Human Mirror System is Involved in Automatic Processing of Musical Emotion: Evidence from EEG

Authors: Zhao Huaiyang, Jiang Jun, Zhou Linshu, Jiang Cunmei, Jiang Cunmei

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Abstract

The human mirror system is considered a crucial component of social cognition. The μ suppression wave (including and frequency bands) evoked by midline electrodes constitutes an electrophysiological indicator of human mirror system activity. Although musical emotional expression is believed to be achieved through the mimicry of individuals' mental states, this hypothesis has not yet been empirically investigated. The present study utilizes EEG technology and a cross-modal emotional priming paradigm to investigate whether the human mirror system is involved in the automatic processing of chord emotions. Pleasant or unpleasant chords served as primes for target faces that were emotionally congruent or incongruent. Behavioral results demonstrated that participants responded significantly faster to emotionally congruent faces than to emotionally incongruent faces. EEG results revealed that, between 500~650 ms following auditory stimulus onset, the emotionally incongruent condition elicited -band desynchronization relative to the emotionally congruent condition. Between 300~450 ms after auditory stimulus onset, both emotionally congruent and incongruent conditions elicited -band desynchronization. Source analysis results indicated that μ suppression waves predominantly emerged in core brain regions of the human mirror system, specifically the inferior parietal lobule and inferior frontal gyrus or premotor cortex. These findings suggest that automatic processing of musical emotion is closely associated with activity in the human mirror system.

Full Text

The Human Mirror System Participates in Automatic Processing of Musical Emotion: Evidence from EEG

ZHAO Huaiyang[1], JIANG Jun[2], ZHOU Linshu[2], JIANG Cunmei[2]
[1] Department of Psychology, College of Education, Shanghai Normal University, Shanghai 200234, China
[2] Music College, Shanghai Normal University, Shanghai 200234, China

Abstract

The human mirror system is considered a crucial component of social cognition. Mu rhythm suppression (including and frequency bands) evoked at midline electrodes serves as an electrophysiological indicator of human mirror system activity. Although musical emotion expression is thought to be achieved by imitating individuals' mental states, this hypothesis has not been empirically investigated. The present study used EEG technology and a cross-modal affective priming paradigm to examine whether the human mirror system participates in the automatic processing of chord emotions. Pleasant or unpleasant chords served as primes for target faces that were either emotionally congruent or incongruent. Behavioral results demonstrated that participants responded significantly faster to emotionally congruent faces than to incongruent ones. EEG findings revealed that, during the 500-650 ms window following auditory stimulus onset, the incongruent condition elicited greater band desynchronization compared to the congruent condition. During the 300-450 ms window after auditory stimulus onset, both congruent and incongruent conditions induced band desynchronization. Source analysis localized mu suppression primarily to core regions of the human mirror system—the inferior parietal lobule and inferior frontal gyrus/premotor cortex. These findings indicate that automatic processing of musical emotion is intimately linked to human mirror system activity.

Keywords: chord emotion; mu rhythm; alpha frequency band; beta frequency band; human mirror system

The human mirror system encompasses a core parietofrontal network comprising the inferior parietal lobule and inferior frontal gyrus/premotor cortex (Hobson & Bishop, 2017; Iacoboni & Dapretto, 2006; Molenberghs, Cunnington, & Mattingley, 2012; Rizzolatti & Craighero, 2004). Research indicates that action imitation activates the human mirror system (Hobson & Bishop, 2017; Iacoboni & Dapretto, 2006; Molenberghs et al., 2012; Rizzolatti & Craighero, 2004). Moreover, both action observation and execution (Caspers, Zilles, Laird, & Eickhoff, 2010; Iacoboni et al., 1999; Sakreida et al., 2018; Simos et al., 2017), as well as motor imagery (Hétu et al., 2013; Lui et al., 2008; Simos et al., 2017), activate the human mirror system. Additionally, listening to speech (Jardri et al., 2007; Tettamanti et al., 2005, 2008) and action-related sounds such as paper tearing or ball kicking (Di Cesare, Fasano, Errante, Marchi, & Rizzolatti, 2016;

Gazzola, Aziz-Zadeh, & Keysers, 2006; Ricciardi et al., 2009) also activate the human mirror system.

In EEG (Electroencephalogram) research, mu rhythm suppression recorded at midline electrodes is considered an electrophysiological indicator of human mirror system activity (Fox et al., 2016; Hobson & Bishop, 2016). This claim rests on several lines of evidence. First, mu rhythm activity shares functional properties with activation of human mirror system brain regions. Studies have found that when individuals observe and execute the same actions, mu suppression activity increases, and the pattern of EEG activity resembles the activation pattern of the human mirror system (Debnath, Salo, Buzzell, Yoo, & Fox, 2019; Liao, Acar, Makeig, & Deak, 2015). Recent meta-analytic results also demonstrate that mu suppression shows high stability during both action observation and execution (Fox et al., 2016). Furthermore, subsequent research has verified that mu suppression exhibits additional functions of the human mirror system, such as involvement in language processing (Bechtold, Ghio, Lange, & Bellebaum, 2018; van Elk, van Schie, Zwaan, & Bekkering, 2010).

Second, mu suppression occurs in human mirror system brain regions. Simultaneous EEG and functional magnetic resonance imaging (fMRI) studies have found that increases in blood oxygenation level dependent (BOLD) signals in human mirror system regions during both action observation (Arnstein, Cui, Keysers, Maurits, & Gazzola, 2011; Braadbaart, Williams, & Waiter, 2013) and action execution (Arnstein et al., 2011; Mizuhara, 2012) correlate significantly with suppression in the and frequency bands. Magnetoencephalography (MEG) studies have also confirmed these results, localizing the source of mu suppression to human mirror system brain regions (Muthukumaraswamy & Singh, 2008).

Third, a causal relationship exists between mu suppression activity and activation of human mirror system brain regions. Previous studies using transcranial magnetic stimulation have investigated this relationship, revealing causal links between mu suppression activity and human mirror system regions (Berntsen, Cooper, & Romei, 2017; Keuken et al., 2011). Whether inhibitory magnetic stimulation was applied to the inferior frontal gyrus (Keuken et al., 2011) or the inferior parietal lobule (Berntsen et al., 2017), researchers found that mu suppression activity was significantly reduced or eliminated under inhibitory conditions. These findings demonstrate a causal relationship between mu suppression activity and human mirror system activation.

In fact, mu suppression encompasses both the frequency band (8–13 Hz) and the frequency band (15–25 Hz) (Hobson & Bishop, 2017). band suppression is associated with motor preparation or planning (Chen et al., 2016; Stančák, Riml, & Pfurtscheller, 1997; Tzagarakis, Ince, Leuthold, & Pellizzer, 2010; Zhang, Chen, Bressler, & Ding, 2008). For instance, when individuals perform index finger extension movements with added weight on the finger, requiring greater muscle contraction preparation, this motor preparation leads to increased band suppression (Stančák et al., 1997). Unlike the band, band activity is related to movement or action execution (Désy & Lepage, 2013; Fox et al., 2016; Frenkel-Toledo, Bentin, Perry, Liebermann, & Soroker, 2013). In Frenkel-Toledo et al.’s (2013) study, for example, participants were asked to squeeze a ball with one hand. The results showed stronger band suppression during action execution compared to resting states.

Although the anterior insula and anterior cingulate cortex are not core regions of the human mirror system, studies have found that observing and imitating facial expressions of happiness, sadness, anger, fear, and surprise (Carr, Iacoboni, Dubeau, Mazziotta, & Lenzi, 2003) as well as disgust (Phillips et al., 1997; Wicker et al., 2003), or feeling others' pain (Lamm, Decety, & Singer, 2011; Singer et al., 2004) also activate these brain regions. These findings suggest that the human mirror system may be connected to emotion processing. Consistent with the human mirror system, research has shown that mu suppression is associated with empathy for pain (Peled-Avron, Goldstein, Yellinek, Weissman-Fogel, & Shamay-Tsoory, 2018; Yang, Decety, Lee, Chen, & Cheng, 2009) and facial emotion processing (Moore, Gorodnitsky, & Pineda, 2012; Moore & Franz, 2017; Rayson, Bonaiuto, Ferrari, & Murray, 2016).

Music is considered an imitative art form: it conveys musical information by imitating certain objects (Leman, 2007). Regarding emotional imitation, musical emotion primarily imitates changes in human mental activity through variations in acoustic elements and their relationship to action or movement (Sievers, Polansky, Casey, & Wheatley, 2013; Koelsch, 2013). Research has found that when in a happy state, people walk faster, speak louder, and exhibit upward pitch contours with greater variation; when in a sad state, people walk slower, speak more softly, and show downward pitch contours with smaller variation (Johnson-Laird & Oatley, 2008). Indeed, happy music is associated with major mode, consonant harmony, fast tempo, high volume, and ascending pitch, whereas sad music is linked to minor mode, mild dissonance, slow tempo, low volume, and descending pitch (Juslin & Sloboda, 2013).

On the other hand, from the perspective of emotion perception, judging emotional vocalizations also activates the human mirror system (Warren et al., 2006). Music is believed to imitate human facial, vocal, and gestural expressions (Davies, 1994; Koelsch, 2013; Leman, 2007). Studies have found that understanding musical emotion automatically evokes corresponding facial expression movements (Chan, Livingstone, & Russo, 2013). Molnar-Szakacs and Overy (2006) predicted that the human mirror system might be involved in processing musical emotion. However, no study has yet examined this issue.

Based on this, the present study employed a cross-modal affective priming paradigm with a stimulus onset asynchrony (SOA) of 200 ms to investigate whether the human mirror system participates in the automatic processing of musical emotion. The experimental logic of this study is as follows. First, we employed a cross-modal affective priming paradigm because it allows for the examination of chord emotion processing. According to spreading activation theory (Collins & Loftus, 1975), processing chord emotions in a priming paradigm can automatically activate related emotional representations, thereby facilitating processing of the target stimulus' s emotional representation and producing an affective priming effect (Steinbeis & Koelsch, 2008, 2011). Therefore, the affective priming effect elicited by chords as prime stimuli can reflect listeners' processing of chord emotions. This paradigm has been widely used in musical emotion research (Goerlich et al., 2012; Logeswaran & Bhattacharya, 2009; Sollberge, Rebe, & Eckstein, 2003).

Second, the affective priming paradigm can exclude the influence of stimulus-specific perceptual processing. In this study, the prime stimuli were chords expressing pleasant and unpleasant emotions, while the target stimuli were facial images expressing pleasant (happy) and unpleasant (angry and fearful) emotions. Since the prime and target stimuli were identical across congruent and incongruent conditions, differing only in their emotional relationship, comparing congruent versus incongruent conditions can eliminate effects attributable to stimulus-specific perceptual processing.

Third, to investigate automatic processing of chord emotions, we employed an SOA of 200 ms. Research shows that an SOA of 200 ms taps into automatic processing of chord emotions (Steinbeis & Koelsch, 2008, 2011). This is because longer SOAs allow participants to develop conscious response strategies that can influence subsequent reactions (Musch & Klauer, 2003). Additionally, consistent with previous research (Steinbeis & Koelsch, 2008, 2011), participants' task was to judge the emotion type of the target stimulus, which did not require conscious processing of the chord primes, thereby revealing the automatic processing mechanism of chord emotions. Based on these considerations, we hypothesized that automatic processing of chord emotions would activate midline mu suppression.

Specifically, if the frequency band is related to motor planning (Chen et al., 2016; Tzagarakis et al., 2010), we expected differences in band power between emotionally congruent and incongruent conditions. If the frequency band is associated with action execution (Désy & Lepage, 2013; Fox et al., 2016), we anticipated band suppression during the music listening phase.

2.1 Participants

To ensure adequate statistical power, we used G*Power 3.1.9.4 software (Faul, Erdfelder, Lang, & Buchner, 2007) to determine the sample size a priori. Based on previous similar research (Steinbeis & Koelsch, 2011) showing a large effect size for emotional congruence (F(1, 19) = 10.82, d = 1.51), we predicted a large effect size for the present experiment. According to the software calculation, a minimum sample size of 11 was required to achieve 99% statistical power at a significance level of 0.05. Therefore, we recruited 18 participants. However, three participants were excluded from data analysis due to excessive movement artifacts that resulted in poor signal quality and insufficient valid trials. The final sample consisted of 15 participants (4 males) aged 20–25 years (M = 23.17, SD

= 2.37). All participants were right-handed, had normal or corrected-to-normal vision, had no history of psychiatric or neurological disorders, and had not received professional musical training. Prior to the experiment, all participants provided informed consent and completed

2.2 Stimuli

This experiment employed a cross-modal affective priming paradigm. The prime stimuli consisted of two types of chords: one type comprised a root position chord (C-E-G-C) and its second inversion (G-C-E-G), which were consonant and expressed pleasant emotion (Blood, Zatorre, Bermudez, & Evans, 1999; Koelsch, Fritz, Cramon, Müller, & Friederici, 2006). The other type consisted of two non-triadic chords: one built from augmented fourth, perfect fourth, and minor second intervals (C-F#-B-C), and the other from minor second, perfect fourth, and augmented fourth intervals (C-C#-F#-C). These non-triadic chords were dissonant and expressed unpleasant emotion (Crowder, Reznick, & Rosenkrantz, 1991; Johnson-Laird, Kang, & Leong, 2012). Each of the four chords was presented in all 12 keys, resulting in a total of 48 chord primes. Each chord lasted 800 ms. The chords were created using Sibelius 7.5 software and rendered with a grand piano timbre using Cubase 5.1 software (Steinberg Media Technologies GmbH). The chords had a sampling rate of 44100 Hz, 16-bit resolution, and a bit rate of 1411 kbps. Finally, all chords were normalized to -3 dB using Adobe Audition CS 6 software (Adobe Systems Inc.).

To verify that consonant and dissonant chords indeed differed in emotional pleasantness, eight musically untrained participants (who did not participate in the formal experiment) rated each chord' s pleasantness (1 = very unpleasant, 7 = very pleasant) and arousal (1 = very calm, 7 = very excited) on 7-point scales. Paired-samples t-tests revealed that consonant chords (M = 4.77, SD = 1.49) were rated as significantly more pleasant than dissonant chords (M = 3.88, SD = 1.63), t(7) = 3.45, p = 0.011. However, no difference in arousal was found between consonant (M = 4.99, SD = 0.77) and dissonant (M = 4.88, SD = 0.85) chords, t(7) = 0.54, p = 0.606.

Target stimuli consisted of 96 facial expression images selected from the Chinese Facial Affective Picture System (Gong, Huang, Wang, & Luo, 2011), including 48 pleasant (happy) and 48 unpleasant (angry and fearful) expression images, with equal numbers of male and female faces. As shown in Figure 1 [Figure 1: see original paper], each chord was paired with one pleasant and one unpleasant facial image, creating 96 trials: half were emotionally congruent pairings and half were incongruent. Although sad and angry emotions differ in arousal, this study focused on processing chord valence based on differences in pleasantness/unpleasantness, which represents a fundamental and universal emotional experience (Lindquist, Satpute, Wager, Weber, & Barrett, 2016). In contrast, the arousal dimension is conceptually ambiguous, with different measurement indices across studies, such as increased attention, behavioral engagement, intensity of emotional experience, physiological activation, or subjective feelings of activation (see review by Lindquist et al., 2016).

2.3 Procedure

After the electrode cap was fitted, participants completed a practice session. Before practice began, participants listened to a non-experimental prime stimulus and adjusted the volume of their Philips SHM 1900 headphones to a comfortable level. The practice block consisted of 8 trials designed to familiarize participants with the experimental procedure; no feedback was provided. Following practice, the formal experiment began. Trials were presented using E-Prime 2.0 software (Psychology Software Tools Inc.). Each trial began with a 500 ms red fixation cross "+" at the center of a gray screen, indicating that the prime stimulus (chord) would soon appear. The target stimulus (facial expression image) appeared 200 ms after prime onset. Participants were instructed to judge as quickly and accurately as possible whether the facial expression was pleasant or unpleasant and to respond with a key press. Response mappings were counterbalanced across participants. After the participant' s response, a 1500 ms mask consisting of the string "XXXXX" was presented. Trials were presented in a pseudo-random order according to the following constraints: (1) no more than three consecutive trials with congruent or incongruent pairings; (2) no more than three consecutive trials with prime stimuli of the same emotional type; (3) no more than three consecutive trials with target stimuli of the same emotional type; (4) adjacent trials used chords in different keys; and (5) no more than three consecutive trials with target faces of the same gender.

2.4 EEG Recording

EEG signals were recorded using a NeuroScan Synamps 2 system (Compumedics NeuroScan Inc.). Before participants performed the task, they were fitted with an international 10-20 system 64-channel Ag/AgCl electrode cap. Horizontal electrooculogram (EOG) electrodes were placed 1 cm lateral to the outer canthi of both eyes, and vertical EOG electrodes were positioned 1 cm above and below the left eye orbit. The left mastoid served as the reference electrode, the right mastoid as a recording electrode, and the ground was located at the midpoint of the line connecting Fz and Cz. Signals were amplified with an AC amplifier, filtered with a bandpass of 0.05-100 Hz, and sampled at 500 Hz. Impedance for all electrodes was maintained below 5 kΩ.

2.5 Data Analysis

2.5.1 Frequency Analysis

During offline data analysis, we used NeuroScan 4.5 software for data preprocessing. First, the raw EEG data were re-referenced to the average of the bilateral mastoid electrodes. Then, ocular artifacts were automatically corrected using the software' s regression procedure. After applying a zero-phase-shift low-pass digital filter at 30 Hz (24 dB/oct slope) using an FIR digital filter, the EEG was segmented from 200 ms before to 1000 ms after target stimulus onset. Subsequently, data were baseline-corrected using the 200 ms interval preceding target onset. Finally, trials with amplitudes exceeding ±75 V were considered artifacts and automatically rejected.

Following preprocessing, we conducted further analysis using the Brainstorm toolbox (http://neuroimage.usc.edu/brainstorm) running on MATLAB R2016a software (MathWorks Inc, Natick, MA, USA). First, the data were filtered with a high-pass of 1 Hz and a low-pass of 35 Hz. Second, the EEG was segmented from 500 ms before to 1200 ms after prime stimulus onset. We performed time-frequency analysis using wavelet transforms with a Gaussian kernel full width at half maximum of 3 s and a center frequency of 1 Hz. Third, time-frequency representations were averaged across trials and baseline-corrected using the event-related synchronization/desynchronization (ERS/ERD) method with a baseline of 450-50 ms before prime onset. We used the percentage of ERS/ERD as the observed value for band power: ERS/ERD % = (post-baseline power -mean baseline power) / mean baseline power × 100%.

In this study, we determined the time windows and electrode sites for frequency analysis based on previous research (Steinbeis & Koelsch, 2008, 2011) and visual inspection. Previous studies have shown that the frequency band appears approximately 300 ms after stimulus onset, primarily at midline electrodes (Fu & Franz, 2014), while the frequency band appears 200-600 ms after stimulus onset at midline electrodes (Chen et al., 2016). Based on inspection of our results, we defined the band time window as 300-450 ms after auditory stimulus onset and the band time window as 500-650 ms after auditory stimulus onset (i.e., 300-450 ms after picture onset). We selected the midline electrodes Fz, Cz, and Pz for analysis.

2.5.2 Source Analysis

To identify the sources of the and frequency bands, we conducted source analysis using the Brainstorm toolbox. As individual MRI structural images were unavailable, we first employed the default MNI template as the brain structural template. We used the OpenMEEG function (Gramfort, Papadopoulo, Olivi, & Clerc, 2010) to compute a symmetric boundary element model, which served as the EEG forward model (using default parameters). Second, a noise covariance matrix was calculated from the 450-50 ms pre-prime data to estimate electrode noise levels. Third, we used a weighted minimum norm estimates approach to project data from each trial onto 3×5005 elementary current dipoles for unconstrained source localization (Lin et al., 2006). Finally, frequency analysis was performed using wavelet transforms, and results were averaged across trials for each condition and Z-score transformed using the 450-50 ms pre-prime interval as a baseline. Based on the time-frequency analysis results described above, we selected band data from 300-450 ms after auditory stimulus onset and band data from 500-650 ms after auditory stimulus onset for statistical analysis.

3.1 Behavioral Results

We conducted t-tests on accuracy and reaction times with emotional congruence (congruent vs. incongruent conditions) as a within-subjects variable. For accuracy, no significant difference was found between congruent (M = 98%, SD = 2.4%) and incongruent (M = 97%, SD = 2.5%) conditions, t(14) = 1.03, p = 0.320, d = 0.32. For reaction times, participants responded faster in the congruent condition (M = 575.17 ms, SD = 75.34) than in the incongruent condition (M = 605.38 ms, SD = 87.74), t(14) = -2.19, p = 0.046, d = 0.57.

3.2 EEG Results

3.2.1 Frequency Analysis Results

Frequency Band

As shown in Figure 2 [Figure 2: see original paper]-a,b, band power was higher in the congruent condition than in the incongruent condition during the 500-650 ms window after auditory stimulus onset. A repeated-measures ANOVA with emotional congruence (congruent vs. incongruent) and electrode site (Fz, Cz, Pz) as within-subjects factors confirmed these observations. The main effect of emotional congruence was not significant, F(1, 14) = 1.83, p = 0.197, $p^2 = 0.12$, indicating no significant difference in band power between congruent and incongruent conditions. The main effect of electrode site was significant, F(2, 28) = 12.17, $p < 0.001$, $p^2 = 0.47$, showing that band power was lowest at the Fz site. The interaction between emotional congruence and electrode site was also significant, F(2, 28) = 8.44, p = 0.001, $p^2 = 0.38$. Simple effects analysis revealed that at the Fz site, band power was higher in the congruent condition than in the incongruent condition, F(1, 14) = 30.04, $p < 0.001$, $p^2 = 0.68$. At the Cz site (F(1, 14) = 2.13, p = 0.167, $p^2 = 0.13$) and Pz site (F(1,14) = 0.06, p = 0.815, $p^2 < 0.01$), the difference in band power between the two conditions was not significant.

Frequency Band

As shown in Figure 2-a,b, prominent band desynchronization was observed during the 300–450 ms window after auditory stimulus onset compared to the 450–600 ms window after prime onset. Since band desynchronization occurred in both congruent and incongruent conditions, we used the adjacent time window (450–600 ms) as a control condition and included time window as a factor. This yielded a repeated-measures ANOVA with time (300–450 ms, 450–600 ms), electrode site (Fz, Cz, Pz), and emotional congruence (congruent vs. incongruent) as within-subjects factors. The results showed a significant main effect of time only, F(2, 28) = 19.97, $p < 0.001$, $p^2 = 0.59$, indicating significantly lower band power during the 300–450 ms window after prime onset. All other main effects and interactions were non-significant (F(2, 28) < 1.33, $p > 0.270$, $p^2 < 0.09$).

3.2.2 Source Analysis Results

To further identify the sources of and band activity, we conducted source analysis. For the band, nonparametric cluster-based t-tests revealed significant differences between congruent and incongruent conditions in frontoparietal regions ($p < 0.05$) (see Figure 3-a). For the band, nonparametric cluster-based t-tests showed that band signals in both congruent and incongruent conditions originated primarily from anterior and middle brain regions, including inferior frontal gyrus, premotor cortex, superior parietal lobule, and inferior parietal lobule—areas belonging to the human mirror system (see Figure 3-b).

This study investigated the electrophysiological mechanisms underlying automatic processing of musical emotion using an affective priming paradigm. Behavioral results showed that participants had shorter reaction times for emotionally congruent faces compared to incongruent faces. EEG time-frequency analysis revealed that, during the 500–650 ms window after auditory stimulus onset, the incongruent condition elicited band desynchronization relative to the congruent condition. During the 300–450 ms window after auditory stimulus onset, both congruent and incongruent conditions induced band desynchronization. Moreover, these effects primarily occurred in core regions of the human mirror system, including the inferior parietal lobule, inferior frontal gyrus, and premotor cortex. These findings indicate that the human mirror system participates in the automatic processing of musical emotion.

At the behavioral level, our results showed faster responses to emotionally congruent faces. According to spreading activation theory (Collins & Loftus, 1975), concepts are stored as nodes in an associative network, and processing a prime stimulus' s conceptual representation can pre-activate representations of conceptually congruent nodes at the conceptual level, thereby facilitating processing of related representations. Our findings indicate that participants' perception of emotional chords automatically activated emotional representations, which facilitated processing of emotionally congruent facial images and produced a priming effect. These results are consistent with previous studies (Steinbeis & Koelsch, 2008, 2011), demonstrating that listeners can automatically process musical emotion.

At the neurophysiological level, we found that during the 500–650 ms window after auditory stimulus onset, the incongruent condition elicited band desynchronization compared to the congruent condition. This suppression effect did not result from differential processing of facial emotions, as the target stimuli (emotional faces) were identical across congruent and incongruent conditions. Therefore, the band desynchronization obtained by subtracting congruent from incongruent conditions should be attributed to the effect of the chord stimulus: whether it facilitated or inhibited processing of the target image. Indeed, previous affective priming studies have found that incongruent emotions, whether in facial or vocal prosodic stimuli, elicit band desynchronization during processing (Chen et al., 2016). band desynchronization is associated with motor preparation (Stančák et al., 1997; Tzagarakis et al., 2010; Zhang et al., 2008). Similar to these studies, the band desynchronization observed in our study is also related to motor preparation. Specifically, when chord emotion was congruent with facial emotion, participants did not need to re-engage in corresponding motor preparation; conversely, when chord emotion was incongruent with facial emotion, participants needed to re-engage in motor preparation, manifested as band power suppression.

We also found that during the 300–450 ms window after auditory stimulus onset, both congruent and incongruent conditions elicited band desynchronization. Although chords and facial images were both present during this time window, this result is attributable to processing of chord emotion rather than facial emotion. This is because band power changes induced by facial emotion processing typically appear around 500 ms after emotional face presentation (Moore et al., 2012); therefore, band power changes in this time window could not have originated from facial emotion processing. On the other hand, this result also did not stem from integration of chord emotion and facial emotion, as cross-modal information integration is primarily reflected in changes in band power (Lense, Gordon, Key, & Dykens, 2014; Schneider, Debener, Oostenveld, & Engel, 2008).

Previous research has found that band suppression is related to action execution or imitation (Désy & Lepage, 2013; Fox et al., 2016; Frenkel-Toledo et al., 2013). Similarly, the band suppression observed in our study is related to imitation of chord emotion. Indeed, in our study, listeners needed to imitate chord emotion in both congruent and incongruent conditions, leading to reduced band power. Since band power changes primarily originate in the central sulcus (which includes the human mirror system) (Kuhlman, 1978; Wolpaw, McFarland, Neat, & Forneris, 1991), our findings suggest that automatic processing of musical emotion involves the human mirror system.

Although cross-modal affective priming paradigms may involve emotional conflict processing, our experimental results are unrelated to emotional conflict for the following reasons. First, our SOA of 200 ms is associated with automatic emotional processing. Indeed, previous research has found that short SOAs can only facilitate emotional processing and cannot produce emotional conflict, as conflict primarily manifests at the conscious processing level (de Groot, 1984; Neely, 1977). Second, if our results were due to emotional conflict processing, we should have observed band activity at midline frontal sites, as numerous EEG studies have shown that conflict processing is associated with midline frontal band activity (e.g., Cohen & Ridderinkhof, 2013; Nigbur, Cohen, Ridderinkhof, & Stürmer, 2012; Tang, Hu, & Chen, 2013). However, we did not find changes in this frequency band in our study.

To further verify whether the mirror system participates in automatic processing of musical emotion, we localized the sources of mu suppression. Consistent with previous source analysis results for mu suppression (Moore & Franz, 2017), we found that and band suppression primarily occurred in anterior and middle brain regions, such as the inferior parietal lobule, inferior frontal gyrus, and premotor cortex—all of which belong to the human mirror system (Iacoboni & Dapretto, 2006; Molenberghs et al., 2012; Rizzolatti & Craighero, 2004). Thus, the mu suppression observed in our study indeed reflects human mirror system activity. However, it should be noted that brain regions identified through EEG source localization can only represent areas of large-scale oscillatory activity. Future MEG studies are needed to provide further validation.

Our study found that automatic processing of chord emotion induced changes in and band power of mu suppression, with suppression effects in both frequency bands occurring in human mirror system brain regions. These findings also validate the reliability of mu suppression as an electrophysiological indicator of human mirror system activity. Previous research has shown that human mirror system activation is not only related to action or movement (e.g., Sakreida et al., 2018; Simos et al., 2017; Tettamanti et al., 2008) but also to emotion imitation/experience (Carr et al., 2003; Lamm et al., 2011; Wicker et al., 2003). Nevertheless, our study extends the functional understanding of the human mirror system from an electrophysiological perspective, providing the first evidence that the human mirror system participates in automatic processing of musical emotion.

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Role of the human mirror system in musical emotion automatic processing: Evidence from EEG

ZHAO Huaiyang[1]; JIANG Jun[2]; ZHOU Linshu[2]; JIANG Cunmei[2]
[1] Department of Psychology, College of Education, Shanghai Normal University, Shanghai 200234, China
[2] Music College, Shanghai Normal University, Shanghai 200234, China

Abstract

The human mirror system (HMS) consists of a core parietofrontal network of regions in the inferior parietal lobule and inferior frontal gyrus/premotor cortex, which can be activated by action observation and execution. Mu rhythm suppression is considered an electrophysiological indicator of the HMS given their similarity in reaction to action observation and execution. Mu rhythm comprises (8-13 Hz) and (15-25 Hz) frequency bands, which are typically measured at the power change of midline electrode sites. The frequency band is related to the movement preparation, whereas the frequency band is suppressed during the execution of movement.

Consistent with the role of the HMS in social cognition, such as emotion understanding, theory of mind, and empathy, mu rhythm suppression is modulated by the processing of social information, such as facial emotional information. Emotion is an important component of social communication. In addition to the emotional facial expression, music is an effective means of expressing emotions through imitation, and for most of people, the main purpose of listening to music is to process musical emotions. However, information on whether mu rhythm suppression is involved in the processing of musical emotions is limited.

The aims of the present study were to examine whether mu rhythm suppression is modulated by the processing of musical emotions using Electroencephalogram (EEG). Given that the HMS is involved in the automatic processing of musical emotions, the present study focused on this point by using a cross-modal affective priming paradigm with an SOA of 200 ms. Fifteen musically untrained normal individuals participated in the experiment. Target faces with pleasant and unpleasant emotions were primed by affectively congruous or incongruous chords. Forty-eight congruous and 48 incongruous trials were included in the present study. The participants were instructed to decide as fast and accurately as possible whether the emotion of the face was pleasant or unpleasant.

Behavioral results showed that the affectively congruous target faces (M = 575.17 ms, SD = 75.34) were judged faster than affectively incongruous target faces (M = 605.38 ms, SD = 87.74). However, no difference was observed in the percentages of correct responses to the affectively congruous (M = 98%, SD = 2.4%) and incongruous (M = 97%, SD = 2.5%) target faces.

Electrophysiological results revealed that the frequency band (18–24 Hz) oscillations were less strong for incongruous than for congruous target faces at a time window of 500–650 ms after the onset of chords. A significant desynchronization of the frequency band was observed for both the congruous and incongruous target stimuli at a time window of 300–450 ms after the onset of chords. Moreover, source analysis exhibited three sources responsible for the EEG waves of interest. The three sources were located in the inferior parietal lobule, inferior frontal gyrus, and premotor cortex.

Overall, the present study showed that mu rhythm suppression was involved in the automatic processing of chord emotions, as shown in the and frequency bands. The results extend the role of the mu rhythm and provide electrophysiological support for the role of the HMS in the processing of musical emotions.

Key words: chord emotion; μ rhythm; frequency band; frequency band; human mirror system