Alpha EEG Frontal Asymmetries during Audiovisual Perception in Cochlear Implant Users

A Study with Bilateral and Unilateral Young Users

A. G. Maglione[1]; A. Scorpecci[2]; P. Malerba[3]; P. Marsella[2]; S. Giannantonio[2]; A. Colosimo[1]; F. Babiloni[4,5]; G. Vecchiato[6]

[1]Department of Anatomy, Histology, Forensic Medicine and Orthopedics, Sapienza University of Rome, Rome, Italy;
[2]Centro Impianti Cocleari, IRCCS Ospedale Pediatrico „Bambino Gesù", Rome, Italy;
[3]Cochlear Italia s.r.l., Bologna, Italy;
[4]Department of Molecular Medicine, Sapienza University of Rome, Rome, Italy;
[5]IRCCS Fondazione Santa Lucia, Rome, Italy;
[6]Department of Physiology and Pharmacology, Sapienza University of Rome, Rome, Italy

Keywords
Electroencephalography, frontal asymmetry, cochlear implant, young users

Summary

Objectives: The aim of the present study is to investigate the variations of the electroencephalographic (EEG) alpha rhythm in order to measure the appreciation of bilateral and unilateral young cochlear implant users during the observation of a musical cartoon. The cartoon has been modified for the generation of three experimental conditions: one with the original audio, another one with a distorted sound and, finally, a mute version.

Methods: The EEG data have been recorded during the observation of the cartoons in the three experimental conditions. The frontal alpha EEG imbalance has been calculated as a measure of motivation and pleasantness to be compared across experimental populations and conditions.

Results: The EEG frontal imbalance of the alpha rhythm showed significant variations during the perception of the different cartoons. In particular, the pattern of activation of normal-hearing children is very similar to the one elicited by the bilateral implanted patients. On the other hand, results related to the unilateral subjects do not present significant variations of the imbalance index across the three cartoons.

Conclusion: The presented results suggest that the unilateral patients could not appreciate the difference in the audio format as well as bilaterally implanted and normal hearing subjects. The frontal alpha EEG imbalance is a useful tool to detect the differences in the appreciation of audiovisual stimuli in cochlear implant patients.

1. Introduction

Most cochlear implant recipients report difficulties with music perception even after many years of implant use [1–3]. This seems due to the fact that the signal processing of cochlear implants provides only limited spectral and temporal information, besides producing a much narrower dynamic range than acoustic hearing [3, 4]. Limitations in the appreciation of the timbre and pitch of musical tone sequences have been reported in implanted patients when compared with normal hearing subjects [5– 8]. Like adults, prelingually deaf children with cochlear implants show poorer pitch and melody discrimination skills than their normal-hearing (NH) peers [9–12]. Nonetheless, they seem to enjoy music listening and are often engaged in musical activities both in school and during their leisure time, possibly because they have no musical memory as a reference. Such an apparent inconsistency suggests that besides discrimination and identification skills, the emotional/affective element is important in the experience of music listening, being the predominant factor underlying the overall enjoyment of music by young cochlear implant users [13].

One of the main problems related to the perception of music is the assessment of the intrinsic pleasure derived from listening. The self-reported psychological scales are often inadequate to convey precise information about the cerebral processing associated with the pleasantness of the perceived music. However, in these last years, objective measures of the cerebral activity have been put in strict relation with the pleasantness of an individual perception [14].

In fact, indirect variables of emotional processing could be identified by tracking variations of the activity of specific anatomical structures linked to the emotional processing activity in humans, such as the pre- and frontal cortex (PFC and FC, respectively) [15–18]. The role of the PFC in emotion regulation is testified by the large

Patient	Gender	Etiology	Age at 1st CI (mo)	Side of 1st CI	Age at 2nd CI (mo)	Side of 2nd CI	Processor
1	F	Unknown	50	L	87	R	Freedom/CP810
2	F	Unknown	17	R	52	L	CP810
3	F	Unknown	89	R	–	–	CP810
4	F	Unknown	21	R	–	–	Freedom
5	F	Unknown	27	R	36	L	CP810
6	M	Prematurity	21	R	67	L	CP810
7	F	Unknown	21	R	–	–	CP810

amount of experimental evidence tracing the neural origins of the approach-withdrawal theory and the role of the PFC in emotions [19–26]. Specifically, the activity of the frontal cortex is lateralized for behaviours of approach and inhibition [27]. Thus, an activity increase across the left frontal regions is correlated with motivation and approach while, asymmetrically, the right frontal areas play an important role in the modulation of withdrawal tendencies.

The main goal of the present study is to investigate deaf and NH children's appreciation of cartoons through an analysis of the frontal imbalance of the electroencephalographic (EEG) alpha rhythm. Specifically, the variations of the asymmetrical pattern of activation were compared across unilateral and bilateral CI users (UCI and BCI, respectively) and NH children, as the subjects were watching different versions of audiovisual stimuli. Hence, we created three versions of the same musical cartoon: one with the original audio (Normal), one characterized by a reversed audio track (Distort), and one without music (Mute). The EEG data sets were compared in terms of frontal spectral imbalance for each population and for each of the three experimental conditions. The methodological framework and the achieved results will be shown in the next sections.

2. Methods

2.1 Subjects

Seven children have been recruited for the cochlear implant (UCI) group (5.07 ± 3.03 ys), four of them underwent the sequential implant (BCI). Personal and clinical data have been summarized in ►Table 1.

In the month before the EEG registration, all patients had their cochlear implant controlled and mapped with a mixed behavioral and objective method. In addition, they received a warble-tone free-field audiometry and a comprehensive speech perception and recognition assessment. All of them had all CI electrodes active with normal impedance levels, were using an ACE strategy, a 900 pps stimulation rate and an ADRO pre-processing algorithm. Informed consent was obtained from the parents of all subjects after explanation of the study. On the day the registration was performed, patients received a warble-tone free-field audiometry and a speech audiometry to make sure their hearing and speech recognition abilities were good.

The NH group is composed by six aged matched (7.67 ± 5.56 ys; Student's t = 1.18, p = 0.26) young children with normal hearing.

All procedures were approved by the ethics committee of the IRCCS Fondazione Santa Lucia (Rome, Italy).

2.2 Experimental Design and EEG Signal Processing

The musical cartoon was composed by a piece of 4-minute length of the Fantasia movie (Walt Disney, 1940) in which the original music of D. Paradisi was included. Three versions of this piece were proposed: the cartoon with its original audio (Normal); the original video and a distorted audio (Distort); the original video and no sound (Mute). The Distort condition was obtained by reversing the flow of the audio of the Normal stimulus: it causes a linear change of the pitch and the interval when compared with the original music. Professional software for audio manipulation was used (Audacity, 2.0.4 version). The acoustic pressure, provided for all the 4 minutes of stimulation, was identical for Normal and Distort conditions. Randomization of the stimuli was made to remove possible sequence confounding effect. In order to provide clues to the researcher about children's attention during the observation of the cartoons, patients were interviewed at the end of each piece to assess attention and memory during the videoclip sequence.

During the EEG data acquisition, all subjects were comfortably seated on a chair, in an electrically-shielded, dimly-lit room. A 64-channel EEG system (BEPlus, EBNeuro spa, Italy) at a sampling rate of 256 Hz was used to record scalp potentials by means of an electrode cap with 15 channels located according to the 10–20 international system. Since alpha activity in the frontal areas has been related to the phenomena we aim to investigate [27], we used the left (AF7, F3) and right (AF8, F4) frontal and prefrontal electrodes to compute the following analysis in the frequency domain. The EEG signals have been band pass filtered at 1–45 Hz and depurated of ocular artefacts by employing the Independent Component Analysis (ICA). The recording sessions have been segmented in one-second trials, in order to analyze the EEG activity elicited during the Normal, Distort and Mute conditions. Later, a semi-automatic procedure has been adopted to reject trials presenting muscular artifacts. Only artifact-free trials have been considered for the following analysis. As reported in the literature [28], Individual Alpha Frequency (IAF) has been calculated
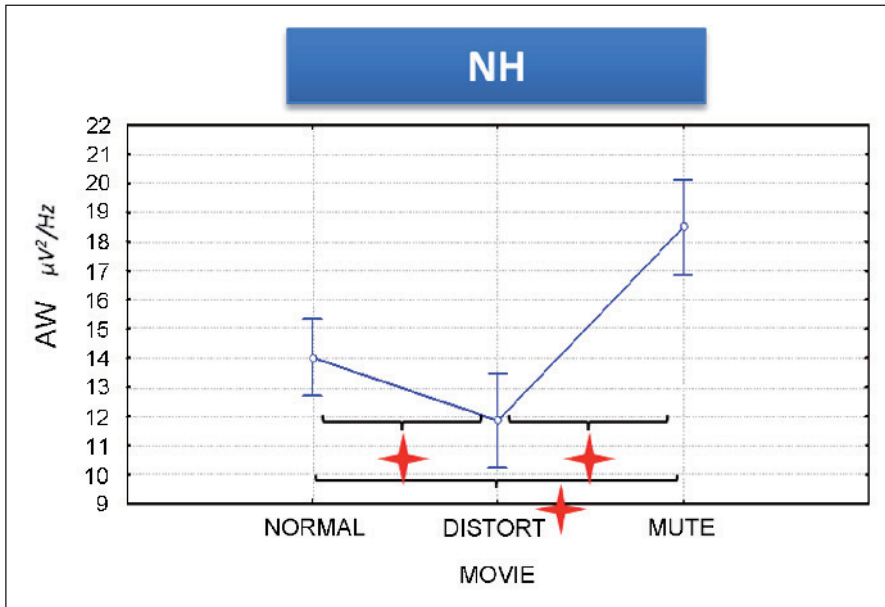
Figure 1 Average and standard deviation of the Approach/Withdrawal index across the different experimental conditions of the factor MOVIE (Normal, Distort and Mute) for the population of normal hearing subjects (NH). Duncan test reveals a statistical significant difference across all the different levels of MOVIE factor at the 5% significance level as illustrated by the red cross.

for each subject in order to define the investigated alpha band. Such band is in the following reported as IAF + x, where IAF is the Individual Alpha Frequency, in Hertz, and x is an integer displacement in the frequency domain which is used to define the alpha band as (IAF-4, IAF + 2), i.e. the frequency band between IAF-4 and IAF + 2 Hz. The estimation of the Power Spectral Density (PSD) in the alpha band has been performed according to the Welch method [29].

In order to investigate the cerebral frontal asymmetry in the alpha band, we calculated the following spectral imbalance of Approach/Withdrawal:

$$AW = PSD_R - PSD_L \qquad (1)$$

where *PSD* stands for the average spectral activity calculated among right and left electrodes, respectively. According to the EEG frontal asymmetry theory [15, 27, 30], this index has been defined such that positive values are related to left (right) alpha de-synchronization (synchronization). Positive (negative) values of this index correlate with the perception of approaching (withdrawing) stimuli. The spectral imbalance has been calculated for

all the recorded subjects in the three experimental conditions, as reported in the following paragraph.

The details of the experimental design and the whole signal processing performed on the recorded data set have been presented in previous works [31–34], and are not mentioned here due to space limitations.

The statistical analysis has been performed by computing a repeated-measures ANOVA, one for each population NH, BCI and UCI, with factor "MOVIE" (Normal, Distort, Mute) at α = 0.05, for assessing variations of the frontal imbalance index among the proposed audiovisual stimuli. Duncan test has been performed to retrieve differences among pairwise comparisons.

3. Results

The ANOVAs returned significant differences related to the factor MOVIE for the NH and BCI populations. Averages and standard values are represented for each population and for each experimental condition in the following pictures. ▶Figure 1 shows the average AW index for the NH group across the three kinds of audiovisual

stimulation, i.e. Normal, Distort and Mute. Particularly, the statistical test highlighted significant differences for the factor "MOVIE" (p < 0.01) and for all the pairwise comparisons (Normal vs Distort, p < 0.05; Normal vs Mute, p < 0.01; Distort vs Mute, p < 0.01; Duncan's test). Overall, the results present a higher AW value for the Mute condition , which is followed by the Normal version of the cartoon and finally by the Distort one.

Pretty similar results can be observed for the BCI population (▶Figure 2). In fact, even the BCI users showed lower values of AW related to the observation of the Distorted cartoon as compared to both the Mute movie and the Normal one. However, only in the former case the difference was significant (p < 0.01). A different pattern of cerebral activation has been found for the UCI population: as illustrated by ▶Figure 3, in this category the AW has no significant modulation across experimental conditions (p > 0.05).

Overall, the study results indicate a significant modulation of the AW index across audiovisual stimuli which is similar for the NH and BCI groups. In particular, the frontal imbalance is able to discriminate the appreciation of the proposed audiovisual stimuli returning higher cerebral values for the Normal condition when compared with the Distort one. The highest values of the AW index are related to the Mute condition.

4. Conclusions

The present study presents an objective method to estimate the appreciation of cartoons in groups of bilateral and uniateral cochlear implant recipients and normal-hearing subjects. The analysis of the alpha EEG rhythm in terms of frontal imbalance index, performed in the present study, suggests that the pattern of modulation of such cerebral variable is in agreement with the EEG frontal asymmetry theory [27]. Similar findings have also been observed in previous studies performed on NH adult subjects watching TV commercials [30, 35, 36]. In the present study, for the NH subjects and the BCI users, the lowest values of the frontal imbalance index are related to

the observation of the cartoon in its distort version which therefore can be considered as the less approaching. Not surprisingly, the observation of the normal version of the cartoon returned higher values of the imbalance index, although the highest are related to the mute stimulation. This result suggests that NH and BCI children are able to appreciate the difference between the normal and mute version of the cartoon but they seem to prefer the mute videoclip. Taking into account that the audio stimulation is related to a piece of classical music, we hypothesize the enrolled children are overall more interested and attracted by the visual stimulus instead of the combination of audio and video, maybe because the music was difficult to interpret.

Moreover, the presented results indicate a substantial difference of frontal/prefrontal cortex activation pattern between BCI and UCI users, BCI users showing a pattern which is more similar to the one observed in NH subjects. A possible interpretation of this finding is that in UCI users the perception of the music, or quality of sound, is not sufficiently contrasted, among the conditions, to elicit an asymmetrical power spectrum response in the alpha band. Possibly, the application of a second CI allows a more comprehensive stimulation of cortical areas in both hemispheres, and thus a cortical activation pattern which better corresponds to the withdrawal/approach model. Therefore, a UCI could determine a defective appreciation of music pleasantness, although such a conjecture needs to be supported by a more robust experimental sample.

Overall, the results of this study prove the usefulness of the EEG technique to address the issue of music perception and its pleasantness in cochlear implant patients. Despite the limited number of subjects enrolled in the present experiment, and the subsequently low statistical power, these results show the capability of the approach/withdrawal index to estimate the appreciation of a movie in cochlear implant children. Future developments of the research will estimate functional connectivity patterns and indices derived from the graph theory [37–39] to provide additional quantitative indices describing the investigated phenomena.
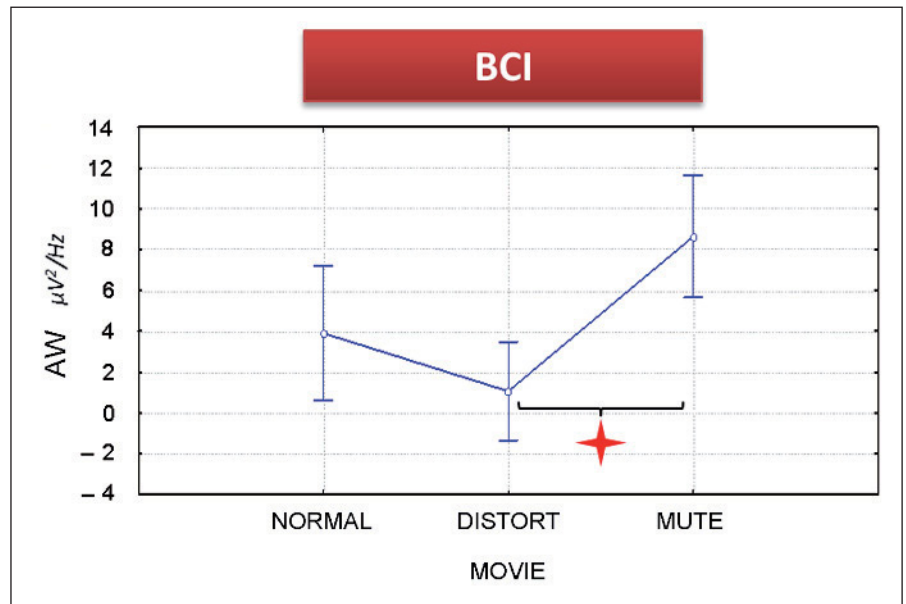
Figure 2   Average and standard deviation of the Approach/Withdrawal index across the different experimental conditions of the factor MOVIE (Normal, Distort and Mute) for the population of bilateral cochlear implant users (BCI). Duncan test reveals a statistical significant difference between Mute and Distort levels of MOVIE factor at the 5% significance level as illustrated by the red cross.
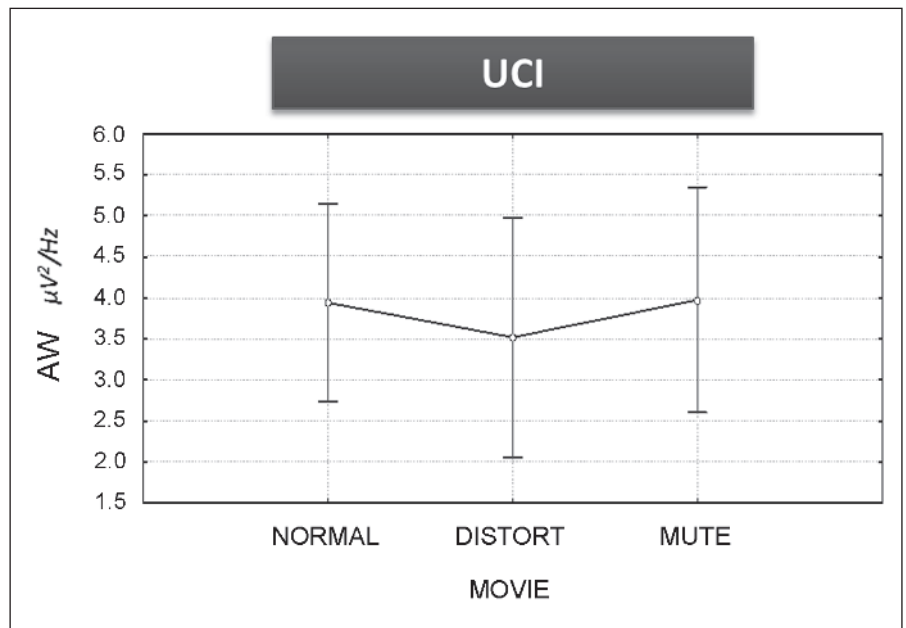
Figure 3   Average and standard deviation of the Approach/Withdrawal index across the different experimental conditions of the factor MOVIE (Normal, Distort and Mute) for the population of unilateral cochlear implanted users (UCI). No statistical differences.

References

1. Gfeller K, Christ A, Knutson JF, Witt S, Murray KT, Tyler RS. Musical backgrounds, listening habits, and aesthetic enjoyment of adult cochlear implant recipients. J Am Acad Audiol 2000; 11: 390–406.
2. McDermott HJ. Music perception with cochlear implants: a review. Trends Amplif 2004; 8: 49–82.
3. Veekmans K, Ressel L, Mueller J, Vischer M, Brockmeier SJ. Comparison of music perception in bilateral and unilateral cochlear implant users and normalhearing subjects. Audiol Neurootol 2009; 14: 315–326.
4. Galvin JJI, Fu QJ, Nogaki G. Melodic contour identification by cochlear implant listeners. Ear Hear 2007; 28: 302–319.
5. Gfeller K, Jiang D, Oleson JJ, Driscoll V, Olszewski C, Knutson JF, Turner C, Gantz B. The effects of musical and linguistic components in recognition of real-world musical excerpts by cochlear implant recipients and normal-hearing adults. J Music Ther 2012; 49 (1): 68–101.
6. Gfeller K, Turner C, Oleson J, Zhang X, Gantz B, Froman R, Olszewski C. Accuracy of cochlear implant recipients on pitch perception, melody recognition and speech reception in noise. Ear and Hearing 2007; 28 (3): 412.
7. Kong Y, Cruz R, Jones J, Zeng F. Music perception with temporal cues in acoustic and electric hearing. Ear and Hearing 2004; 25 (2): 173–185.
8. Gfeller K, Olszewski C, Rychener M, Sena K, Knutson JF, Witt S, et al. Recognition of "real-world" musical excerpts by cochlear implant recipients and normal-hearing adults. Ear Hear 2005; 26: 237–250.
9. Looi V, Radford CJ. A comparison of the speech recognition and pitch ranking abilities of children using a unilateral cochlear implant, bimodal stimulation or bilateral hearing aids. Int J Ped Otorhinolaryngol 2011; 75: 472–482.
10. Scorpecci A, Zagari F, Mari G, Giannantonio S, D'Alatri L, Di Nardo W, et al. Investigation on the music perception skills of Italian children with cochlear implants. Int J Pediatr Otorhinolaryngol 2012; 76: 1507–1514.
11. Mitani C, Nakata T, Trehub SE, Kanda Y, Kumagami H, Takasaki K, et al. Music recognition, music listening, and word recognition by deaf children with cochlear implants. Ear Hear 2007; 28: 29S–33S.
12. Vongpaisal T, Trehub SE, Schellenberg EG. Song recognition by children and adolescents with cochlear implants. J Speech Lang Hear Res 2006; 49: 1091–1103.
13. Hopyan T, Gordon KA, Papsin BC. Identifying emotions in music through electrical hearing in deaf children using cochlear implants. Cochlear Implants Int 2011; 12: 21–26.
14. Mauss IB, Robinson MD. Measures of emotion: A review. Cogn Emot 2009; 23 (2): 209–237.
15. Davidson RJ. Anxiety and affective style: role of prefrontal cortex and amygdala. Biol Psychiatry 2002; 51 (1): 68–80.
16. Davidson RJ. Affective style, psychopathology, and resilience: brain mechanisms and plasticity. Am Psychologist 2000; 55 (11): 1196–1214.
17. Davidson RJ. Neuropsychological perspectives on affective styles and their cognitive consequences. In: Dalgleish T, Power MJ, editors. Handbook of cognition and emotion. New York: Wiley; 1999. pp 103–123.
18. Davidson RJ, Irwin W. The functional neuroanatomy of emotion and affective style. Trends Cogn Sci 1999; 3 (1): 11–21.
19. Heller AS, Lapate RC, Mayer K, Davidson RJ. The Face of Negative Affect: Trial-by-Trial Corrugator Responses to Negative Pictures Are Positively Associated with Amygdala and Negatively Associated with Ventromedial Prefrontal Cortex Activity. J Cogn Neurosci 2014; 26 (9): 2102–2110.
20. Shenhav A, Greene JD. Integrative moral judgment: dissociating the roles of the amygdala and ventromedial prefrontal cortex. J Neurosci 2014; 34 (13): 4741–4749.
21. Vecchiato G, Astolfi L, De Vico Fallani F, Toppi J, Aloise F, Bez F, Wei D, Kong W, Dai J, Cincotti F, Mattia D, Babiloni F. On the use of EEG or MEG brain imaging tools in neuromarketing research. Comput Intell Neurosci 2011; 2011: 643489. doi: 10.1155/2011/643489.
22. Motzkin JC, Philippi CL, Wolf RC, Baskaya MK, Koenigs M. Ventromedial Prefrontal Cortex Is Critical for the Regulation of Amygdala Activity in Humans. Biol Psychiatry 2015; 77 (3): 276–284.
23. Hooker CI, Benson TL, Gyurak A, Yin H, Tully LM, Lincoln SH. Neural activity to positive expressions predicts daily experience of schizophrenia-spectrum symptoms in adults with high social anhedonia. J Abnorm Psychol 2014; 123 (1): 190–204.
24. Lin CH, Tuan HP, Chiu YC. Medial frontal activity in brand-loyal consumers: a behavior and near-infrared ray study. J Neurosci Psychol Econ 2010; 3: 59–73.
25. Li X, Lu ZL, D'argembeau A, Ng M., Bechara A. The Iowa gambling task in fMRI images. Hum Brain Mapp 2010; 31: 410–423.
26. Santos JP, Seixas D, Brandão S, Moutinho L. Investigating the role of the ventromedial prefrontal cortex (vmPFC) in the assessment of brands. Frontiers in Neuroscience 2011, 5 (77).
27. Davidson RJ. What does the prefrontal cortex "do" in affect: perspectives on frontal EEG asymmetry research. Biol Psychol 2004; 67 (1–2): 219–233.
28. Klimesch W. EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. Brain Res Brain Res Rev 1999; 29: 169–195.
29. Welch PD. The Use of Fast Fourier Transform for the Estimation of Power Spectra: A Method Based on Time Averaging Over Short, Modified Periodograms. IEEE Trans Audio Electroacoustics 1967; 15: 70–73.
30. Vecchiato G, Cherubino P, Maglione AG, Herrero MT, Marinozzi F, Bini F, Trettel A, Babiloni F. How to Measure Cerebral Correlates of Emotions in Marketing Relevant Tasks. Cogn Comput 2014. doi: 10.1007/s12559-014-9304-x.
31. Marsella P, Scorpecci A, Vecchiato G, Maglione AG, Colosimo A, Babiloni F. Neuroelectrical imaging investigation of cortical activity during listening to music in prelingually deaf children with cochlear implants. Int J Pediatr Otorhinolaryngol 2014; 78 (5): 737–743. doi: 10.1016/j.ijporl.2014.01.030.
32. Astolfi L, Vecchiato G, De Vico Fallani F, Salinari S, Cincotti F, Aloise F, Mattia D, Marciani MG, Bianchi L, Soranzo R, Babiloni F. The track of brain activity during the observation of TV commercials with the high-resolution EEG technology. Comput Intell Neurosci 2009: 652078. doi: 10.1155/2009/652078.
33. Maglione AG, Vecchiato G, Leone CA, Grassia R, Mosca F, Colosimo A, Malerba P, Babiloni F. Different perception of musical stimuli in patients with monolateral and bilateral cochlear implants. Comput Math Methods Med 2014; 2014: 876290. doi: 10.1155/2014/876290.
34. Vecchiato G, Maglione AG, Scorpecci A, Malerba P, Marsella P, Di Francesco G, Vitiello S, Colosimo A, Babiloni F. EEG frontal asymmetry related to pleasantness of music perception in healthy children and cochlear implanted users. Conf Proc IEEE Eng Med Biol Soc 2012; 2012: 4740–4713. doi: 10.1109/EMBC.2012.6347026.
35. Vecchiato G, Toppi J, Astolfi L, De Vico Fallani F, Cincotti F, Mattia D, Bez F, Babiloni F. Spectral EEG frontal asymmetries correlate with the experienced pleasantness of TV commercial advertisements. Med Biol Eng Comput 2011; 49 (5): 579–583.
36. Vecchiato G, Kong W, Maglione AG, Wei D. Understanding the Impact of TV Commercials: Electrical Neuroimaging. IEEE Pulse 2012; 3 (3): 42–47.
37. Toppi J, De Vico Fallani F, Vecchiato G, Maglione AG, Cincotti F, Mattia D, Salinari S, Babiloni F, Astolfi L. How the Statistical Validation of Functional Connectivity Patterns Can Prevent Erroneous Definition of Small-World Properties of a Brain Connectivity Network. Computational and Mathematical Methods in Medicine vol 2012, Article ID 130985, 13 pages, doi:10.1155/2012/130985.
38. Toppi J, F. Babiloni, G. Vecchiato, Cincotti F, De Vico Fallani F, Mattia D, Salinari S, Astolfi L. Testing the asymptotic statistic for the assessment of the significance of partial directed coherence connectivity patterns. Conf Proc IEEE Eng Med Biol Soc 2011. pp 5016–5019. doi: 10.1109/IEMBS.2011.6091243.
39. De Vico Fallani F, Costa Lda F, Rodriguez FA, Astolfi L, Vecchiato G, Toppi J, Borghini G, Cincotti F, Mattia D, Salinari S, Isabella R, Babiloni F. A graph-theoretical approach in brain functional networks. Possible implications in EEG studies. Nonlinear Biomed Phys 2010; 4 (Suppl 1): S8. doi: 10.1186/1753-4631-4-S1-S8.