Electroencephalographic dynamics of musical emotion perception revealed by independent spectral components

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This study explores the electroencephalographic (EEG) correlates of emotional experience during music listening. Independent component analysis and analysis of variance were used to separate statistically independent spectral changes of the EEG in response to music-induced emotional processes. An independent brain process with equivalent dipole located in the fronto-central region exhibited distinct δ-band and θ-band power changes associated with self-reported emotional states. Specifically, the emotional valence was associated with δ-power decreases and θ-power increases in the frontal-central area, whereas the emotional arousal was accompanied by increases in both δ and θ powers. The resultant emotion-related component activations that were less interfered by the activities from other brain processes complement previous EEG studies of emotion perception to music. *NeuroReport* 00:000–000

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Introduction

The link between brain dynamics and music-induced emotion has been explored by various brain imaging modalities, including functional magnetic resonance [1–3], electroencephalography (EEG) [4–6], and positron emission tomography [7]. These literatures have shown that music could be a powerful tool to evoke emotional responses. The advantage of functional magnetic resonance and positron emission tomography is its superior spatial specificity at the deep brain structures but with poor temporal resolution in comparison to EEG. As the primary interest of this study is to observe the continuous changes of brain activity, this study focuses on continuous EEG dynamics associated with emotional processes.

Some EEG changes in response to music-induced emotion have been reported earlier, including α-power activity at the posterior regions [5], α-power asymmetry at frontal region [6], and θ-power at mid-line region [8]. The relationship between α-power changes and emotional states has been a controversy, which may attribute to different experiment designs and process procedures [9]. However, one formidable problem that has plagued these and many other cognitive EEG studies has been its poor spatial specificity. Owing to the volume conduction, the recorded EEG signals at the scalps are generated by partial synchrony of local field potentials in many distinct cortical domains [10]. The signal mixing of EEG was in part responsible for EEG's poor spatial specificity and has made it difficult to distinctly uncover the correlation between brain functions and recorded EEG signals [11]. Independent component analysis (ICA), whose mathematical objective is to estimate statistically independent sources from the mixtures, has been widely applied to multichannel EEG signals for not only removing the noncortical activity, such as eye blink and muscle tension, but also separating sources with temporally independent yet spatially fixed sources [12]. The resultant source contributions would tend to have more focal and distinct brain activity compatible with physiological responses [10].

This study applies ICA to address three specific issues of the brain activations associated with emotional processes during music listening: (i) which functionally independent brain processes revealed by ICA involve in the emotion perception, (ii) which emotion-related spectral changes of these brain processes would accompany emotional processing, and (iii) what are the specific brain dynamics associated with valence and arousal of the emotion model. To this end, this study proposes the applications of ICA to spectral changes of multichannel scalp EEG data to find spatially and spectrally fixed independent sources that modulate the spectral information of the brain during music listening. This study also tests the consistency of emotion-related brain activity across multiple participants.

Materials and methods

Participants

Twenty-four right-handed healthy volunteers (14 males, 10 females; age 24.61 ± 2.52 years) participated in a

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music-listening study [13]. Participants' handedness was defined by their hands used for writing. Two left-handed (outlier) participants were excluded from further analysis. Most of participants were undergraduate or graduate students from College of Electrical Engineering and Computer Science or College of Engineering at National Taiwan University. They had minimal formal musical education and can thus be considered as nonmusicians. All participants gave informed consent before participating in a protocol approved by the Human Research Protections Program of the National Taiwan University, Taipei, Taiwan.

Experiment procedure

Participants were instructed to keep their eyes closed and remain seated in a music-listening experiment. Music excerpts were presented by a PC to induce four basic emotional states (joy, angry, sadness, and pleasure) following a two-dimensional emotion model [14] composed of valence and arousal axes. Participants were also instructed to listen carefully to the music and to judge and report the emotion they had experienced after each music excerpt. Participants were not instructed to discriminate specific music structures. Sixteen excerpts from Oscar's film soundtracks were selected as stimulus materials according to the consensus of emotional labels reported by Wu and Jeng [15]. Each was edited into a 30-s music excerpt. Four of 16 music excerpts were randomly selected without replacement to form a four-run experiment. A 15-s silent rest was inserted between music excerpts. After each trial, the participants were requested to give the emotion labels (joy, anger, sadness, and pleasure) to each music excerpt based on what they felt.

Data acquisition

A 32-channel EEG system (Neuroscan Inc., Charlotte, North Carolina, USA) was used to record the EEG and electrooculogram signals. The scalp electrodes were placed according to the International 10–20 system, all referred to the linked mastoids (average of A1 and A2). EEG and electrooculogram signals were sampled at 500 Hz with a bandpass filter (bandpass 1–100 Hz) and a 60 Hz notch filter to avoid powerline contamination. The impedances of all electrodes were kept below 10 kΩ.

Data preprocessing

The recorded EEG data were first preprocessed to remove obvious and large motion artifacts using visual inspection. The 512-point short-time Fourier transform with a 90% overlapping Hanning window of 1 s was then applied to compute EEG spectrogram for each of the 30 channels, and merged into several frequency bands including δ (1–3 Hz), θ (4–7 Hz), α (8–13 Hz), β (14–30 Hz), and γ (31–50 Hz). The spectral time series for each experiment thus consisted of around 3500 EEG power estimates at five frequency bands after subtracting the mean baseline spectra derived from the first 5 s of music stimulation duration.

Independent component analysis

ICA was then applied to the multiband spectral time series of the EEG across multiple channels to assess independent components (ICs) that modulate the spectral changes of multichannel scalp EEG data. This method was inspired by the idea of Anemuller *et al.* [16], which performed the ICA decomposition on frequency-domain data at different frequency bands individually. In this study, the statistically independent spectral components were derived using the infomax ICA algorithm implemented in EEGLAB toolbox [17]. For each participant, the input data, X, to the ICA decomposition were composed of five EEG spectral features (δ, θ, α, β, and γ power spectra) on each of 30 scalp channels for ICA decomposition. The dimensionality of the matrix was first reduced to its first 20 principal dimensions by principal component analysis. The dimension-reduced data were then decomposed by infomax ICA to find an unmixing matrix, W, that linearly 'unmixed' the input data into an estimated source matrix, U, calculated by equation of $U = WX$. The rows of this output data matrix, called the component activations, were the time courses of relative strengths of activity of the respective ICs. The columns of the inverse of the unmixing matrix, W^{-1}, give the relative projection strengths of the respective components onto each of the scalp sensors to form a scalp map. To localize the sources of ICs, DIPFIT2 routine from EEGLAB was used to fit single-dipole source models to the IC scalp topographies using a four-shell spherical head model [18].

Component selection

For each participant, components of interest were selected based on their relevance to his/her own self-reported emotional states. Participant's self-reported emotion label was first separated into categories of valence and arousal. The valence level comprises positive valence (joy and pleasure) and negative valence (angry and sadness), whereas arousal level contains high arousal (joy and angry) and low arousal (pleasure and sadness). A two-way analysis of variance [valence (positive and negative) $\times$ arousal (high and low)] was then used to examine the activation of each IC for each participant. Those ICs related to valence, arousal, and interaction (valence $\times$ arousal) with significant level ($P < 0.01$) would be separately tagged and reported below.

Component clustering

To study the cross-subject stability of independent spectral components derived by infomax ICA applied to EEG spectral data, we grouped components obtained from multiple participants into clusters based on their scalp maps, equivalent dipole locations, and the component activations. Finally, the activation time series of the component clusters associated with valence, arousal, and interaction could be explored systematically and characterized by their mean cluster map.

Results

The ICs of interest selected using a two-way analysis of variance were grouped into clusters with comparable scalp maps, dipole source locations, and power spectra. Figure 1 shows the individual scalp maps, mean scalp maps, and the corresponding three-dimensional dipole source locations of two IC clusters significantly associated with the valence, arousal, and their interaction, which show the consistency of the emotion-related components across participants. Figure 1a shows the component cluster with IC spectrum peaked at the δ band, whereas Fig. 1b shows another emotion-related component cluster with IC spectrum peaked at the θ band. Note that not all of the participants have the same equivalent components in all clusters. According to the dipole location plots, most of individual ICs have equivalent dipoles located at or near the fronto-central midline regions for all IC clusters of interest.

Figure 1a shows that the emotion valence was associated with distinct δ-band power changes of the fronto-central components in 11 of 24 participants (45.83%). In contrast, there were seven of 24 participants (29.17%) exhibiting δ-band power changes associated with both emotion-arousal and valence–arousal interaction (Fig. 1a). The corresponding dipole source location was also near the fronto-central region. Figure 1b shows the θ-band power changes associated with emotion valence, arousal, and their interaction in nine of the 24 participants (37.5%). The equivalent dipole sources for these ICs were located in or near the middle cingulate cortex.

In addition, the spectral fluctuations of above components under emotional valence (positive and negative) and arousal (high and low) were further individually back projected onto the scalp sensors ($X' = W^{-1}U$) and further analyzed. Figure 2 shows the average contributions of the emotion-related brain processes onto the scalp. Overall, the emotional valence was associated with δ power decreases and θ-power increases in the frontal-central region, compared with the resting power baselines. The positive valence emotion was apparently accompanied by less δ-power decreases but more θ-power increases from the resting baselines in the frontal-central region compared with the negative valence emotion. In contrast, the emotional arousal was accompanied by increases in both the δ and θ power spectra. Upon closer inspection, the high-arousal emotion tended to induce less δ-power increases but more θ-power increases from the resting baselines in the frontal-central region, compared with the low-arousal emotion. In general, the δ-band power exhibited larger spectral changes across emotional states, compared with the θ-band power.

Discussion

Unlike the previous scalp EEG studies in emotion and music [5,6,8], this study employed ICA to linearly unmix the multichannel scalp EEG data into temporally independent and spatially fixed components that were closely linked to distinct brain processes. The component activations associated with emotional processes induced by natural music listening were then statistically assessed.

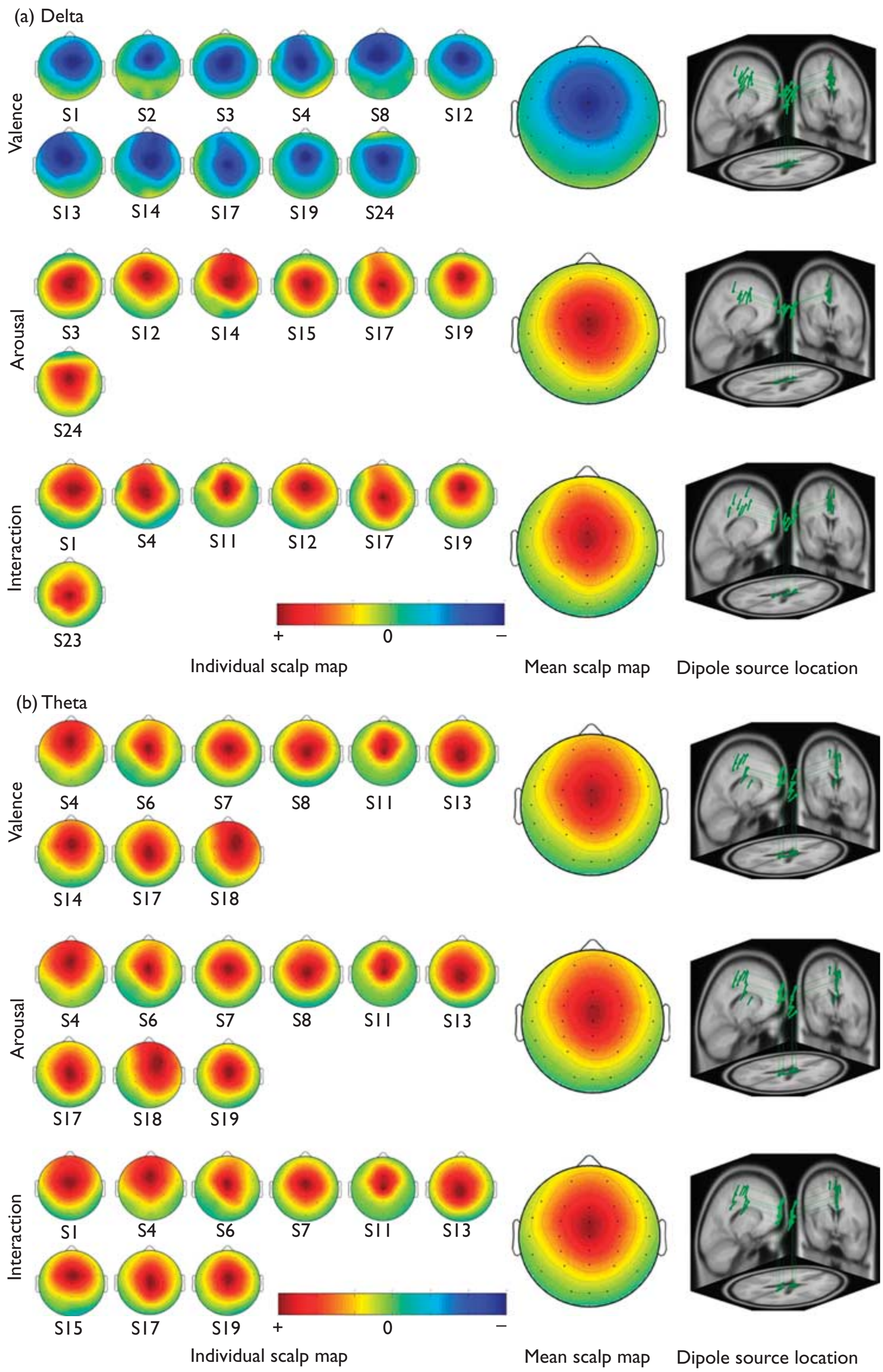
Emotion-related components

First of all, the frontal midline θ power changes have been linked to the cerebral metabolism in the anterior cingulate cortex (ACC) [19]. The ACC is part of the limbic system and has been reported to be largely engaged in emotional processing [2,20]. The relationship between the frontal midline θ and emotional processing has further been reported to be correlated during listening to pleasant music [8]. The results of this study showed that the positive valence emotion was significantly related to the θ-power increases, consistent with the earlier findings. In addition, the fronto-central θ-power increase was found highly related to high-arousal emotions (Fig. 2b). However, an equivalent current dipole model of the fronto-central component was located in or near the middle cingulate cortex (Fig. 1b) rather than the ACC. The discrepancy of the dipole locations might be attributed to the low-density 32-channel montage and the imprecise standard montreal neurological institute head model [21]. Further, the standard EEG sensor locations rather than the actual locations were used in the source estimation, leading to some errors in the source locations.

In our analysis, δ-band ICs were found associated with emotional responses as well. Delta rhythm has mainly been featured as an important indicator for monitoring the transition of sleep stages [22]. Recently, Bhattacharya and Petsche [23] in a music perception study showed that δ band synchrony over distributed cortical areas was significantly increased in nonmusician participant group during music listening tasks. Second, as Khalfa *et al.* [2] suggested, both music perception and emotion perception might involve some common brain areas. The results of this study also supported the finding of widespread spectral changes in the δ band during emotion perception in music listening (Fig. 2a).

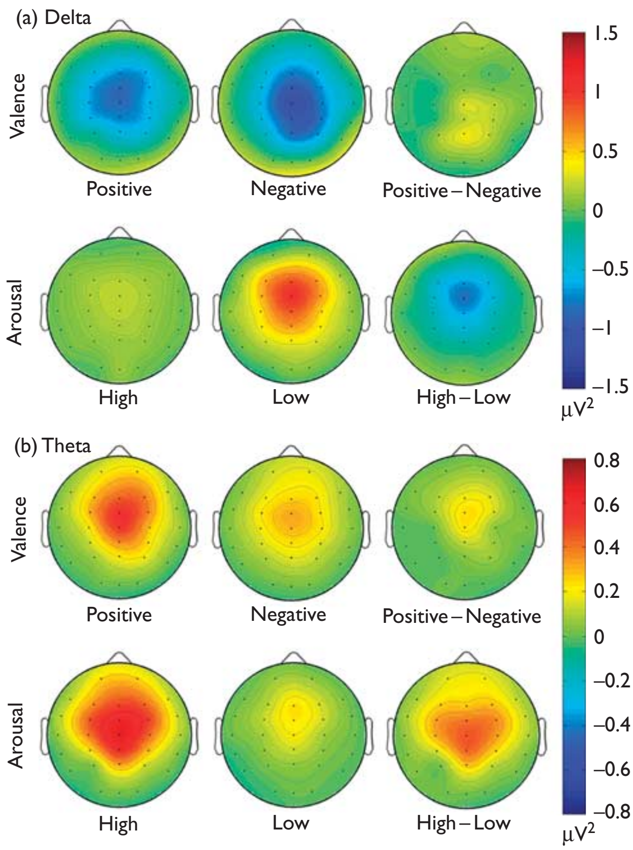
Emotion induced during music listening could be manipulated by varying the structure and rendering of the music itself, such as the change of tempo [2], mode [2], and degree of dissonance [7]. According to Blood *et al.* [7], for example, the changes of musical structures is only one way of eliciting emotional responses to music. However, as the primary interest of this study is to discover the brain dynamics during natural music listening as used in [4,20], we did not manipulate the music structures in our experiments.

Fig. 1



Mean and individual scalp maps and equivalent dipole source locations for two independent component clusters exhibiting distinct (a) δ- and (b) θ-band changes across emotional states. Here, a two-way analysis of variance was used to test the significance of the relation between the activations of these components and valence, arousal and interaction ($P < 0.01$). Each individual scalp map indicates a component found in a single participant. The right panels plot three-dimensional dipole source locations and their projections onto a template brain image.

Fig. 2



Distribution maps of average spectral changes under different conditions of emotion perception, separately for valence (upper) and arousal (lower) and positive/high (left), negative/low (middle) in the (a) δ and (b) θ bands. The rightmost column plots the spectral difference between positive and negative valence or between high and low arousal.

Brain area(s) engaged in multiple emotions

Further, the dipole locations of ICs exhibiting δ and θ band power changes during music listening were found located in the same or adjacent cortical brain areas. The similarity of source locations might be caused by the fact that the EEG processes often exhibit dynamics with multiple frequency bands, resulting in ICs with different dominant frequencies originated from the same or spatially nearby EEG source generators [16]. A meta-analysis on functional neuroanatomy of emotion [24] also showed that the medial prefrontal cortex was activated across multiple emotions (happiness, anger, sadness and disgust) in at least 40% of 55 studies.

Individual differences

The results of this study showed that a subgroup of participants tended to engage the fronto-central θ activity, whereas another subgroup involved δ activity that has less commonality in arousal and valence–arousal interaction condition. These results suggested that different individuals might involve different brain circuits to process emotions, consistent with the individual differences in the use of emotion regulation strategies reported in [25].

Other components

In addition, α-related components with equivalent dipoles located in or near the right parietal lobe, central lobe, and occipital lobe also exhibited significant spectral changes in the α band in response to emotion perception. These results were consistent with previous findings that α-power activity would increase over posterior sites when participants listened to emotional musical excerpts [5]. However, unlike the δ and θ band ICs, α-laden ICs were less consistent across participants in terms of the locations of the equivalent dipoles and spectral changes (not shown). In this study, the directions of the α power changes corresponding to emotion perception also varied across participants.

Conclusion

This study employed ICA to separate the activities arising from distinct brain processes, alleviating the uncertainty of the signal-mixing of volume conduction. The resultant emotion-related component activations were thus less interfered by the activities from other brain processes, allowing the assessment of emotion-related brain dynamics. Across participants, the changes in the emotion valence, arousal, and their interaction were accompanied by the δ and θ band changes of the fronto-central components during music appreciation.

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