstrate an increase of functional connectivity as well as a more random network structure in the alpha2 band during music perception. The present study offers support for the effects of music on human brain functional networks with a trend toward a more efficient but less economical architecture.

Key words: electroencephalography, music, graph theory, small-world network, synchronization.

INTRODUCTION

The brain is considered to be a complex system, comprised of spatially interconnected areas. Structural and functional connectivity of the brain possess properties of complex networks and can be investigated using graph theoretical measures (Stam and Reijneveld, 2007; Bullmore and Sporns, 2009; He and Evans, 2010; Bullmore and Bassett, 2011). One effective model is small-world networks in terms of graph theory. Small-world networks appear as regular, lattice-like structures with a few random long-range connections (Watts and Strogatz, 1998). They are characterized by high local clustering, signifying dense local connectivity, and short path length between any two vertices. Small-world organizations are interesting for complex brain networks since they confer high local and global efficiency of information transfer with a low wiring cost (Bullmore and Sporns, 2009; He and Evans, 2010).

There is increasing evidence for small-world configurations in structural networks of animals (Sporns and Zwi, 2004; Sporns et al., 2007). These configurations are extended to studies of human brain structural networks based on cortical thickness measurements (He et al., 2007), diffusion tensor imaging (DTI) (Iturria-Medina et al., 2008; Yan et al., 2011) and diffusion spectrum imaging (DSI) (Hagmann et al., 2008). In several functional magnetic resonance imaging (fMRI) studies, networks of functional connectivity also exhibited small-world characteristics (He et al., 2009; Hayasaka and Laurienti, 2010; Tian et al., 2011). While neuronal activities frequently occur in time-scales shorter than those reflected in fMRI signal fluctuations (Palva et al., 2010), the use of electroencephalography (EEG) and magnetoencephalography (MEG) guarantees an adequate temporal resolution. And such dynamic techniques are inherently appropriate to detect oscillatory synchronization (Sporns et al., 2000), which takes a crucial role in interregional communication (Fries, 2005; Schnitzler and Gross, 2005). Network analyses of EEG and MEG are consistent with the fMRI data, indicating small-world features in synchronization patterns (Stam et al., 2007a, 2009; Deuker et al., 2009; Douw et al., 2011; Jin et al., 2012). The small-world network attributes could be found not only in resting but also during task conditions, such as finger tapping and music listening (Eguíluz et al., 2005). Interestingly, brain maturation may be associated with a shift toward a more small-world network architecture (Boersma et al., 2011). In contrast, brain networks deviate from the optimal, normal small-world organization in brain pathology (Stam et al., 2007a, 2009; Rubinov et al., 2009).

It has been suggested that brain networks exist in a critical state between chaos and order (Kitzbichler et al., 2009; Petermann et al., 2009). Small-world properties support rapid adaptive reconfiguration of functional

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Abbreviations: DSI, diffusion spectrum imaging; DTI, diffusion tensor imaging; EEG, electroencephalography; EOG, electrooculogram; FIR, finite impulse response; fMRI, functional magnetic resonance imaging; GLS, GuangLingSan; MEG, magnetoencephalography; MHSN, MeiHuaSanNong; OLWJ, OuLuWangJi ; PLI, phase lag index; PSD, power spectral density; SD, standard deviation.

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connectivity in response to varying cognitive demands (Bassett et al., 2006). Several empirical studies have identified task-related changes in network organization during finger movements (Bassett et al., 2006; Jin et al., 2012), working memory (Palva et al., 2010; Kitzbichler et al., 2011) and learning (Bassett et al., 2011).

Another potential task that can cause network reconfiguration is music perception. Music is widely recognized as a universal language. Music in various forms has a profound impact on all cultures, and even on animals (Gray et al., 2001). Listening to music is a complex cognitive task and implicates processing and integration of meaningful elements including harmony, rhythm or melody (Schmithorst, 2005). Modulating effects of music have been observed on functional connectivity such as default mode network (DMN) (Kay et al., 2012) and oscillatory synchronization (Petsche et al., 1997; Bhattacharya et al., 2001; Bhattacharya and Petsche, 2005; Flores-Gutiérrez et al., 2007, 2009; Ruiz et al., 2009). Wu et al. (2012) have identified a topological change in EEG alpha-band networks in a music listening task while preserving the small-world characteristics comparable to the findings of Eguíluz et al. (2005).

While the previous study has reported network reconfiguration during music perception, three issues demand further attention: (i) the topological differences between musical excerpts have not been considered; (ii) the earlier analysis was focused merely on the alpha band, whereas the functional networks were usually probed in multiple frequency intervals (Deuker et al., 2009; Stam et al., 2009; Boersma et al., 2011; Kitzbichler et al., 2011; Jin et al., 2012) since different frequency components might represent different biological significances; (iii) estimation of brain functional connectivity from EEG recordings can be affected by volume conduction, which may make interpretation unreliable.

The problem of volume conduction refers to the inclination of nearby EEG electrodes to pick up activity of common neural sources, introducing high synchronies that do not reflect factual functional connectivity (Nunez et al., 1997; Stam et al., 2007b). There are two main approaches proposed to tackle this problem. A first approach attempts to use reconstructed sources as a basis to assess functional correlations (Gross et al., 2001; Lehmann et al., 2006; Amor et al., 2009). Although this method indeed makes a contribution to detecting functional co-operations between anatomically well-specified brain areas, a primary defect is the absence of a unique solution to the EEG inverse problem. A second approach is to determine true interactions between time series which are not likely to be biased by volume conduction. One could adopt the imaginary part of the complex coherency, which is not owing to volume conduction effects (Nolte et al., 2004). However, it contains mixed information on both amplitudes and phase delays, and consequently is not an appropriate measure of functional correlations. Stam et al. (2007b) proposed phase lag index (PLI) as an alternative. The PLI estimates consistency of phase difference between two time series. It can determine a reliable evaluation of synchronization that is less sensitive to the influence of volume conduction. Therefore we utilize the PLI to quantify functional connectivity.

In this study, we intend to further explore the effects of music on EEG functional networks. Our questions are: (i) whether network reorganization takes place during music perception in different frequency bands and (ii) whether differences in network organization can be observed between musical pieces. The experiment used three pieces of Chinese Guqin music as musical stimuli. Guqin music is regarded as a symbol of Chinese civilization (Zhu et al., 2008, 2009) and has been selected as a Masterpiece of the Oral and Intangible Heritage of Humanity by UNESCO. Cognitive neuroscientific research on Guqin music perception will deepen our understanding of the perception of Eastern music.

EXPERIMENTAL PROCEDURES

Participants and materials

This study involved 16 right-handed subjects (mean age 22.25 years, standard deviation (SD) 1.65; eight males). All subjects were recruited from the university campus and nurtured in China. Structured interviews guaranteed that the subjects had normal hearing, no formal or informal training in music, and were free from neurological diseases or psychoactive drugs use. Each subject was informed of the experimental procedure and gave a written consent to participate. The subjects were paid for the participation in the experiment.

All subjects were instructed to listen attentively to three pieces of Guqin music: OuLuWangJi (OLWJ), MeiHuaSanNong (MHSN), and GuangLingSan (GLS) (music conditions). These selected musical pieces were unfamiliar to all participants. In addition, subjects also listened to a segment of pink noise (noise condition). The presentation of each acoustic stimulus lasted 40 s and their order was counterbalanced among subjects. EEG at rest was recorded for 2 min and used as a control condition (silence condition). The subjects were comfortably seated inside a dimly illuminated and sound attenuated chamber. The sound backgrounds were presented in two stereo speakers located at 2 m in front of the subjects. The volume arriving at the subjects was adjusted to 60 dB SPL. Subjects were asked to keep their eyes closed during the experiment.

EEG recordings

EEG was recorded using the Neuroscan system (Neuroscan Inc., El Paso, TX) with 64 electrodes arranged according to the international 10–20 system. All leads were referenced to left and right earlobes. To monitor eye movements and blinks, horizontal and vertical electrooculograms (EOGs) were recorded from two bipolar electrodes placed slightly lateral to the outer canthus of each eye and above and below the left eye. Inter-electrode impedance levels were kept below 5 kΩ.