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Mozart's music between predictability and surprise: results of an experimental research based on electroencephalography, entropy and Hurst exponent

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Abstract

OBJECTIVE: The main goal of our work was to simultaneously study musical and electroencephalogram (EEG) signal while listening to Mozart's K448 Sonata, a piece known for the "Mozart effect", with the aim to better understand the reasons of beneficial effect of music on the brain.
DESIGN: To this purpose, in a small sample of young healthy subjects, we examined the EEG correlates of modifications of brain activity, also applying the concepts of entropy and Hurst exponent H to K448 Sonata compared to a selection of Mozart's excerpts, so that to expose the peculiar characteristics of this compositions in terms of predictability and surprise for the listener
RESULTS: Spectral analysis showed that mean beta rhythm significantly grew during the listening to K448, and that this effect remaining immediately after, but to a lesser extent. Furthermore, we found that maximum values of entropy and lower values of H were reached by K448 compared to a selection of Mozart's pieces.
CONCLUSIONS: The results support the hypothesis of an overall effect of activation of the superior cortical functions during listening to K448, and immediately afterwards, in healthy young adults, and of a greater complexity of this sonata compared to a selection of Mozart's pieces.

Introduction

Music is a peculiar arrangement of notes of different acoustic frequencies (pitches) in succession (melody), in combination (harmony), and spaced by temporal succession (rhythm) (Hsü KJ & Hsü AJ 1990). Through music we could learn much about the human brain, being music an effective means of accessing and/ or stimulating specific cerebral circuits (Kučikienė & Praninskienė 2018; Trimble & Hesdorffer 2017). The correlation of music with the brain state may be reflected in modifications of neuronal electrical activity recorded by electroencephalogram (EEG) (Rideout BE & Laubach 1996); in particular the study of beta and theta rhythms may help in better understanding the effects of music on cognition and attention. The main goal of our work was to study simultaneously the EEG signal, while listening to Mozart's music, and the musical signal aimed to better explain the reasons of beneficial effect of music on the brain. Accordingly, by using an experimental research protocol based on EEG, we have mapped the brain activities in eight healthy young adults, after brain stimulation provided by listening to Mozart's K448 Sonata. The present pilot study was then made with two main purposes:

- to examine the EEG correlates of modifications of brain activity, during and after 8 min listening to K448 (first movement of the sonata) compared to the baseline,
- to apply the concepts of entropy (Shannon 1948), and Hurst exponent (Hurst 1951) to K448, compared to a selection of Mozart's excerpts, to estimate the balance between predictability and surprise for the beholder, as possible reason of the beneficial effect on the brain. Moreover, entropy profiles were compared to the ratio of alpha to beta rhythms of EEG signals. Finally, Hurst analysis was also applied to EEG channels to further investigate the effect of listening to K448.

The choice of K448 Sonata is related to the so-called "Mozart Effect". Rauscher *et al.* (1993; 1995) introduced the "Mozart Effect" in the early 1990s, showing that K448, in particular the first movement, was able to improve the brain capacity for spatial-temporal reasoning in healthy young individuals, although for a limited time. Numerous studies were performed to check whether (Rideout *et al.* 1998; Hetland 2000; Picazio *et al.* 2013) or not (Chabris 1999) the "Mozart Effect" exists. The original "Mozart Effect" researchers based their rationale on the trion model of the cerebral cortex. The trion model, developed by Leng *et al.* (1992), showed that similar neural firings patterns occur when listening to music and performing spatial tasks. Leng and co-workers hypothesized that listening to certain types of complex music may "warm-up" neural transmitters inside the cerebral cortex and thereby improve spatial performance. Furthermore, this particular sonata has proven effective in reducing seizure activity in patients even in coma, with status epilepticus or with periodic lateralized epileptiform discharges (Hughes *et al.* 1998), recently also in a randomized controlled pilot study in children (Paprad *et al.* 2020).

Materials and methods

EEG experimental protocol and signal processing

The studies involving human participants are reviewed and approved by the Ethics Commission of the University of Pisa. The research was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. The participants provided their written informed consent to participate in this protocol.

EEG signals were recorded during a standardized experimental protocol conducted at the Department of Clinic and Experimental Medicine (Bonanni *et al.* 2006). Six female and two male subjects, 21–29 years old, right-handed, with no musical training were involved in the study.

When the subject entered the laboratory, he/she was asked to sit on a chair and rested for at least 5 min. The brain signals were recorded by using a cap with 19 electrodes, positioned according to the 10-20 International System (Silverman 1963). Recording length was approximately 30 min, using an electroencephalography system (EB Neuro S.p.A., Firenze) for signal acquisition and recording. Impedance was kept below 5kOhm for all electrodes, and the sample rate was set at 256 Hz. Recording was performed by an expert EEG technician, with subjects with closed eyes, seated on a comfortable armchair, in a quiet room. EEG signals were registered at baseline (8 min), while listening to the first movement of the K448 Sonata (8:24 min, played by Murray Perahia & Radu Lupu), and after the listening (8 min). The musical stimulus was transmitted via earphones, in convenient loudness. The EEG technician was careful to check that the subjects did not fall asleep, and this never happened. The signals were firstly examined by an expert neurologist in order to eliminate EEG segments containing artifacts.

The main purpose of this part of the work was to analyze what happened in the brain while listening to music. So, raw EEG were saved in Ascii format before elaborated via the package Matlab R2019, for Mac Os X. The signals were pre-processed (Butterworth passband filter) for minimize the noise signals coming from eyes blinking (low-frequency noise) and muscle movement (high frequency noise).

We computed the Power Spectrum Density (PSD), by standard Fast Fourier Transform (FFT) approach (Welch procedure: average of non-overlapped epochs of 2 s, over intervals lasting 120 s).

To obtain a measure of global activity, in each subject, we averaged PSD measures for each channel, before, during and after the listening. This procedure was repeated dividing the channels longitudinally, separately for the 8 channels of the right and left hemisphere, in order to study brain asymmetry. Finally, we have considered, for each subject, the brain topography of power spectra along the antero-posterior axis. Spectra were computed for the anterior (channels: F7, F3, Fz, F4, F8), middle (T4, C4, Cz, C3, T3), and posterior (T6 P4 Pz O2 O1 T5 P3) regions. In particular, spectral potentials of the theta, alpha, and beta rhythms were computed, for each individual. Subsequently, $\frac{\alpha}{\beta}$ and $\frac{\alpha}{\theta}$ ratios for these spectral potentials were calculated. The global activity of the brain was estimated by $\frac{\alpha}{\beta}$

power ratio, where a ratio < 1 level indicated a relatively greater activity in the beta frequency band (i.e. greater cortical activity).

Hemisphere asymmetry was estimated by the natural logarithm of the ratio of the mean right alpha power *(RαP)* to the mean left alpha power *(LαP)* (Cacioppo *et al.* 2007):

$$\ln(R\alpha P)\text{-}\ln(L\alpha P) = \ln\left(\frac{R\alpha P}{L\alpha P}\right) \quad (1)$$

Because of EEG-correlated magnetic resonance imaging studies have demonstrated that alpha power is inversely related to neural electrical activity, a ratio below the 0 value designated a relatively greater activity in the right hemisphere.

Moreover, we have studied the shape of the $\frac{\alpha}{\beta}$ ratios simultaneously to the redundancy profiles for the 10 musical sections in which the K448' first movement can be partitioned (Hinson & Allison 2014).

Characteristics of the first movement of K448 Sonata

The sonata was composed for a performance Mozart would give with fellow pianist Josepha Auernhammer, in 1781, during the Vienna period. The first movement is an "Allegro in Sonata form". The thematic structure of the first movement of a sonata is typically composed by three main parts: Exposition, Development and Recapitulation (Newman 1983; Rosen 1988). There may also be an Introduction, usually in slow tempo, and a Coda. During the Exposition the main theme is introduced, while during the Development and Recapitulation the theme is developed, expanded and reintroduced in the end. Exposition and Recapitulation will themselves be divided in three successive areas: Main Theme, Transition and Subsidiary Theme, that can be viewed as a concatenation of different passages. There may be an Introduction and a Codetta too. Following the composition of a sonata, we have partitioned the first movement of K448 into the following 10 sections (Table 1), and that partition has been used in the present work.

Tab. 1. Sections of the first movement of K448

Introduction	
Exposition	*Main Theme*
	Transition
	Subsidiary Theme
Development	
Recapitulation	*Introduction*
	Main Theme
	Transition
	Subsidiary Theme
Coda	

Construction of time series extracted from Mozart' musical pieces

The main purpose of this part of the research project was to build the time series for the subsequent analysis of the musical signal. We focused on the sonata for two pianos K448 and on a selection of Mozart's string quartets (K80, K155, K156, K458), considering each instrument of the quartet (two violins, viola and cello) separately. The whole first movement was analyzed for each excerpt and, for K448, the subsections of the movement were also analyzed.

We considered each musical piece in two different ways: as a sequence of integer numbers, each of them labelling a different musical tone (first sequence), or a different melodic interval (second sequence). The numbers were automatically extracted from MusicXML files, utilizing Music21 for Mac Os X, a Python-based open-source toolkit for computer-aided musicology created by the M.I.T. (Massachusetts Institute of Technology), for each instrument. Briefly, when the pitches are consecutive, their distance is referred as melodic interval. We have estimated the number of tones between two adjacent pitches, considering that both the ascending and the descending intervals were positive. For simplicity, if the number of tones was greater than 12, the value modulo 12 was considered. Thus, melodic interval could vary between 1 and 12. Automatically identifying melodic intervals, and the melody, in a polyphonic structure is still an only partially solved problem. Thus, we have separately extracted the solo parts of violin I and II, viola and cello, while a professional musician collaborated with us for the detection of melodic intervals of the two pianos for the K448 Sonata. The time series were associated to a single instrument of the piece.

Assessment of predictability and surprise in time series, by using entropy

The main purpose of this part of the work was to identify those possible peculiar characteristics of the K448 Sonata that could explain its effects on the listener's brain. We then measured predictability and surprise levels, through entropy and Hurst exponent, in the time series previously extracted from the musical signal. Concerning the concept of entropy, it is observed that, in information theory (Shannon 1948), the information content (or the surprisal) I of an event x emitted from a source X, is defined as:

$$I(x) = -\log_2 P(x) \quad (2)$$

where P is the probability of occurrence of the event x. As expressed by the formula, high predictability results in low information, and low predictability in high information. If the source X can emit an alphabet of N symbols, the entropy E of X is the expected value of the information, and it measures the average amount of information:

Tab. 2. Information, entropy and redundancy values of musical excerpts

Excerpt – 1st movement	I (mean and SD)	E (mean and SD)	R (mean and SD)
K448	51.99 ± 0.50	3.09 ± 0.01	13.81 ± 0.05
K80	34.22 ± 7.15	2.93 ± 0.02	18.41 ± 0.48
K155	47.20 ± 6.71	2.97 ± 0.10	17.29 ± 2.78
K156	51.64 ± 2.35	2.87 ± 0.15	20.01 ± 4.12
K458	40.73 ± 4.14	2.82 ± 0.02	21.27 ± 0.42

I = information; E = entropy; R = redundancy; SD = standard deviation.

$$E(X) = -\sum_{i=1}^{N} P(x_i)\log_2 P(x_i) \quad (3)$$

where x_i is the event emitted from the source X with probability $P(x_i)$. According to Shannon, the most uncertain situation has the maximum entropy:

$$E_{max}(X) = \log_2 N \quad (4)$$

i.e. when the $P(x_i)$ are all equal, we are in the state of maximum uncertainty, or we have the maximal amount of information. The ratio between $E(X)$ and $E_{max}X$ is defined as relative, or normalized, entropy $E_r(X)$, while the redundancy:

$$R(X) = 1 - E_r(X) \quad (5)$$

is the percentage of information that remains automatically associated with the constraints of the alphabet, or that portion of the message which is predetermined by the source X. If applied to music, information refers to the freedom of choice which a composer has in working, and/or to the degree of surprise which a listener feels in responding to the results of a composer's tonal choices (Youngblood 1958). Thus, in the last interpretation, entropy may be considered as a measure of novelty, and surprise. Redundancy, as the name implies, measures how much may be discarded without losing essential information, i.e. the amount of constraints imposed on a musical piece due to its musical structure. In this study, we have estimated I, E and R twice, after calculating the occurrence of each musical tone, and the occurrence of each melodic interval, for the time series.

Assessment of predictability and surprise in time series, by using Hurst exponent

The English engineer and hydrologist Harold Edwin Hurst, who spent much of his academic life studying water storage issues, invented a statistical method, Hurst Exponent (H) that is applied in several areas of data elaboration, including fractals and chaos theory, long-memory processes and spectral analysis (Hurst 1951; Hurst *et al.* 1965). It provides information on correlation and persistence of time series, which makes

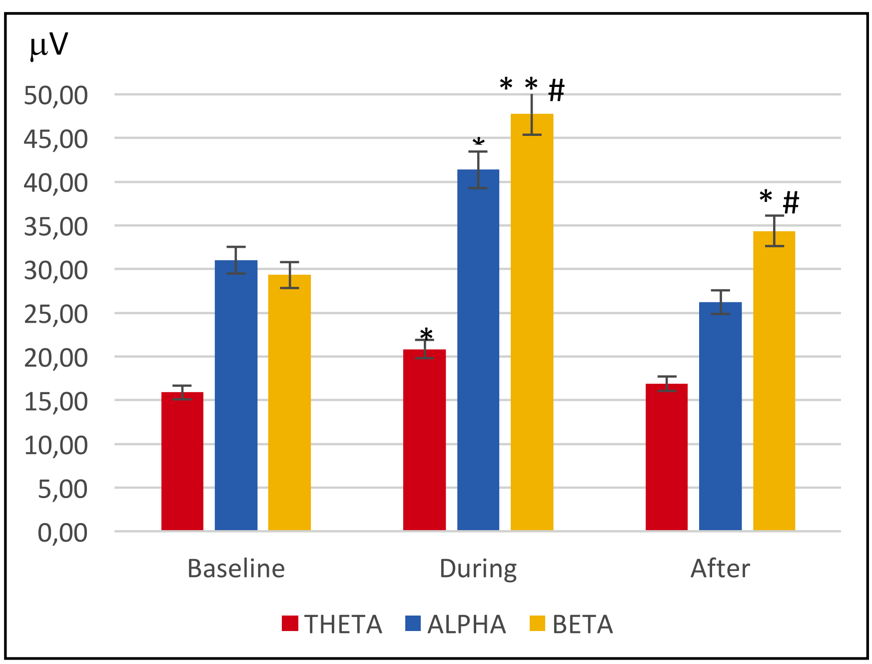

Fig. 1. EEG rhythms before, during and after music listening
*$p < 0.05$ vs. baseline; **$p < 0.01$ vs. baseline; #$p < 0.05$ vs theta and alpha rhythms

Tab. 3. Comparison of entropy and redundancy values among composers

Mean values	Mozart	Schubert	Mendelssohn	Schumann
E	2.91	3.13	3.03	3.05
R	19	13	15	14

E = entropy; R = redundancy.

H a good index for studying complex processes. The values of the Hurst Exponent can be estimated using the Rescaled Range ($\frac{R}{S}$) analysis of time series. The $\frac{R}{S}$ analysis has been originally developed by Hurst to elaborate long records of natural phenomenon, precisely of the floods the Nile River, when he observed the accumulation of values above and below the mean while tabulating the river level over the years.

Briefly, a log-log plot of the $\frac{R}{S}$ statistics vs the number of points of the time series should be a straight line with the slope being an estimation of H. We have implemented the $\frac{R}{S}$ method, by using R 3.6.1 package for Mac Os X. Hurst analysis was carried out both on the time series of the semitones and melodic intervals, and also on the EEG channels. Regarding the EEG channels, we followed the procedure previously described by Rahmani *et al.* (2018). Mandelbrot & Wallis (1968) showed that the Hurst exponent can take a value between 0 and 1, so one can classify any time series according to the value H assumes. In particular, if $\frac{1}{2} < H < 1$, then H indicates the presence of a persistence in the series. Therefore, if the variable has maintained an increasing trend over a certain time interval, it is likely to continue with the same sign in the following interval. This behavior was called by Mandelbrot the "Joseph Effect", the name deriving from the biblical story of the seven-year prediction of abundance followed by seven years of famine. If it is applied to EEG, H is a measure of the long-memory properties of signals. Similarly, when H is used for music, we could interpret the possible persistence of the time series as a scarce presence of surprising elements in the piece, over a long interval.

Statistics

Statistical analysis was performed using IBM SPSS® Statistics package, version 20, for Mac Os X. Summary of the data was expressed as mean and standard deviation. T-test and one-way analysis of variance or, if necessary, Wilcoxon and Kruskal-Wallis test, were used to compare data. The significance level p was set at 0.05.

Results

Results on the elaboration of EEG signals before, during and after K448' listening

Global levels of theta, alpha, and beta rhythms, prior, during and immediately after listening to the K448 were estimated (Fig. 1). Spectral analysis showed that mean beta rhythm significantly grew (63% of the basal value; $p < 0.01$), this effect remaining immediately after listening, but to a lesser extent (17%; $p < 0.05$). Mean theta and alpha waves also significantly increased

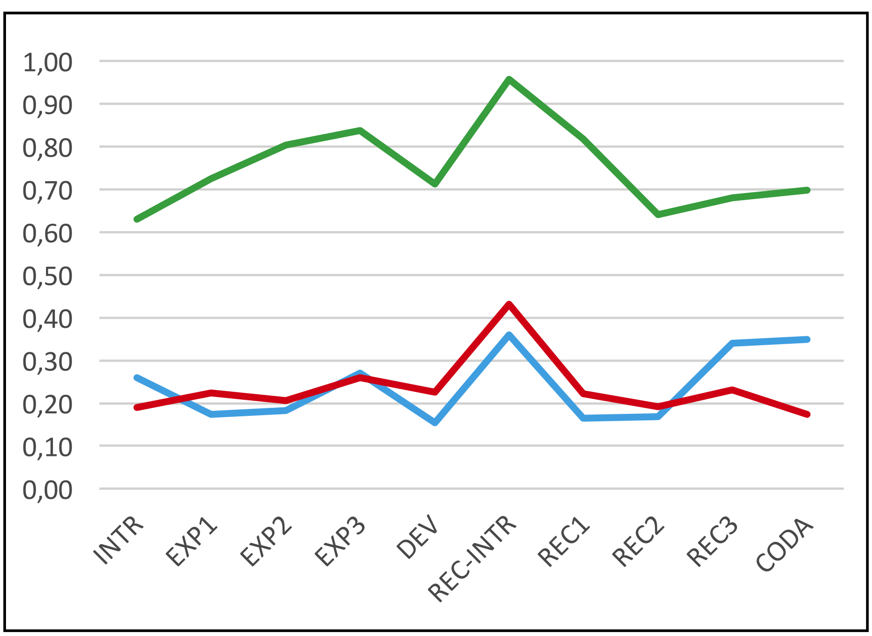

Fig. 2. Curves of redundancies and $\frac{\alpha}{\beta}$ ratio
Blue: profile of redundancy of time series of musical semitones;
Red: profile of redundancy of time series of melodic intervals; Green: line of right $\frac{\alpha}{\beta}$ ratios.

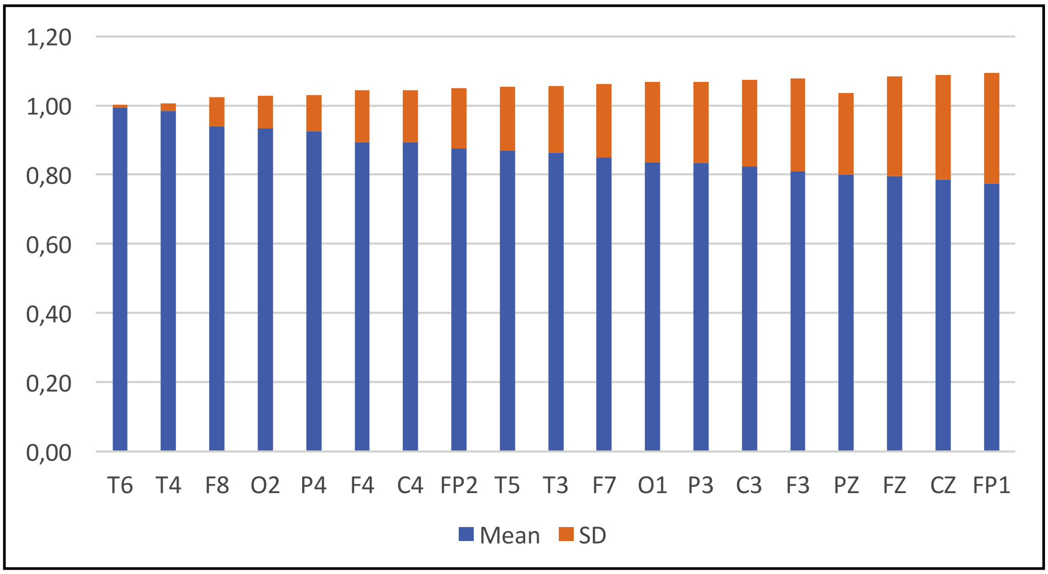

Fig. 3. Hurst exponents of EEG channels
Blue: mean values; Orange: standard deviation (SD).

during the listening (31% and 33% of the basal value, respectively; $p < 0.05$), but then returned to the initial values. Furthermore, we observed a slight predominance of alpha waves compared to beta, in basal condition, and a significant prevalence of beta rhythm during and after the listening to music. The results of the analysis of the EEG signals of the anterior, middle and posterior regions showed that the predominance of the alpha rhythm, in basal conditions, was more evident in the posterior region. On the contrary, the prevalence of the beta rhythm while listening to Mozart's music, maintained even immediately following, was similar in all three brain regions. When we compared the mean right and left hemispheres, the natural logarithms of the right / left alpha power ratio were negative numbers, especially during the listening to music (before: - 0.05; during: - 0.12; after: - 0.06), suggesting a relatively greater activity in the right hemisphere. Concerning the indices, $\frac{\alpha}{\beta}$ ratio was below 1 value both during (0.87), and after (0.76) Mozart's music, while $\frac{\alpha}{\theta}$ ratio was always greater than 1 (1.95; 1.98; 1.65 before, during and after, respectively). Furthermore, a simultaneous analysis of the EEG signal and redundancy profile while listening to K448, after splitting the sonata into 10 sections, was performed. Interestingly, the maximum $\frac{\alpha}{\beta}$ ratio (0.96 in Introduction of Recapitulation section of sonata) in the right hemisphere, probably suggesting lower cortical activation, coincides with the peaks of redundancy, indicating more predictability (Fig 2).

Results on the application of entropy to Mozart' musical pieces

Concerning the application of entropy concept on the analysis of musical semitones of Mozart' pieces, the mean values estimated on musical instruments, are given in Table 2. We found that maximum values of entropy and information were reached by K448, while the highest values of redundancy from K458.

By repeating the same procedure to melodic intervals, results confirmed that the peak of entropy was reached by K448 (2.98 ± 0.02), and the maximum of information by K458 and K448 (56.49 ± 8.25 and 55.78 ± 1.01, respectively).

To complete this phase of the study, the mean values of the entropy and redundancy of all the considered Mozart's pieces were compared with the values obtained by Youngblood (1958) for a selection of compositions by Mendelssohn, Schubert and Schumann. Results are shown in Table 3.

In the complex, although with the limit of a partial selection of pieces and composers, from the observation of tables, it emerged how, in average, Mozart presented lower entropy than Schubert, Mendelssohn and Schumann but, in the considered set of Mozart excerpts, K448 had higher entropy.

Finally, when we have studied the entropy profile while listening to K448, after splitting the first movement into sections, we found higher levels of entropy in the Exposition.

Results on the application of the Hurst exponent H

We have firstly estimated the Hurst exponent H of both the time series of semitones and melodic intervals of Mozart's pieces. H was greater than 0.50 for each composition, suggesting a strong correlation in the data, which leads to long-term memory. However, while the H exponents obtained for melodic intervals were comparable among the musical pieces, as far as semitones were concerned we observed lower value of H for K448 (0.69 ± 0.01) than the other excerpts (maximum value for K80: 0.79 ± 0.06), in line with the results obtained with entropy.

We have also employed Hurst analysis on EEG signals during the listening to K448, for each channel. The figure 3 presents the average level of H of our sample, for each channel of the EEG, while listening to the first movement of sonata. The picture shows that, for each channel, H was persistent (minimum value: 0.77). Furthermore, mean Hurst exponent of the right channels was found to be significantly higher than the left one ($p < 0.05$).

Discussion and conclusion

The purpose of this research was to explore the reasons of the positive effect of Mozart's music on the brain, using an analysis of both the EEG and the musical signal. Some Authors (Rideout 1996; Nakamura 1999) described that exposure to music correlated with changes in EEG power spectrum, suggesting power spectrum as a marker of music effects. We have performed a spectral analysis of the EEG signal, aimed to estimate relative brainwave power, focusing our attention on theta (4–8 Hz), alpha (8–13 Hz) and beta (13–30 Hz) rhythms. Generally speaking, in humans, theta band appears to reflect active operations of the generative cortex, especially during high-level cognitive processes (Cavanagh & Frank 2014). Alpha band is the major rhythm seen in normal relaxed adults, and it is predominantly in the awake-resting state (Klimesch 2012). When the subject is relaxed with eyes closed, the background is usually characterized by the posteriorly dominant alpha rhythm, what actually recorded in the present study. Beta is primarily related to cortical integrity, increased alertness, and cognitive process (Kučikienė & Praninskienė 2018).

In our research, we found that Mozart's K448 induces cortical EEG activity changes. A growth of over 60% of beta band during the listening to music, and a prevalence of beta rhythm during and after the listening were observed. Since human beta oscillations have been linked to attention, cognitive control and emotion (Symons 2016), the effect of music on the beta increase could be related not completely to attention but also to emotion. Nevertheless, an increase of 30% in the theta band was also observed, reinforcing the hypothesis of an effect of music on cognitive control. This hypothesis is in accordance with several researchers. For example, Finnigan and Robertson (2011) demonstrated an association between theta and cognitive performance in healthy older adults. Moreover, increased theta oscillations have been described during a variety of learning tasks (including recognition, recall, and virtual spatial navigation), working memory tasks, and across a variety of meditation practices (Lee *et al.* 2018). Finally, there was an increase in alpha waves, possibly related to a relaxing effect of the music, and/or because at 13 Hz there was an overlap of the spectrum of alpha and beta bands.

We have also observed that theta and beta have a comparable trend in the brain regions considered, during and after the listening, as if music increased couplings linking anterior, middle and posterior regions. This result appears in line with the fact that theta rhythms are synchronized across brain regions, especially during complex tasks (Mizuhara 2004).

Furthermore, before listening the $\frac{\alpha}{\beta}$ ratio was greater than 1, while listening to music the relationship reversed confirming a growth in the cortical activation. It is intriguing how this ratio remains less than 1 even immediately after listening to the K448, in support of the data that there is an effect of Mozart's music at least in a short term (Rauscher *et al.* 1993).

On the contrary, the trend of $\frac{\alpha}{\theta}$ ratio proved less sensitive in detecting cortical changes, being substantially comparable during the experimental test. According to Schmidt *et al.* (2013), who defines a level greater than 1 as normative value of the $\frac{\alpha}{\theta}$ ratio in healthy subjects, our ratio varied between 1.65 and 1.98.

Concerning the study of brain symmetry, we have observed a slight predominance of the right hemisphere. The result is not surprising. Indeed, although music listening is a complex process regarding both hemispheres, the involvement of right brain hemisphere is well established [34]. The same model of the trion (Leng *et al.* 1992) predicted increased synchrony between musical and spatio-temporal centers in the right cerebral hemisphere. Furthermore, none of our subjects were musicians, and functional symmetry appeared increased in musicians compared to non-musicians (Burunat 2015). It is interesting how Twomey and coworkers looked at failure to induce "Mozart effect" in a musician group on verbal and spatiotemporal tasks, probably in correlation with a ceiling effect due to the long-term effects of music training (Twomey & Esgate 2002).

It is worth noting that, when we applied Hurst analysis to the EEG signal, while listening to the first movement of the K448, we found bigger persistence in the channels of the right hemisphere, probably supporting greater complexity in the activation of the superior cortical functions in the right side of the brain.

The elaboration of musical signal, in order to identify peculiar characteristics of K448, was mainly based on the application of entropy. We have tested the concepts of entropy and redundancy (Shannon 1948; Cover & Thomas 2006) for the first time to Mozart's music, precisely to the first movement of the sonata for two pianos K448, and of a selection of string quartets. In our analysis, we have noticed more entropy in romantic composers (Mendelssohn, Schubert, Schumann) compared to Mozart, although the method used by Youngblood (1958) was slightly different. We cannot exclude that the highest entropy is partially explained from the progression of musical style over time, specifically in the passage from the Baroque period to the Romantic period. For example, Margulis and Beatty (2008) found a high correlation between the entropy and the date of birth of the composer. This result confirms the largest repeatability of Mozart music, as known to music critics, also in agreement with Hughes and Fino (2000). Hughes and coworkers, in an attempt to determine distinctive aspects of Mozart music that may explain the "Mozart Effect" in reducing seizure activity, found long-term periodicity in Mozart music significantly more often than other classical composers and was especially absent in the control music that had no effect on epileptic activity.

Returning to entropy, originally the concept of entropy was considered as a measure of disorder in a closed system (Law & Rennie (2015). Then, Wilson (2010) defined entropy as a "super-concept", because it was originated from physics, but can be applied to many interdisciplinary fields, like music. When applied to music, entropy is primarily a measure of surprise and complexity (Margulis & Beatty 2008). Therefore, higher entropy observed in the first movement of the K448 Sonata compared to the first movements of the other Mozart's compositions, may also indicates greater complexity, and it could suggest that it is this architecture of optimal complexity to "resonate" with the complexity of higher cortical functions of the brain. This result is reinforced by the observation of a lower Hurst index, albeit higher than 0.50, in the K448, found mainly in the time series of musical semitones. In other words, Mozart's K448 seems to present an "optimal complexity", that both stimulates and comforts audiences. On the contrary, too repetitive popular music seems to be ineffective in enhancing the spatial and/or spatial-temporal tasks (Rauscher *et al.* 1994). It is also probable that the differences between K448 and the other compositions can be explained by the fact that Mozart, in his genius, had an instinctive feel in balancing order and disorder of the specific piece.

Another important result concerned the simultaneous analysis of the EEG signal and redundancy profile while listening to K448, after splitting the sonata into 10 sections: the peak of EEG $\frac{\alpha}{\beta}$ ratios coincided with the maximum of redundancy. The maximum of $\frac{\alpha}{\beta}$ albeit less than 1, could indicate less cortical involvement, precisely in conjunction with greater repeatability and predictability of music. In other words, even if the hypothesis needs to be deepened by increasing the number of subjects, this data seems to confirm that it is the complexity of the architecture of music that activates cortical functions. According to some researchers, probably music acts as an exercise for exciting and priming the common finding and sequential flow of cortical firing pattern for higher brain functions (Rauscher *et al.* 1995; Verrusio *et al.* 2015).

The entropy profile of the first movement of K448 from section to section turned out to be an interesting tool to characterize the piece. We have found higher levels of entropy in the Exposition section, where in a previous work of our group (Georgiev & Manca 2019), the presence of golden number was observed. Incidentally, as the golden section is considered an indicator of beauty and aesthetic, it might be useful to spend a few words on the relationship between beauty and disorder, understood as high entropy. In our case, the association is between beauty and disorder, but in other examples in arts the link is with order. An example could be the mosaic in New Saint Apollinaire Church in Ravenna, Italy, in which the harmony for the beholder is related to the ordered repetition of the figures of saints. It is hard to draw firm conclusions, even considering that beauty is mediated by the brain, what the viewer perceives of a work of art is global, and the viewer spontaneously tends to reconstruct some internal order, whether it is faced with a simple realization or, on the contrary, very chaotic (Arnheim 1974). This topic deserves further research.

Our research is a pilot study and has some limitations, such as the small sample size, all young and female, the lack of a control condition to compare EEG during the listening to K448, the number of pieces, having investigated only some dimensions of the music (for example we have not analyzed the harmony), not having explored further subdivisions of the EEG bands (alpha 1 and 2 or beta 1 and 2).

However, albeit with the limitations reported, the present work supports the hypothesis of an overall effect of activation of the superior cortical functions during listening to K448's first movement, and immediately afterwards, in healthy young adults, of a greater complexity of this sonata compared to a selection of Mozart's pieces, and a possible relationship between the brain activation and the complex architecture of K448. Better understand the neural basis of music listening can be potentially used to determine targets for therapeutic neuromodulation, for example in patients affected by epilepsy or mild cognitive impairment. Moreover, the joint application of EEG, entropy, and Hurst exponent analysis, proved to be a useful approach in characterizing the complexity of Mozart's music and its effects on the human brain.

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Conflict of interest

All authors declare no financial interest in this manuscript and no affiliations (relationships) to disclose.

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