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How functional coupling between the auditory cortex and the amygdala induces musical emotion: A single case study

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ABSTRACT

Music is a sound structure of remarkable acoustical and temporal complexity. Although it cannot denote specific meaning, it is one of the most potent and universal stimuli for inducing mood. How the auditory and limbic systems interact, and whether this interaction is lateralized when feeling emotions related to music, remains unclear. We studied the functional correlation between the auditory cortex (AC) and amygdala (AMY) through intracerebral recordings from both hemispheres in a single patient while she listened attentively to musical excerpts, which we compared to passive listening of a sequence of pure tones. While the left primary and secondary auditory cortices (PAC and SAC) showed larger increases in gamma-band responses than the right side, only the right side showed emotion-modulated gamma oscillatory activity. An intra- and inter-hemisphere correlation was observed between the auditory areas and AMY during the delivery of a sequence of pure tones. In contrast, a strikingly right-lateralized functional network between the AC and the AMY was observed to be related to the musical excerpts the patient experienced as happy, sad and peaceful. Interestingly, excerpts experienced as angry, which the patient disliked, were associated with widespread de-correlation between all the structures. These results suggest that the right auditory–limbic interactions result from the formation of oscillatory networks that bind the activities of the network nodes into coherence patterns, resulting in the emergence of a feeling.

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1. Introduction

Music is a sound structure of remarkable acoustical and temporal complexity and although it cannot denote specific meaning, it is one of the most potent and universal stimuli for inducing mood, evoking comparable emotional responses across different musical categories and cultures (Peretz & Hebert, 2000; Fritz et al., 2009). The induced affective states can be strong and long-lasting (Krumhansl, 1997) and very short stimuli may be sufficient to trigger emotional responses (up to 250 msec, Bigand, Filipic, & Lalitte, 2005). Understanding the underlying mechanism of how emotion is induced by listening to music remains a matter of study tracking down the underlying mechanisms. Juslin and collaborators (Juslin, 2013; Juslin & Västfjäll, 2008) have proposed a comprehensive framework taking into account several physiological mechanisms underlying emotions induced by music, the BRECVEMA model (**B**rainstem reflexes-**R**ythmic entrainment, **E**valuative conditioning-emotional **C**ontagion, **V**isual imagery-**E**pisodic memory-**M**usical expectancy, **A**esthetic judgment). In addition, the phenomenon of entrainment should be mentioned as an important candidate for emotion induction through music, with recent empirical evidence showing a strong link between the feeling of entrainment and emotion (Labbé & Grandjean, in press). From another angle, it is largely acknowledged that the acoustic feature content in musical excerpts covaries with its emotional valence. Converging evidence shows that musical features such as the tempo (speed of the beat in music) and the mode (major or minor) are relevant in evoking a sense of happiness or sadness (Dalla Bella et al., 2001; Khalfa, Schön, Anton & Liégeois-Chauvel, 2005) and are associated with specific brain signatures (Trochidis & Bigand, 2013). Numerous studies have contributed to the identification of brain areas in the right and left hemispheres that seem likely to support some stage of the perceptive or emotional processing of music (for reviews see, Peretz & Zatorre, 2005; Stewart, Von Kriegsten, Warren & Griffiths, 2006).

With respect to auditory processing, it has been argued that auditory cortices in the two hemispheres are relatively specialized: the right auditory cortex (AC) underlies fine-grained pitch (frequency) processing, whereas the left AC processes rapidly changing broadband stimuli (Liégeois-Chauvel, de Graaf, Laguitton, & Chauvel, 1999; Liégeois-Chauvel, Giraud, Badier, Marquis, & Chauvel, 2001; Warrier & Zatorre, 2004; Zatorre & Belin, 2001; Zatorre, Belin, & Penhune, 2002). In addition, brain imaging, electrophysiological and neuropsychological studies have established that secondary AC (particularly in the right hemisphere) is associated with the processing of contour properties of unfamiliar melodies (Behne, Scheich, & Brechmann, 2005; Brechmann & Scheich, 2005; Brattico, Tervaniemi, Näätänen, & Peretz, 2006). In contrast, primary AC (PAC) only processes features of isolated sounds (Samson & Zatorre, 1988; Johnsrude, Penhune, & Zatorre, 2000; Patterson, Uppenkamp, Johnsrude &Griffith, 2002).

Music-evoked emotional activations involve brain regions known to also be activated by emotional pictures and reward/motivation situations. These regions include limbic [amygdala (AMY)] and paralimbic structures (orbito frontal cortex, parahippocampal gyrus), as well as the medio-ventral prefrontal cortex, anterior cingulate cortex and the ventral striatum (Blood & Zatorre, 2001; Levitin & Menon, 2003; Menon & Levitin, 2005; Gosselin et al., 2006; Pereira et al., 2011; Schmithorst & Holland, 2003). Strong AMY activation is reported for negative emotions (Koelsch, Frotz, von Cramon, Muller & Friederici, 2006; Mitterschiffthaler, Fu, Dalton, Andrew, & Williams, 2007) and for both positive and negative stimuli (Eldar, Ganor, Admon, Bleich, & Hendler, 2007). Yet, the modulation of AMY activity is more likely to be observed during a subject's emotional experiences, or when emotional music is combined with either movies or affective pictures, suggesting that the involvement of this region depends on the context of the subjective emotional experience associated with the stimuli (Blood & Zatorre, 1999; Eldar et al., 2007; Baumgartner, Esslen, & Jäncke, 2006).

Up to now, few studies have investigated the neural mechanisms underlying how acoustical features of stimuli modulate emotional feeling by looking at the functional coupling between the AC and AMY. Recently, Kumar, Stephan, Warren, Friston & Griffiths (2012) showed that aversive sounds are first processed in the AC, which can foresee the assignment of valence in the AMY. The AMY, in turn, can modulate the AC in accordance with the valence of the sounds. The AMY has extensive connections with many cortical and subcortical areas, including back projections to the AC, that may modulate sensory processing in these areas based on emotional signals (Amaral & Price, 1985; Price, 2003; Hoistad & Barbas, 2008). This is in line with studies showing the increase of AC activation in response to pleasant and/or unpleasant sounds compared to neutral sounds, which would suggest this modulation could be primed by the AMY through re-entrant projections (Grandjean et al., 2005; Plichta et al., 2011).

Emotion induced by music is a dynamic process; therefore, its evolution over time in relation to listening is more precisely tracked by electrophysiological recordings than functional imagery. Simultaneous and bilateral depth electrode recordings from both AC and AMY in a single epileptic patient during presurgical evaluation, allowed us to study the neural activity underlying this process with great spatio-temporal precision. We investigated the functional coupling between these structures by applying nonlinear correlations of intracerebral EEG while the patient listened either to musical excerpts conveying different emotions (such as happiness, sadness, peacefulness & anger) or to a sequence of pure tones (neutral stimuli). Although emotion evoked by music may be analyzed in numerous ways (see Zentner, Grandjean, & Scherer, 2008 for a full account), in the present study, we used a more convenient and traditional way to evaluate the feelings experienced by the patient, which was more appropriate for the clinical setting.

The rationale behind this approach was to examine whether the AC–AMY coupling: (i) is influenced by the emotional valence judgments or by the complexity of the stimuli (music *vs* pure tones), and (ii) is modulated as a function of hemisphere.

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