Chapter

EEG Analysis during Music Perception

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Abstract

This review presents the most interesting results of electroencephalographic studies on musical perception performed with different analysis techniques. In first place, concepts on intra-musical characteristics such as tonality, rhythm, dissonance or musical syntax, which have been object of further investigation, are introduced. Most of the studies found use listening musical extracts, sequences of notes or chords as an experimental situation, with the participants in a resting situation. There are few works with participants performing or imagining musical performance. The reviewed works have been divided into two groups: a) those that analyze the EEGs recorded in different cortical areas separately using frequency domain techniques: spectral power, phase or time domain EEG procedures such as potentials event related (ERP); b) those that investigate the interdependence between different EEG channels to evaluate the functional connectivity between different cortical areas through different statistical or synchronization indices. Most of the aspects studied in music-brain interaction are those related to musical emotions, syntax of different musical styles, musical expectation, differences between pleasant and unpleasant music and effects of musical familiarity and musical experience. Most of the works try to know the topographic maps of the brain centers, pathways and functions involved in these aspects.

Keywords: EEG, network-graph, phase synchronization, functional connectivity, music

1. Introduction

The literature on the use of EEG analysis in musical perception processes engage very different aspects related to the effects and processes of music in the brain, such as musical emotion, cognition, musical syntax, etc. In this review at the introduction, we summarize different aspects of the characteristics of musical styles to afterwards develop the EEG applications in different music-brain interactions.

Music is an art present in our daily life through numerous styles and forms. We know that musical perception involves different human factors, on the one hand it produces emotion and sensations, and it is also related to syntactic processing [1–4]. Musical perception is also modulated by factors associated with the personal characteristics of the listener: age, cultural level, socioeconomic and cultural context in which they live, musical experience and learning, familiarity with the type of music hearing, psychological state and preferences [5–7]. On the other hand, the dichotomy between cognition and musical sensation has been widely studied; the literature finally proposes a continuum between the both concepts [8]. The reception of musical content not only consists of sensations (e.g. happiness or melancholy) it also implies aspects such as recognition of structures and/or predictability of musical discourse. For all this, it is a mixture of concepts that leads to cognitive and sensitive perception.

When talking about musical perception, the importance of tonality (previously modality), should be highlighted, which is known to have been present in Western academic and popular music since medieval times. Harmony is the structure from which the tonal system departs. This structure consists of intervallic relations that can be consonant, perceived by humans as pleasant, or dissonant, perceived as unpleasant or at least as a moment of tension. In musical syntax consonant chords tend to be associated with relaxation, and dissonant with tension. Music theory, and harmony in particular, is a very extensive and complex field of knowledge that has been transformed by musical styles and the evolution of history, hence our simplified summary of intervallic relations. Different fields of knowledge such as the electroencephalography literature have analyzed many of these concepts.

The cognitive component in music recognition has been of great importance. So, musical cognition is related to the use of long-term memory, since it refers to the perceptual and to what the brain has learned in terms of the tonal hierarchical structure overwhelmingly present in our culture [6]. The sensory is related to short-term memory, to how we receive the sound result of the tonal distributions in Western music [9]. Another very important issue that has been extensively dealt is the predictability of the tonal system. Structurally, tonal music evolves temporarily within specific tonal/spectral ranges and with relatively low uncertainty (entropy) limits that make it reasonably predictable. Recent theories along these lines, such as that of McDermot, analyze familiarization with the tonal system of society against theories of auditory neurobiology underlying the attraction factor to the tonal structure [10]. This aspect of neurobiology has been discussed by Bowling et al., who analyze this issue and conclude that without the exposure of the general population to the system or tonal structure, it is undeniable that there is underlying biological evidence that demonstrates that both concepts are closely linked [11].

In addition to tonality, concerning Western academic music also contains defined rhythmic forms. This means that when listening, we can recognize patterns that develop temporarily (or within a sequence of time) and that lead to a continuous generation of expectations and predictions [12–14] together with a certain capacity for anticipation [15]. These three concepts: expectation, prediction, and anticipation are closely linked to our perception of music and occur without us being aware of them. Two main sources of musical expectations have been described: the explicit knowledge of how a piece of music with which one is familiar will develop and the implicit understanding that comprises the knowledge of the rules of music while listening [16]. The implicit expectations arise because each musical style, genre, and culture contains specific rules, patterns, sound characteristics, and time. Exposure to music training or social and cultural influences affect and determine an individual's emotional response [17].

Musical preferences are also believed to be due to the completion of the expectation of a pattern [18], that is, whether the expectation is met positively or negatively. When listening to music, –for regular listener- the listener expects certain patterns of notes or phrases, and this entails a prediction of the musical event [12], which can be frustrated in some musical styles like contemporary/new music. Zatorre's review, identifies some of the auditory cortical circuits responsible for coding and storing tonal patterns, and discusses evidence that shows the importance of cortical loops between auditory and frontal cortices for maintaining musical information in working memory and for the recognition of structural regularities in musical patterns that then lead to expectations [19]. In the tonal system, the emotional effects of the alteration of predictions include surprise. Irregular or unexpected chord types evoke skin conductivity responses, and the range of such emotional responses is related to the degree of surprise at the unexpected [20]. Therefore, the three cognitive aspects -expectation, prediction and anticipation- that occur when listening to tonal music are also related in generating musical emotions.

The different aspects of musical perception mentioned above have been investigated since the last century by means of different types of analysis and techniques based on electroencephalographic signals. In fact, it has been considered that the EEG frequency oscillations are crucial to link different elements and merge them into a coherent perception something relevant for the processing of music considered as a multifunctional stimulus [21]. There is a review of the neural bases of musical perception by Koelsch in which different signal and neuroimagen techniques are considered including some based on EEG signals [22].

2. Electroencephalographic (EEG) signals analysis during music perception

The first quantitative analyzes of brain activity using EEG signals date back to the 70s of the 20th century after the appearance of the fast Fourier transform that allowed the representation the EEG signal spectral power in different frequency bands. Specifically, electrical brain activity has been used in brain music research using univariate procedures, that is, analyzing the individual activity of EEG/MEG (magneto-EEG) /ERP (event related potentials) signals extracted from certain cortical brain areas/channels. Multivariate procedures have also been used where interdependence, correlation or synchronization between two or more channels are evaluated (see **Figure 1**).

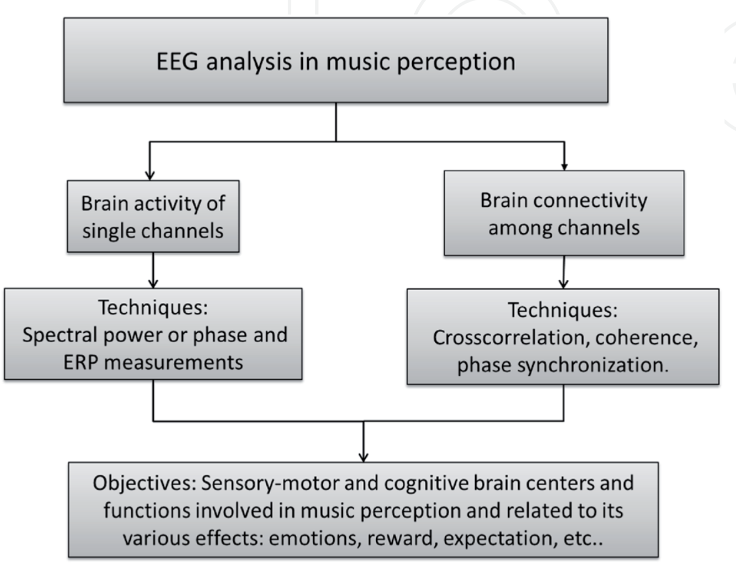

Figure 1.
Summary block diagram of the sections included in the EEG review.

2.1 Single channel analysis

2.1.1 General effects of listening music

EEG spectral power measurements from different cortical areas appear to indicate that musical processing may entail local and/or distant neural networks whose communication may affect different EEG frequency bands [23], such as changes in alpha power in the parieto/occipital and fronto/temporal regions [24], in beta power in the right parietal/temporal cortex [25], or in gamma power in the right parietal region [26]. Also, depending on the type of tonal music heard, different alterations in EEG spectral power occur in different bands [27, 28], located bilaterally in certain cortical areas [29].

2.1.2 EEG and musical emotions

Others studies have examined changes in spectral power in different EEG frequency bands at different brain regions as indicators of musical emotion processing. Concerning music emotions, in a review by Koelsh about music processing, it is reported that sounds are structured in time, space, and intensity, and that the perception of musical structures has emotional effects, which emerge from the music itself [20]. This occurs due to the processing of the intra-musical structure and the concept of musical tension. This author, gives an extensive explanation of the underlying structural factors that give rise to this concept and that nowadays we can observe/identify in many musical styles, including some as current as pop or rock. On the other hand, musical emotions are closely related to the concept of musical familiarization, it is worth highlighting the familiarization with the tonal system in which practically all the music that we perceive are immersed and that we have mentioned above. In this line with the image analysis technique (FMRI) familiar music appears to activate the limbic and allocortex systems, and areas associated with the reward mechanism: areas of the cingulate and frontal lobe, which in turn are not activated with unfamiliar music [5]. Also, brain areas in the right striatum and the orbitofrontal cortex have been related to specific emotions such as joy [30] and music that produces happiness increases activity in the striatum, cingulate, and posterior Heschl's gyri, while sad music activates the anterior hippocampus and the amygdala [31]. As well areas reported to be activated in the reward system in musical emotion are the ventral striatum, the insula, and the orbitofrontal cortex [32]. It is a fact that most people derive pleasure from music. Hearing especially expressive musical stimuli is reported to evoke emotion and neuronal activations relating to the reward system. It also produces an affective impact on the listener's brain, which can be altered by the subjects' musical training [33]. In other words, familiarity with music affects perception of it. Zatorre considers the evidence on how the mesolimbic striated system participates in reward, motivation, and pleasure in other domains [19]. In this line, several authors consider that the areas associated with emotions and reward is also involved in the emotional response to music [34, 35]. Limbic and paralympic areas respond to the dynamic expression of the musical interpretation of humans [33], specifically accord to tonal music, the cingulate subcallosal gyrus, the anterior prefrontal cingulate, the retrosplenial cortex, the hippocampus, and the anterior insula [36]. Therefore, through the analysis of neural networks, the literature suggests that the subcortical dopaminergic regions work in conjunction with important cortical regions to give rise to esthetic pleasure. These regions are related to the reward system, a set of structures that, through stimuli, in this case the auditory, provide humans with pleasure or can modify behaviors through positive reinforcement.

Several studies have analyzed increases or decreases in power in different bands when listening to pleasant or unpleasant music [26, 37]. Furthermore, it has been reported that pleasant as opposed to unpleasant music appears to increase the strength of the frontal midline theta band [38]. On the other hand, the hypothesis of asymmetry has been postulated, which proposes that positive and negative emotions are processed mainly in the left and right frontal brain regions, respectively [39]. Various measures of asymmetry, not necessarily in the frontal cortex, have been used to develop quantitative tools to assess emotions caused by visual [40] and musical [41] stimuli. It has also been reported lateralization of EEG activity in the alpha band due to opposite valences and different cortical topographies of lateralized alpha activation have been found for different musical patterns [28, 42]. In addition, theories about the cortical topography of musical emotion where the hemispheres would have specialized functions have been studied [43].

Another aspect that can modulate musical emotions is the musical familiarization which is normally closely linked to musical genres. Thus, bilateral frontal-temporal alteration in EEG spectral power has been reported while the subjects listened to musical extracts of different genres -structure-tonal or environmental origin- [29]. Moreover, the preferences of the subjects towards different musical extracts have also been studied, using characteristics extracted from the frequency-time analysis of the EEG signals. Once the listeners' familiarity with the excerpts was considered, the classification accuracy increased for familiar music [44]. Another point of interest is the musical concept of dissonance that has been widely discussed in the literature. Dissonance can be part of harmonic language creating musical tension and is in fact common in musical languages until the 20th century. But dissonance has also been studied as an isolated concept and related as an uncomfortable or unpleasant sound in some relation to noise. Thus, several centuries of the established use of dissonance to create unexpected and disconcerting moments is altered, the general EEG activity recorded in the left hippocampus has been reported to discriminate changes from consonance to dissonance [45], said of another as from the consonance of musical intervals to the dissonance of, for example, a major or minor second [46]. Also using PET images, it has been reported that the gradual variation from consonance to dissonance is accompanied by a gradual decrease in neuronal activity in some cortical areas (orbital and ventromedial prefrontal and subcallosal cingulate) but increases in other subcortical areas such as the parahippocampal and precuneus gyri [34]. Evidently, if we grow up and develop in a cultural environment of tonal music, our neuronal brain centers relating to emotion and musical cognition will adapt. For this reason, the sounds that make up a piece of music can be considered esthetically pleasing or not, depending on acoustic properties such as the use of harmony within that system [47] which can give pleasure to the listener or not.

2.1.3 EEG and music styles and experience

The style of music heard and its intramusical characteristics show different alterations in the spectral power of the EEG in different bands [27, 28]. On the other hand, there are research papers that reveal the impact of musical experience on musical brain processing. Thus, using MEG, it has been found signal oscillations phase blocking in gamma improved in expert musicians versus non-musicians during audition of dissonant and minor chords [48]. Moreover, in an EEG study carried out with expert musicians, in this case saxophone players playing in ensemble (quartet), found alterations in power potency in brain areas BA44/45 involved in semantic functions [49]. It therefore seems evident that musical experience is an important condition that intervenes in musical processing by the brain.

2.1.4 ERP analysis in brain musical processing

There is abundant literature in relation to musical syntax studies by using the EEG event related potentials (ERP) at different cortical areas. Thus, measuring negative/positive ERP peaks latencies syntactic language and harmony incongruities has been investigated [50] or whether language and music processing share processing resources: both appear to activate non-identical syntactic connections [51] and also has been reported how the two forms of music expectations –explicit and implicit that we explained above- manifest themselves with different neuronal correlations [52]. In ERP experiments where repetitive auditive stimulation was produced, early right anterior negativity (ERAN) has been found [53]. In unpredictability experiments where the position of the irregular chords is unknown, that is, when the musical expectation is broken in a sequence of sounds, the negativity usually has a longer latency and an anterior-temporal distribution (RATN) [54]. Additionally, analysis of incoming harmonic sequences elicited an early effect, taken as the magnetic equivalent of the ERAN (termed mERAN) localized in Broca's area and its right-hemisphere [1]. It has also been shown with this kind of analysis that when listening to melodies with irregular tones, the early right anterior negativity has a shorter maximum latency than that caused by irregular chord functions [55]. Therefore, a difference in musical perception in relation to musical expectation has been demonstrated through different paradigms of syntactic irregularities in chords or melodies. However, in other ERP studies on syntactic processing of music and language report shared neural resources, or what is the same, interactions between music-syntactic and language-syntactic processing [56, 57]. In this line, it should be noted that music is considered a kind of language, hence the interest in seeing if it reflects or shares neural resources with language. In this line, in an ERP work on musical perception [4] has been found that the processing of hierarchical structure with nested nonlocal dependencies -a mechanism fundamental for syntactic processing- is also activated during the perception of music. Therefore, it cannot yet be concluded that the musical syntactic process shares the bases of language but rather certain aspects. The different techniques inform us of various regions related to musical processing, although the exact differences in the syntactic treatment of language and music remain to be elucidated. In musicians' studies about musical phrasing, it is observed that the ERP shows a closure positive shift (CPS) in phrase boundaries -a positive shift in electrical activity at the closure of the phrase- [58–60] Also, the music CPS was observed in subjects of different cultural background listening both to music of their native and an alien culture. These findings add to the generality of the CPS as a marker for the processing of musical phrasing [61].

2.2 EEG channels interdependence measurements

The term functional connectivity (FC), is used to refer to the statistical interdependence between two neural signals (EEG or brain fMRI hemodynamic response signals) from anatomically different brain areas, a concept introduces by [62] and also defined as the temporal statistical correlation between spatially remote neurophysiological events between groups and dispersed neuronal areas [63]. Indeed, FC among different brain areas is important on brain processing since cognitive activity requires in general terms, that different brain regions not only co-act simultaneously, but there is also a functional interaction between them [64]. Furthermore, in the article by Núñez where FC was discussed in the human brain, it was reported that the cross interactions between local, regional and global networks are apparently responsible for a large part of the oscillatory EEG behavior [65]. In addition, this author report that combined EEG and high-resolution EEGs can provide different multiscale estimates of functional connectivity in healthy and diseased brains with measures such us covariance and coherence. In the field of musical perception, it has been reported that the analysis of the coherence or functional coupling between brain areas is of interest regarding the effect of music on the neurological mechanisms related to attention, cognition and emotion [66, 67].

2.2.1 EEG FC while listening to music

Authors have shown that musical perception requires the integration of different cortical areas [68]. This highly important concept has led researchers to use connectivity analysis [69–72] and network theory [73] to examine how different brain regions communicate while listening to music. In this line, related to musical experience, a study carried out in musicians shows synchronization of phase alterations in the alpha band between the right frontocentral cortical regions when musical expectation is violated [74]. Moreover, various EEG studies indicate that musical hearing produces changes in EEG coherence/synchronization in different bands [70, 74–77] and it has been considered of interest to study the configuration of the connectivity networks between different brain areas using modern graph theory that we will see later. Related to emotion, music-induced EEG neural correlations have been found at various frequencies on the prefrontal cortex and a set of functional connectivity patterns, defined by measures of coherence between channels, which are significantly different between the groups of emotional responses induced by music [78]. Recent studies show the integration of different cortical areas is required for musical perception and emotional processing [79] and that the magnitude of the cross-correlation values was significantly higher when we listened to unknown and coded music than when we listened to familiar music. These results are in agreement with those suggesting that the response to unfamiliar music is stronger than that of familiar music [80]. Furthermore, through joint EEG and fMRI spectral coherence measurements, a left cortical network has been identified that is involved with pleasant feelings associated with music [70]. These musical characteristics have been reported to produce greater sensory complexity of unexpected and puzzling situations or moments of unfulfilled expectations and higher levels of arousal [81].

2.2.2 Functional connectivity in musicians' experts

In general, it is known that the musician's brain has specific characteristics related to its functionality and structure [82–84]. There are numerous studies on this issue performed with signal analysis techniques (EEG and EMG) although most of them has been performed through BOLD neuroimagen fMRI signals. Thus, the size of the intranucal length of the precentral gyrus appears to be negatively correlated with age when their musical training starts has been found in keyboard players [85]. Furthermore, musically trained children show greater activation in areas related to executive functions like pre-supplementary motor area/supplementary motor area while performing a task [86]. In relation with FC in neuroimagen there is abundant literature carry out to expert musicians in a resting condition. Thus, musicians have been reported to exhibit stronger FC between the primary auditory cortex, the primary motor cortex [87] and in the right ventral premotor cortex. This is related to functional coupling between the motor and auditory areas and modulated as a function of musical training [88]. Also, in musicians, a significantly higher density of local functional connectivity has been shown in different brain regions [89], greater insular connectivity [90] and parietal opercular connectivity [91]. In musical interpretation condition, activity is reported in the auditory areas functionally connected with activity in the dorsal motor and pre-motor areas, whose connectivity is positively correlated with a good performance in interpretation [92]. Therefore, the musical experience seems to influence the functional connectivity (EEG) of some cortical areas. Indeed, in expert musicians, listening to extracts of tonal music modified the magnitudes of spectral coherence of the EEG in the alpha and beta bands with respect to non-musicians [93] and the phase synchronization of the gamma band, especially the left hemisphere [75]. Furthermore, the phase synchronization of expert musicians was greater than that of non-musicians listening to the same musical extract [76]. Another study reports that during the hearing of major and minor compositions by non-musicians, amateurs, and expert musicians, the EEG activity of the theta and gamma bands of the posterior cortical regions decreased with musical experience [94]. In this line, a study through the analysis of cortical images extracted from the ERPs and the responses of the subjects to the closure of complex musical stimuli (syntactic musical violations on which we have spoken in the univariate approach) reported important differences between groups, attributed to their different musical experience [95].

2.2.3 EEG during musical imagination in musicians

Finally, with regard to the work carried out professional musicians by analyzing signals electroencephalography (EEG) in Imagined interpretation is reported that this task proved to induce activation of the alpha band significantly stronger than the simple musical perception [96]. In this sense, it is known that musical images are a mental representation of music, as well as that its underlying mechanisms of perception are active and committed to it [97]. It is known that musical learning shows certain aspects of behavior that can be observed in the notable acquisition of skills of musicians, which is why the benefits of imagined interpretation in the learning of motor skills is a reason for interest and discussion among authors [98]. The imagined interpretation and the real interpretation or performance are correlated and are believed to activate similar neural structures [99]. There are some characteristics of the imagined interpretation, which we can call simulated action or mental rehearsal, that reveal a close relationship between it and motor action, specifically it has been pointed out that the synchronization patterns of both processes are similar [100] as well as that the changes in corticospinal excitability involve the same muscles in both conditions [101]. Consistent with this hypothesis, fMRI studies investigating imagined interpretation in paradigms where subjects execute hand and finger movements [102] have demonstrated activation of the supplemental motor area (SMA), the premotor cortex, the cerebellum and the primary motor cortex. Therefore, we can say that according to these studies, imagined performance and real performance share certain common characteristics reflected in the cerebral cortex and in the musculature. On the other hand, also in the fMRI technique, a study carried out on piano students [103] in which imagination and interpretation tasks were analyzed, found activations of the frontoparietal-bilateral network that includes the areas premotor, precuneus, and medial part of Brodmann's area (BA) 40 during both tasks. Other areas that appear to be involved in the imagined interpretation are the superior parietal and ventrolateral/dorsolateral frontal areas [104]. In another line of work, the activity of the EEG potentials was investigated in violinist players [105], finding that the bilateral frontal opercular regions are crucial both in the preparation and during the performance of music and during the imagination of the same in agreement with some previously commented fRMI results. The authors suggest that this effect is due to "mirror neurons" that are at the service of the observation or imagination of one's own performance [106]. It has been also observed the activation of different motor areas that were not the same for interpretation as for imagination. Functional interactions between the temporal cortex and the frontal cortex have been found to improve during musical imagination [107]. For all this, it seems that the imagined interpretation is capable of activating different areas of the cerebral cortex such as those belonging to the motor system, the SMA, the auditory cortex.

With the fMRI technique a study observes that, compared to the resting condition, the imagined interpretation increased in extended regions of the brain the FC of the supplementary motor area (SMA), including the sensorimotor cortices, the parietal cortex, the temporal cortex posterior cortex, occipital cortex and inferior and dorsolateral prefrontal cortex, this is related to cognitive control, motor planning and syntactic processing [108]. Increased connectivity with sensorimotor cortices is believed to be potentially involved with planning thought in motor programs. These authors also consider that the reconfiguration of the SMA network reflects the multimodal integration required for imagined musical interpretation and real interpretation/performance, as well as they propose that the SMA network build "the internal representation of musical performance" by integrating multimodal information required for the presentation [108]. The same authors, in a later study with the same task, found that imagined music performance increased the functional connectivity of the angular gyrus with different regions, which attributes a role to this region in the imagined performance [109]. Therefore, it is observed that the FC in the interpretation and imagined interpretation shares the configuration of networks that are involved in the performance process, which is different from neural activity, and therefore is able to connect in the imagined interpretation as in the real one. If the imagined interpretation is capable of activating the connections between brain regions that occur during interpretation, this is a way to study its possibilities from the perspective of imagination interpretation.

2.2.4 EEG FC using graph metric

In the graph theory context EEG channels are taken as the graph nodes and connectivity values between them as edges. The usefulness of this metric has been reported to be of interest in brain neural network research to evidence changes in its topological structure. Two measures are used to define different types of neural network organization: one involves the nodal groups, the clustering coefficient (C) and the other the magnitude of the length of the path between nodes, length of the characteristic path L. For a given node, C measures the tendency to link from neighboring nodes, reflecting the extent of the local domain; while L is associated with the ability to integrate global information and, therefore, with the readiness for communication within the brain [110, 111]. Depending on the relative magnitudes of C and L, different levels of topological organization of a cortical brain network are defined. Thus, a network is considered "regular" when a high value of C and L is obtained from its graph representation, while a network is considered "random" when a low value of C and L is found. Between both types of network, the type called small world (SW) is defined when a graph has a high C magnitude and a low L magnitude. Consequently, SW neural networks are said to have a high level of local information distribution together with a high efficiency for global transfer information, both properties of great relevance for the dynamics of complex brain processing [110, 111]. For determining the SW level of a network NN, the C and L magnitudes are normalized with regard to the mean of a number ($N = 100$) of random networks having the same number of nodes, edges, and degree distributions as the network NN [112]. A network with approximately equal L and larger C than matched random networks (i.e., normalized $L \sim 1$ and normalized $C > 1$) is said to be a SW network. In the context of the musical perception, listening to Chinese music (Guquin music excerpts versus silence and noise) in non-specialist subjects has been reported to produce an increase in functional connectivity (EEG phase coherence) in the alpha band, an improvement in cortical network organization of small world [73] and also a tendency to the random organization of the network as well -when a phase delay index is used that indicates a tendency to a more efficient but less economical architecture during musical listening [113]. Therefore, musical hearing somehow affects the topological structure of brain networks.

3. Conclusions

Since computational algorithms for signal analysis introduction in Biomedicine, different methods of cortical electrical signal analysis (EEG) have been used to study the neural multiple processes involved in musical perception. Applications range since from music recognition and its brain processing to its cognitive and emotional effects. In this broad chain of neural events, many brain centers and functions (central and peripheral) intervene. The participation and importance of some of these, by using different techniques of analysis and processing of EEG signals (including MEG and ERP cortical recordings) have been investigated along the time. In the review, the most interesting results appeared in the literature on the subject have been reported. Among them are those that study aspects such as musical syntax (its comparison with language), the differences between styles including consonances and dissonances, musical expectation and the nature of the different emotions (including rewards) produced by music. From the review carried out it is concluded that the analysis of cortical electrical signals (EEG, MEG, ERP) constitutes, mainly due to its high temporal resolution, a useful methodology for the study of many issues concerning the music-brain interaction.

Conflict of interest

The authors declare no conflict of interest.

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